Rational Global Climate Policy in an Uncertain World

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1. Introduction

1.1. Two decades of failure

> [The] harsh reality we have to grasp is that the process is dead. In 2012 the only global deal for limiting greenhouse gas emissions–the Kyoto protocol–expires. There is no realistic prospect that it will be replaced before it elapses: the existing treaty took five years to negotiate and a further eight years to come into force. In terms of real hopes for global action on climate change, we are now far behind where we were in 1997, or even 1992. It's not just that we have lost 18 precious years. Throughout the age of good intentions and grand announcements we spiraled backwards… How should we respond to the reality we have tried not to see: that in 18 years of promise and bluster nothing has happened?
>
> George Monbiot, *Guardian Newspaper*, 20 September 2010.

This chapter is concerned with the formation of policy to address the issue of global warming through reductions in greenhouse gas (GHG) emissions, chiefly carbon dioxide (CO_2). Serious attention by policymakers has been paid to this issue at least since the United Nations Earth Summit in Rio di Janiero in 1992. Yet after nearly 20 years of intense activity, marked by near-universal agreement among political and social elites that global warming is a crisis requiring immediate and far-reaching intervention, and amidst repeated declarations by political leaders of their determination to take action, very little coherent policy has been implemented, there have been repeated failures by countries to negotiate treaties or other coordinating mechanisms, and there seems to be little agreement about what can or should be done in the foreseeable future.

I argue that this state of affairs is fundamentally attributable to a longstanding failure to put climate policy on an economically rational basis. Many of the most popular climate policy ideas are economically unworkable, and attempts at implementation merely sow the seeds for their later failure. As such there is no prospect for satisfactory progress in climate policy unless the flawed basis of existing global initiatives is recognized and a new direction is sought.

In this paper I will argue that there are four basic flaws in the current approach to climate policy. First, bureaucrats and policymakers have failed to recognize that the CO_2 case is exceptional, and cannot be considered a mere repeat of pollution issues dealt with in the 1970s and 1980s, such as sulfur dioxide (SO_2) emissions and chlorofluorocarbon (CFC) emissions, for which conventional institutions were sufficient to create effective solutions. Negotiating mechanisms and policy initiatives have been copied from those cases to the CO_2 case, but they are ill-suited.

Second, policy advocates have failed to come to terms with the steepness of what economists call the marginal abatement cost (MAC) curve: in other words the rate at which the costs of CO_2 abatement options go up as the emission reduction target deepens. Consequently they have embraced policy targets that cannot be achieved without incurring much higher costs than the public is prepared to accept. Some policy advocates have tried to suggest that GHG reduction policy could be economically beneficial, and much of the recent rhetoric about the "green economy" derives from this fallacious claim. The reality is that under existing technologies, policies that would be stringent enough to achieve the kinds of emission reduction targets commonly advocated would cost far more than the public is willing to incur, and far more even than the politicians making the commitment appear to realize. Consequently there is no democratic consent for the kinds of targets policymakers have regularly agreed to, preventing success at reaching them.

Third, economic analysis shows that GHG reduction policy should be focused on emission pricing, not imposition of emission caps. Regulators can choose whether to put a price on emissions and let the market choose the quantity, or prescribe an emissions target and let the market dictate the price, but they cannot pick both. For technical reasons related to the underlying science and economics, pricing mechanisms are more suitable as a greenhouse gas regulatory strategy. Yet all the major global initiatives to date, including the Kyoto Protocol and similar instruments, have focused on quantity targets. Targeting emission quantities or, worse, indirect regulatory measures aimed at manipulating modes of energy consumption, is costly, intrusive and often futile. Reorienting the discussion towards pricing mechanisms will be the single biggest challenge to putting global climate policy onto a rational basis. A continued emphasis on quantity targets will ensure that the next twenty years will be as much a costly failure as the past twenty years.

Finally, the deep uncertainties, long planning horizons and the expectation that relevant new information about both the magnitude of the environmental damages of GHG emissions and the costs of abatement will emerge over the coming years, make it necessary for policy primarily to focus on state-contingent (or adaptive) pricing rules, as opposed to fixed, long-term emission cap commitments.

The purpose of this essay is to challenge conventional thinking on global climate policy at a very fundamental level. Those who are deeply attached to the current framework of policymaking, and who believe that such a wholesale reappraisal is unwelcome or detrimental, should try to suspend their doubts and approach these arguments with an open mind. Those who want to see a rational and effective climate policy regime cannot view the past two decades with much satisfaction. For that reason the time has come for a thorough reconsideration.

1.2. Emissions versus “climate” policy

As a preliminary matter, and notwithstanding the title of this essay, I begin by pointing out that it is inappropriate to talk about “climate” policy. Instead we should talk about greenhouse gas emissions policy. The distinction is important. Policymakers are in a position to change the path of emissions over time. But nobody is in a position to manipulate the climate.

The confusion on this point sometimes leads to strange rhetoric. In a speech to the Toronto Economic Club on May 30, 2007, California Governor Arnold Schwarzenegger boasted of the deep greenhouse gas emission cuts to which he has committed his state (1990 levels by 2020), saying “I believe we can renew the climate of this planet.” The claim was printed as a headline on the front page of the *National Post* on May 31, 2007.

The claim that state-level policy can “renew” the climate of the planet is preposterous. One might renew the appearance of a chair, or a pair of boots, but in these cases there is an original appearance one is trying to re-create. What are the original conditions for the Earth’s climate, if indeed it were possible to achieve them? On a geological time scale, we might aim for tropical conditions at both poles, or the depths of a planetary ice age, or anything in between. Even if the aim is to go back to climatic conditions of the past century, which era do we aim for? To choose, say, the 1930s or the 1950s or the 1970s is to make the mistake of supposing that there is some optimal climate state and any departure from it—no matter how small—is catastrophic.

What Governor Schwarzenegger apparently meant is that he believes it is feasible to reach the greenhouse gas emission targets he has proposed. That may be true, though it will be costly. Most of his speech extolled the market opportunities for new technologies (such as electric cars and solar panels) that he wants to encourage in California. But his own policy shows that they will require large subsidies and strict legislative mandates in order to be adopted, for the simple reason that they are not profitable—in other words they are costly. Achieving his goals will require more than just minor improvements in energy efficiency and optimistic rhetoric to achieve, it will require people to be willing to incur heavy costs.

Beyond that, the deeper problem in Gov. Schwarzenegger's thinking (and that of many other world leaders) is that any target that can reasonably be said to be affordable involves such small emission reductions as to have largely undetectable effects on the climate system. In this sense there is no such thing as "climate" policy. Nobody can manipulate the climate directly. By referring to "climate" policy, proponents of specific measures create the illusion that their ideas will have direct, predictable and immediate influence on the global climate. As a result, the potential costs of global climate change are sometimes compared to the costs of local emission control policies, and if the latter are small compared to the former, proponents will claim that the policies should be adopted. But this is flawed reasoning, because local emission control policies will typically have little or no influence on the future course of the global climate. Even if multi-country agreements like the Kyoto Protocol were to be implemented, the effect on the climate would be minuscule. This can be shown in complex modeling simulations (for example, Wigley et al. 1998), but the reasons are simple to understand.

- The influence of greenhouse gases depends on the stock of such gases in the atmosphere, not the annual emissions.
- Currently there are about 750 gigatonnes of CO_2 in the atmosphere (in carbon equivalent) (Houghton 1997).
- Annual world emissions are about 8.4 gigatonnes, of which about 3 are naturally sequestered (Marland et al. 2010).
- Of the approximately 5.4 gigatonnes of net emissions, half are from the developed world.
- Of these 2.7 gigatonnes of emissions, the Kyoto Protocol called for a reduction to about 5 percent below 1990 emission levels, or a reduction of about 0.7 gigatonnes from current levels.
- It is expected that if the participants in the Kyoto Protocol fully complied with its terms, a portion of those emissions would be offset by "leakage" – increases in emissions elsewhere as firms relocate away from countries with emission restrictions. Published estimates of the leakage rate go from zero to over 100 percent, depending on assumptions about market structure and fuel supply characteristics. If we assume a 20 percent leakage rate that implies about 0.6 gigatonnes would actually be reduced under Kyoto. This is a reduction of about 0.08 percent of the stock of carbon in the atmosphere.

So even if the Kyoto Protocol had been followed, it would only have resulted in small emission reductions, with only minuscule effects on the global concentration of carbon dioxide. And the Kyoto Protocol turned out to be too costly and difficult for most countries to adhere to. To restate a point made above: *emission reduction targets that are large enough to have a noticeable effect are too costly to be implemented.* This does not mean that nothing should be done, but it does mean that targets and timetables must be based on reality, not rhetoric or wishful thinking.

It is incorrect to point to potential costs of global climate change and compare them to the potential costs of specific local emission reduction policies. The proper comparison is to look at the costs of local emission reduction policies and compare them to the benefits from the likely change in the potential future path of the global climate. If an emission reduction policy has such a small effect on the global atmosphere that a country expects no change in the future climate, then the benefits of the policy, in terms of reduced climate-related damages, are zero.

1.3. The special challenges of controlling CO_2 emissions

It might seem overly pessimistic to say that the affordable emission reduction targets are too small to have a noticeable effect. But it reflects the reality of carbon dioxide, as opposed to other forms of air pollution. Sulfur dioxide, for example, has been successfully controlled in North America and Europe. Policies implemented on both local and national levels led to large reductions in emissions and concentrations of SO_2 since the 1970s, and the costs were not prohibitive. On that basis it might be supposed that an emissions reduction programme could be implemented for CO_2, at low cost and with similarly dramatic results. But there is a problem with this argument: there are very few emission reduction methods available for CO_2 compared to SO_2.

Table 1 outlines the main options for emission reductions, and their availability in the cases of CO_2 and SO_2.

TABLE 1: ABATEMENT OPTIONS AND COSTS

		Availability	
Abatement Option	Relative Cost	SO_2	CO_2
Scrubbers installed on smokestacks	Low	Yes	No
Switch to cleaner version of same fuel	Low	Yes	No
Switch to different fuel	High	Yes	Yes
Reduce overall consumption	High	Yes	Yes

The four main abatement options are: install scrubbers on a smokestack, switch to a cleaner version of the same fuel (e.g. from high-sulfur coal to low-sulfur coal), switch to a different fuel (e.g. from coal to natural gas) and reduce the scale of productive activity. The first two are the cheapest options. In the case of compliance with the 1990 Clean Air Act Amendments, which reduced sulfur emissions in the US by about 40 percent, installation of scrubbers and switching coal types accounted for, respectively, about 45 and 55 percent of the emission reductions achieved during Phase I, particularly during the large 1994-1996 emissions decline (Schmalensee et al. 1998). But these options—which accounted for all the SO_2 reductions during that time—are unavailable for CO_2 control:

- While there is such a thing as low-sulfur coal, there is no such thing as low-carbon coal.
- There are no scrubbers for CO_2.

The latter point is well-known to power plant operators. In a study of air emission abatement options, the Ontario Power Authority (2007) noted that simulated CO_2 emission changes were entirely driven by estimated changes in output levels:

“[Projected] Reductions in CO_2 emissions between 2010 and 2014 were driven by reductions in coal [-fired electricity] production rather than by emission controls. At present there is no viable control technology available to reduce CO_2 emissions from coal plants. Therefore CO_2 reductions under all alternatives are the same.” (OPA 2007, p. 5)

Consequently the only available abatement options for CO_2 are the costlier ones, namely fuel-switching and reducing consumption. Power plants can replace boilers with gas-fired units, or they can reduce total fuel consumption, which in general requires a reduction in total energy output.

The switch from coal to other fuels is costly not only because of the capital costs, but also because of the long-term increase in the price of crude oil and gas relative to coal. Figure 1 shows the real (inflation-adjusted) prices of the three main fossil energy sources in the US market from 1949 to 2009, indexed so that each series begins at 100. Coal prices have hardly changed at all, whereas gas prices are eight times higher, down from a recent peak of 18 times higher. Oil has increased by a factor of two compared to coal, down from a peak of five times higher. It remains the case that, on the basis of relative cost and absence of volatility, coal is the best energy source.

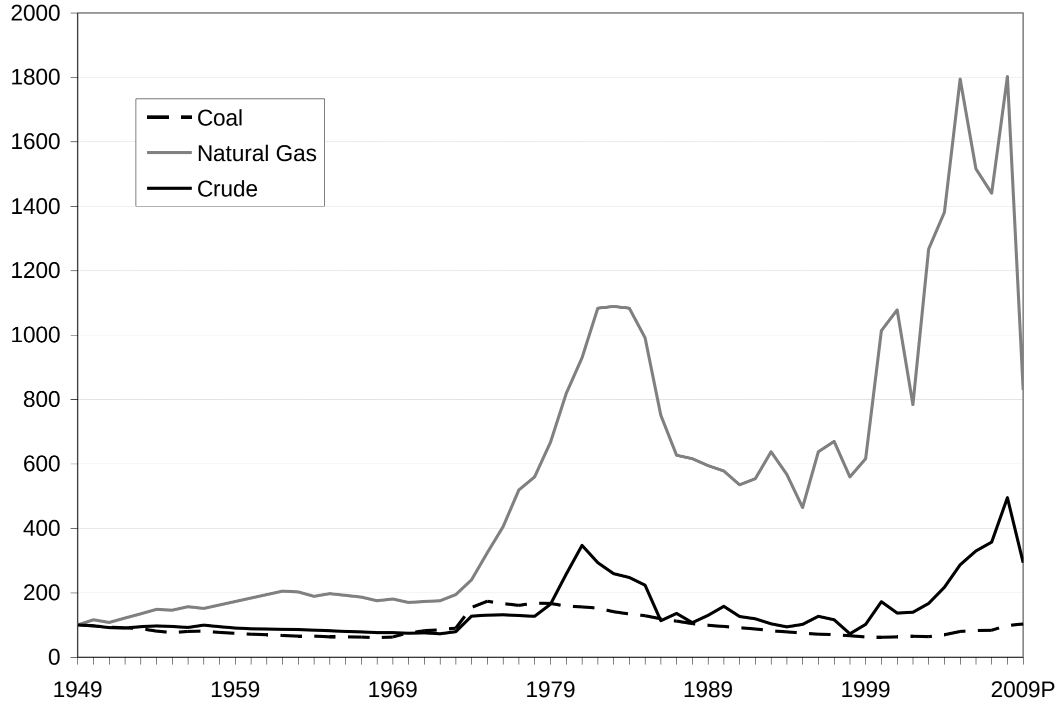

FIGURE 1: Real prices of Coal, Natural Gas and Crude Oil 1949-2009, indexed so 1949=100. Data Source: US Energy Information Administration http://www.eia.doe.gov/overview_hd.html. 2009 data: preliminary (P).

1.4. Europe versus US: Different rhetoric, similar outcome

The European Union signed and ratified the Kyoto Protocol in 2002, promising to cut greenhouse gas emissions by 8% below 1990 levels by 2008. The USA refused to do so, and has not adopted any binding emission reduction goals. Instead, in 2002, then-President George W. Bush announced a non-binding target of reducing emissions intensity by 18% below the 2002 level by 2012—something that continuation of the post-1980 business-as-usual trend would suffice to achieve. Consequently these two large players have, for most of the past decade, followed two very different objectives: in the case of the USA, business-as-usual; in the case of the EU, deep emission cuts.

Yet a look at the data shows that the two regions have not differed all that much in terms of emissions intensity (greenhouse gases per dollar of GDP). From 1995 to 2007, total EU (including Germany) greenhouse gas emissions intensity fell by about 32% (Marland et al. 2010). Over the same interval emissions intensity in the US fell about 23%. Consequently, without even trying, the US reduced its emissions intensity of production at a rate not much less than did Europe. As shown in Figure 2, in terms of declining emissions intensity, the difference between the US and Europe is only in terms of the pace, not the direction.

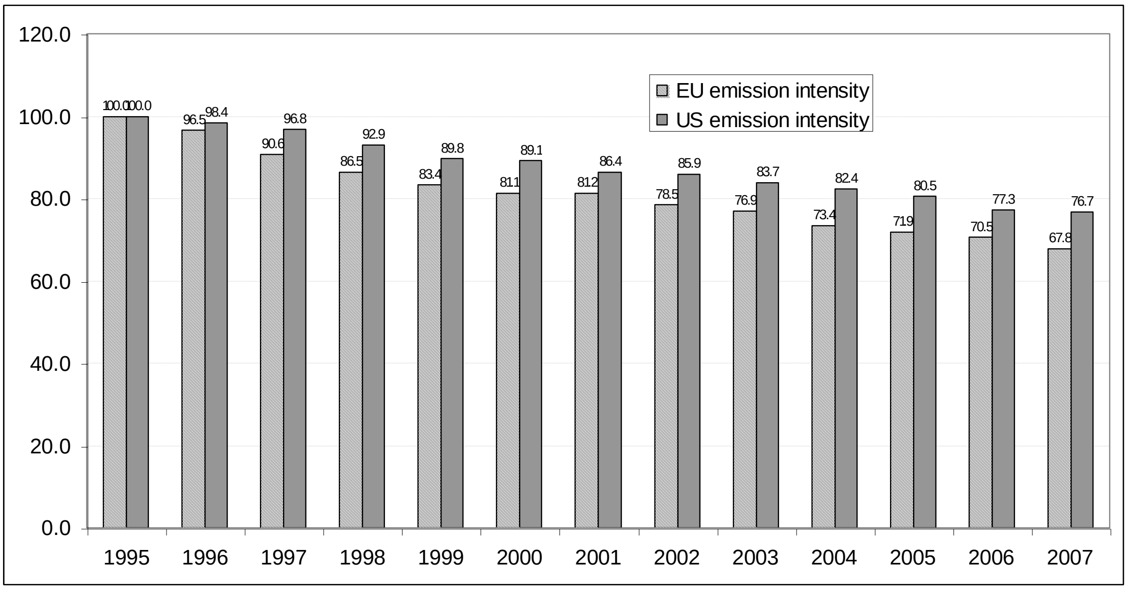

FIGURE 2: Greenhouse Gas Emissions Intensity, USA and Europe (EU-25).
Data sources: EU http://epp.eurostat.ec.europa.eu; US http://www.gpoaccess.gov/eop/tables10.html and http://cdiac.ornl.gov/trends/emis/usa.html; author calculations.

It was emphasized above that reduced CO_2 emissions implies reduced energy consumption. What does this mean for economic growth? The key question is whether increased energy consumption *causes* GDP growth, or is *caused by* GDP growth. The distinction is important. If increased energy consumption is merely a by-product of growth, it could potentially be capped and reduced without dampening economic growth. But if increased energy consumption is an input to growth, the two cannot be easily decoupled.

Detecting the direction of direction of causality (or "Granger-causality" as it is called by economists) in time series data involves statistical techniques called cointegration analysis and vector autoregression. These techniques have been applied to US data (Stern 2000), Canadian data (Ghali and El-Sakka 2004) and others. The results show that energy consumption *causes* economic growth, and in some cases the causality runs both ways. Stern (2000, p. 281) concludes as follows:

> The multivariate analysis shows that energy Granger causes GDP either unidirectionally as indicated by the first of the three models investigated or possibly through a mutually causative relationship… The results presented in this

paper, strengthen my previous conclusions that energy is a limiting factor in economic growth. Shocks to energy supply will tend to reduce output.

The phrase "*energy is a limiting factor in economic growth*" is an important statement of conclusions. Energy consumption is not merely a by-product that can be decoupled from GDP growth. Deliberately reducing energy consumption will likely reduce economic growth, thereby increasing the negative consequences for politicians when they attempt to implement the policies.

In addition, electricity price increases are regressive, meaning that the cost burden is proportionately larger on low-income households than on wealthy households. Some studies of carbon taxes have examined the regressivity issue (Jorgensen et al. 1992), and have found that whether a carbon tax is regressive depends on how it is implemented (and how inequality is measured). Dinan and Rogers (2002) found that a US economy-wide cap and trade system with grandfathered permits would be highly regressive, with the poorest households worse off by $500 per year and the richest households better off by $1,000 per year. The advantage accruing to the high income households arises because they own the companies that receive the grandfathered permits.

2. Framework of analysis

2.1. Marginal damages and marginal abatement costs

In order to truly understand the failure of climate policy, it is necessary to understand some of the incentive mechanisms that connect economies to the environment. Economies are primarily driven by the interaction between "tastes and technology": in other words the constant flow of signals between consumer preferences and producer capacity. Consumers seek goods and services that will satisfy their wants and needs. Firms make production plans for the purpose of maximizing profits. These are the forces of demand and supply that create the price-based market system.

The economic analysis of the environment treats pollution as a "missing market." Firms can increase their profits by producing more pollution (in other words by not spending money on abatement), while consumers prefer less pollution. Since there is no mechanism for consumers to charge firms for pollution, price signals do not exist and over-pollution occurs. This is the rationale for government intervention. It is not a rationale for *limitless* intervention: in particular it does not justify policies that cost more than the benefits they achieve. It is a rationale for governments either to create a meaningful price signal, or to regulate the pollution level to the point it would have reached had a proper market price signal existed. To understand the optimal form of government policy, therefore, we need to understand how the market would generate a price signal for pollution, if demand and supply mechanisms were able to function.

Demand and supply analysis is based on the study of incremental changes, since we are always starting from somewhere and considering moves in a direction. With regard to pollution, regulators are typically concerned with whether allowable levels should go up or down by some amount compared to where they are today. Thus we distinguish between *marginal damages*, or the incremental cost to society of a bit more pollution, and *marginal abatement costs*, or the cost (from society's point of view) of reducing pollution a bit.

The two concepts are shown graphically in Figure 3. Emissions (e) are shown on the horizontal axis. Dollars (or euros) per unit of emissions are shown on the vertical axis. The marginal damages line (MD) slopes upward, indicating that as emissions rise, the social cost per unit of further increments of pollution increases. The marginal abatement cost line (MAC) slopes down, reading it from left to right. If we read it from right to left, it slopes up, indicating that as emissions go down, the marginal cost of further emission reductions rises.

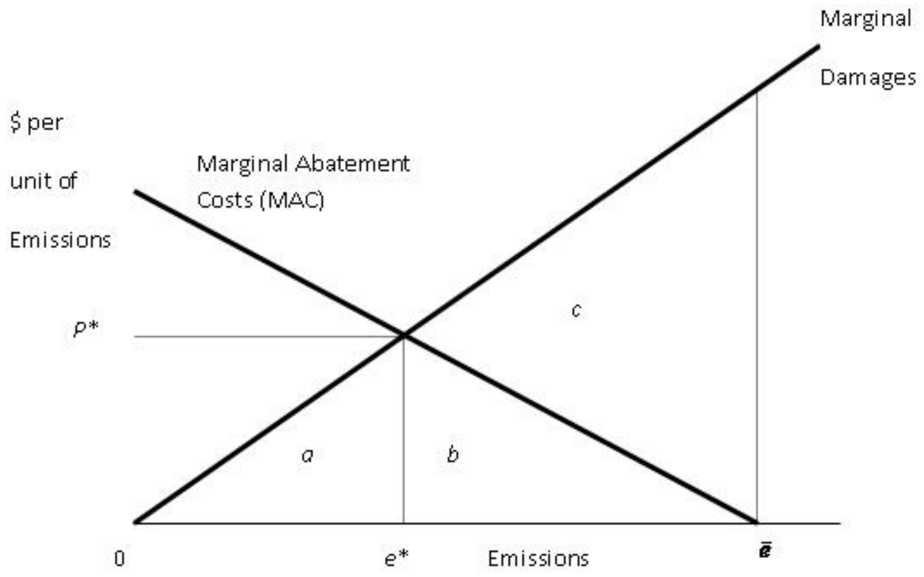

FIGURE 3: Marginal damages, marginal abatement costs and the optimal emissions level.

Both lines can be read in the increasing direction (left to right) or the decreasing direction (right to left). Formally speaking, the MD line does not represent the cost of cleaning up the pollution. Instead it is a conceptual measure based on microeconomic models of public goods. If we read it in the increasing direction, the economic definition of marginal damages is that it represents the amount of additional income that would have to be given to those individuals affected by the pollution to make them as well off in the presence of the extra emissions as they were without them. In other words it is a compensation measure. The area under the MD line over an interval shows the compensation necessary if emissions rise by the amount represented by the interval.

For example, if we compare the graph origin (0) to emissions level *e**, the area *a* shows the total amount of compensation needed for this society to be as well off with emissions *e** as they would be with zero emissions. If emissions rise by one unit, the extra compensation required is shown by the height of the marginal damages line, in this case *P**. If emissions rise to $\bar{e}$, the additional compensation would have to be *b*+*c*.

If the MAC line is read from left to right, it shows the marginal benefit to the polluter (typically a firm or industry) from being allowed to increase emissions by one more unit. If current emissions are at *e**, then the cost to the firm of having to reduce emissions by one unit is *P**, and likewise, the benefit to the firm of being allowed to emit one more unit is *P**. Here the benefit or cost is not simply the expenditure required on abatement equipment, but is the overall change in the firm’s profits. The change results in part from spending on abatement equipment, but also includes the effect of adjusting input and output levels.

The change in the firm’s profits is an indication of the cost to society of the policy change, for two reasons. First, profits arise when a firms’ outputs are worth more than the inputs they use up. That is a signal from the market that the firm is providing a net benefit to households. In this sense, profits are not a signal that firms are taking wealth away from society, but the opposite: it indicates that firms are adding value to the inputs they use. A reduction in the activity that generates value-added is a loss to society in general. Second, profits accrue as income to shareholders, including investors, pensioners, and so forth. So the loss in profits will be passed on to the shareholders in the form of lower incomes.

Suppose a polluting firm is initially restricted to emissions level e^*, and then suddenly all emission restrictions are removed. The firm will begin to increase emissions, since the marginal benefit of doing so at that point is positive, namely P^*. Emissions will continue to increase until the marginal benefit falls to zero, which is the point at which the MAC line crosses the horizontal axis, at $\bar{e}$. The total benefit to the firm of being allowed to increase emissions from e^* to $\bar{e}$ is the area under the MAC between those points, which is area *b*. Likewise, if the firm had to reduce emissions from $\bar{e}$ to e^*, the total abatement cost would be *b*.

At emissions level $\bar{e}$, which is the unregulated emissions level, the marginal damages are high compared to the marginal abatement costs. So it is socially desirable to reduce emissions. It remains so until emissions fall to e^*. At that point, the MAC of the last unit of emissions reduction is P^*, which matches the reduction in MD. If emissions are reduced below that point, the cost of doing so (MAC) would rise higher than the benefit (the reduction in MD). So the socially optimal emissions reduction target in this case is e^*.

If, on the other hand, emissions are initially at 0, then it is advisable to allow them to increase, since MAC is higher than MD; or in other words the marginal benefit of emissions is higher than the marginal damages. It continues to be advisable to increase emissions up to e^*. At that point the marginal benefit of emissions just matches the marginal cost, namely P^*. Beyond that point, additional emissions cause higher MD than the corresponding benefit (MAC), so increases are not advisable.

We refer to e^* as the *optimal emissions level*. It is the level that maximizes the net benefits of the polluting activity, or alternately, maximizes the net benefits of pollution reductions.

Every point on the MD and MAC lines has a price associated with it. This is one of the most important conceptual distinctions between the economic analysis of pollution and analyses based on ecological sciences, law or politics. In the economic analysis of pollution, a choice of an emissions level *e* implies a corresponding price level on each of the MD and MAC lines.

The emitters' response to a policy is determined by the marginal abatement cost curve, MAC. Confronted with an emissions tax at level *P**, firms would emit up to the point *e**, but not beyond that. If they did emit more, the marginal benefit to the firm, as shown by the height of the MAC line, would fall below the amount they would pay in taxes on the additional emissions, which is *P** per unit. Or, in other words, they could adopt abatement strategies that would cost less than the tax rate, so it would be to their benefit to reduce emissions. If an emissions tax were set at, say, $50 per tonne, firms will adopt abatement options that cost less than $50 per tonne rather than pay the tax.

Consequently the emissions tax rate indicates the marginal value to the firm of being allowed to increase emissions by one more unit. In this sense the MAC line is just like a demand curve of the kind shown in introductory economics textbooks.

The price level corresponding to the MD line indicates the amount of money people would need in order to compensate for experiencing one more unit of pollution. In this sense the MD line is like a conventional supply curve from introductory economics. It shows the amount that people would have to be paid to be willing to "supply" one more unit of permission to release pollution.

The combination of price and quantity axes makes Figure 3 look like a conventional supply and demand model from introductory textbooks on the principles of economics. As alluded to, the similarity is not mere coincidence. The upward-sloping MD line is like a supply curve, and the downward-sloping MAC line is like a demand curve. The difference with ordinary supply and demand curves is that, in a regular market, the price signal drives production and consumption decisions to the equilibrium point where the lines cross, but in the case of pollution emissions, the price signal is not transmitted so it cannot coordinate emission levels.

Therefore public policy should aim, as much as possible, at correcting the market failure by introducing pricing mechanisms, then letting people choose their own responses to the price signals. If the policy is set up using market principles, the result will be an approximation to the optimal emissions level *e**. Matters get more complex when we take into account uncertainty, dynamics and other such factors, as we shall do in Section 4. But the basic concept of the economic approach to environmental policy is that the solution to the pollution problem either requires providing correct *price* signals, or choosing an emissions quantity that would have resulted from the existence of price signals.

2.2. Price regulation versus quantity regulation

A price signal can be generated either by setting an emissions price (through an emissions tax) or by limiting the emissions quantity through the issuance of permits, then letting the market trade the permits and thereby establish a price. In other words, the regulator can pick a price and let the market pick the quantity, or pick a quantity and let the market pick the price. But the regulator cannot pick both.

As mentioned, if an emissions tax of P^* is imposed, firms will emit up to e^*. Alternatively, if emission permits are issued up to the amount e^*, firms will bid for them to an equilibrium price of P^*. They will not pay more than that, because they could abate their emissions at a marginal cost of P^* instead of buying another permit at a higher price. Nor will a lower price be maintained in the market, since firms would rather buy the cheaper permit than incur marginal abatement costs at a level P^*. Consequently, if the quantity of permits is e^*, the resulting market price will be P^*.

Because the reasoning is exactly the same as if we were talking about any type of demand curve, we can refer to the MAC as the “demand curve for emissions.”

Since we work under conditions of uncertainty, we need to be realistic about how much information a policymaker has at his or her disposal. For most environmental issues, a regulator can only expect to ascertain a few important details.

a. The current quantity of emissions.

b. The approximate steepness of the marginal abatement cost curve as emissions decline.

c. The approximate steepness of the marginal damage curve as emissions increase.

The first item is obtained by simple observation. The second item can be estimated by technical or economic analysis, or by obtaining information from firms facing potential regulation. In some cases firms have an incentive to exaggerate their abatement costs, but not always.[1] The third item can be obtained by analyses that combine ecological information with economic data, sometimes though the use of the so-called Contingent Valuation method, or through other empirical modeling exercizes.

Regulators cannot typically get precise information about the numbers on the vertical axis. For example, it may be known that the MD curve is fairly flat over the interval of emissions that the regulator is considering regulating, but the precise level cannot be identified with any more precision than to say it is somewhere between $10 and $30 per tonne.

Nevertheless items a—c suffice to allow us to decide whether it is better to regulate the price of emissions or the quantity. The economist who first showed this was Martin Weitzman (1974), and his analysis has been widely studied since. The intuition is as follows.

Suppose the situation is as shown in Figure 4, where the slope of the MD line is believed to be relatively flat compared to that of the MAC over the range of emissions relevant to the regulator. The optimal emissions level is e^*, but we do not know exactly where that level is. If we try to guess the right emissions *quantity*, small errors in the neighbourhood of e^* (the horizontal arrow) will lead to large errors around the optimal *price* (the vertical arrow), which is the corresponding price range on the MAC, or emissions demand curve. The large magnitude of these errors translates into unexpectedly large risks for emitting firms and the economy more generally. The range of the arrows indicates the extent to which the emissions policy will be disruptive, costly and chaotic to the economy.

But by the same token, if we pick a price, errors made on the price axis translate into relatively small errors on the quantity axis. If we aim to impose the optimal price on emissions, and we make a mistake (up or down), it will still leave us reasonably close to the optimal emissions level, and there is little danger of an unexpectedly volatile outcome. Therefore it is better to take our best guess at the price and let the market pick the quantity, than vice versa.

If the MAC is relatively very flat, the reasoning would tend in the other direction: it would be better to try to pick the optimal quantity of emissions and let the market select the price, rather than picking a price and inducing potentially large and costly swings on the quantity axis.

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[1] It depends on the form of the policy that firms expect will be implemented. See McKitrick (2010a) ch. 5.1.

The situation in Figure 4 is a reasonable schematic representation of the situation for CO_2.

- The MD line is relatively flat, because CO_2 is a globally-mixed gas. The climate is affected, not by local emissions, but by the global stock. Over the range of a nation's emissions, the MD associated with the first unit of emissions will be the same as that associated with the last unit, since the global stock will not change by much, if at all, as a result of one country's emissions over one year.

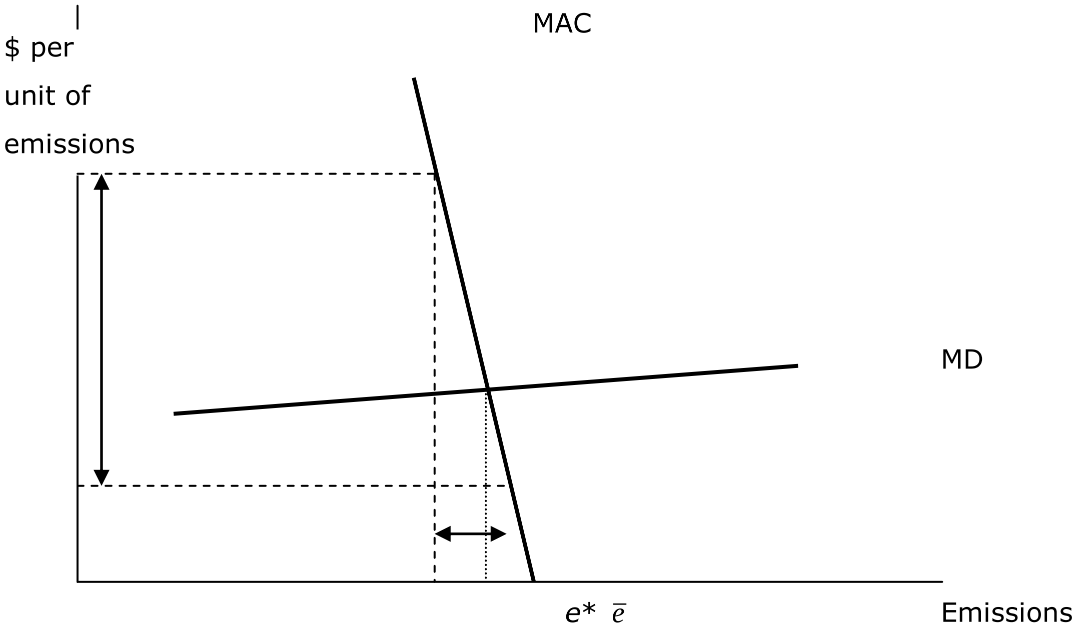

FIGURE 4: Policy choice under uncertainty

- The MAC line is very steep, because there are so few control options, as explained above. In the short run, the only way for households and firms to cut emissions is to reduce energy consumption. In the longer term, emission cuts will require major capital investments to select costlier forms of fuel or alternative energy. Two indicators suggest the MAC must be steep. First, the European emission market has recorded considerable price volatility with comparatively little quantity volatility (Ellerman and Joskow 2008), though this was partly because permits could not be banked in the first phase of the European program. The other indicator is that European emissions have not changed much despite years of effort. This is masked by the collapse of East Germany and other transition economies, and by the UK's transition from coal to gas in the early 1990s, which provided one-time reductions in CO_2 emissions. Diakoulaki and Madaraki (2007) analyse CO_2 emission growth figures for 14 EU countries over 1990-2003 in light of policy targets implemented by all countries except Spain. Emissions were unchanged or increasing in all countries except in the UK and Germany, where all manufacturing-related reductions occurred prior to 1997, growing thereafter. The authors concluded "there are no systematic signals for distinguishing the behavior of the examined countries in the pre- and post-Kyoto period." (p. 655).

The fact that emissions policy is made under conditions of uncertainty indicates that we would be better to target a price rather than a quantity. There are two other reasons to favour emission pricing rather than an emissions cap.

First, it is more cumbersome to administer a tradable permits system, since the regulator has to arrange an initial allocation (via auction, grandfathering or some other method) and must audit the markets that emerge for trades. Second, in practice, governments have typically given permits away free of charge rather than auctioning them. This happened in the case of the US sulfur dioxide allowance market and the new EU carbon permits market. The now-common idea of a "double dividend" is that if pollution policy raises revenue for the state, the revenue can be used to reduce the burden of taxes elsewhere. But a tradable permits system where permits are given away free to polluters rules this out, and offsetting tax cuts cannot be implemented. Empirical work for the US has emphasized that resorting to non-auctioned quotas for CO_2 emissions control severely increases the social cost of the policy (Parry 2003, 2004). The quotas create cartel rents for the recipients, much like agricultural marketing boards and taxi licensing schemes in cities. In effect they amplify the costs on households to fund windfall profits for emitters.

2.3. Five key economic principles

The above analysis leads to five key economic principles that should guide rational climate policy.

1. **PRICING:** Greenhouse gas emissions policy will be less disruptive and costly if it is based on choice of an emissions price, rather than an emissions reduction target.
2. **REALISM:** Because the MAC is currently very steep, the optimal emissions level is, at present, not very far below the unregulated emissions level. Regardless of how often policymakers announce plans for deep cuts, the economic costs of abatement rise rapidly, creating a backlash against any attempt to overshoot the optimal emission reduction target. It would be better to learn how steep the MAC is by observing the response to a price signal, rather than by imposing deep emission cuts and inducing an inevitable crisis as the costs explode beyond reasonable bounds.

3. **NON-REDUNDANCY:** Market mechanisms should be used instead of, not in addition to, regulatory mechanisms. Once policymakers have chosen an emissions price (or quantity), they should refrain from adding in other, superfluous technical regulations and behavioural controls that attempt to dictate how people will comply with the overall policy. For example, if power plants are required to purchase emission permits, that is a sufficient measure to regulate their emissions. To then add in rules telling households what kinds of light bulbs and home appliances they may use, or rules telling power system operators that they must purchase a certain fraction of their power from windmills, is redundant. It simply adds to the costs and creates understandable hostility against the entire concept of climate policy.
4. **COST-EFFECTIVENESS:** To maximize the abatement achievable with the limited resources that a society is willing to spend on the issue, abatement options must be ruthlessly evaluated as to whether the marginal cost exceeds the best estimate of marginal damages. Under a pricing instrument, this occurs automatically on a widespread basis. Under current technology it likely implies relatively little abatement can take place, but as technology evolves and the MAC line flattens, the emissions level will automatically fall.
5. **TARGETING:** Policies, including price instruments, should be targeted on the specific variable of interest, which in this context is CO_2 emissions. All too often policymakers apply rules to other variables (such as fuel efficiency regulations, appliance size, type of light bulb, etc.) that are only indirectly related to the issue of interest. In doing so, the costs of emission reductions are unnecessarily inflated and made less effective.

2.4. The irrationality of the "green economy"

In light of the above analysis we can now understand the problem of the "green economy." This term refers to the trend in which countries around the world, primarily in the developed world, are using special regulations and subsidies to promote the replacement of conventional power production with alternative sources like wind and solar power, and enacting micro-regulation of household electricity and fuel consumption through detailed restrictions on the types of appliances, vehicles and other household conveniences that can be purchased.

The motivation for these policies is somewhat unclear. At times politicians say the goal is job creation. The claim that jobs can be created by subsidies or regulations favoring one sector over others is an old one, and it runs aground on the same problems each time. If the industry is profitable it does not need subsidies or special regulations to grow. If it is not profitable it should not be subsidized or favored by regulators. In ordinary circumstances, when a firm continually loses money, that is society's way of indicating that the outputs it produces are worth less than the inputs used up in the process. If public policy forces the industry to grow nonetheless, this must destroy wealth in the economy. Taking that wealth reduction into account, as well as the costs to taxpayers of funding the subsidy program, ensures that the typical outcome will be that more jobs are lost than are created through such measures. In view of how often it has been tried by governments around the world, if subsidy- or regulation-driven expansion of a sector was a reliable mechanism for creating jobs, we would have done away with unemployment long ago.

Sometimes politicians claim that the green economy is aimed at taking advantage of revolutionary new technologies, out of a fear of "falling behind" in the race to adopt them. Sometimes it is the case that a genuinely new technology emerges, such as the invention of the internet, or the internal combustion engine, or the laptop computer. But the production and use of such goods spreads around the world simply because people want to buy such items and entrepreneurs profit from investing in firms that can supply them. Proliferation of new technologies does not typically occur because government promotes the industry. If it is a genuinely viable innovation, the forces of supply and demand do the work. In other words, if an economically viable technology has emerged, it will spread to the appropriate users through the marketplace. If the technology fails to spread, chances are it is not viable either technologically or economically, or both.

Finally, the green economy is often touted as a form of environmental policy, typically aimed at reducing greenhouse gas emissions. But in this case, the fact that it violates the five principles outlined above means it is an extremely inefficient tool for the purpose. Subsidies for industrial wind turbine installations and large-scale solar arrays are indirect measures that focus on arbitrary quantity targets (such as a requirement that ten percent of electricity must be wind-generated), they are pursued without regard to whether the marginal cost exceeds the marginal benefits, and they are redundant in the presence of other measures that directly cap emissions. If the concern is greenhouse gas emissions, then policy should consist of pricing policies aimed at greenhouse gas emissions. Green economy measures are unnecessary at best, and at worst wasteful and harmful to the economy.

3. Uncertainty over marginal damages

We now turn to a more detailed discussion of the marginal damages (MD) line. If we suppose that the best policy is an emissions tax, there remains the formidable challenge of trying to agree not only on what level the tax should begin at, but how it ought to evolve over time, and answering these questions requires forming a view on the potential damages associated with CO_2 emissions. This section addresses the general question of whether we should consider CO_2 emissions as an extreme hazard requiring drastic intervention, or a trivial issue that can be ignored, or something in between. I will argue the following.

1. There is a reasonable case to view CO_2 emissions as a matter of concern, though it is not obvious how big a concern it is.
2. The environmental impact of CO_2 emissions (and other greenhouse gases) depends on complex natural amplifying feedbacks whose magnitude cannot be known from first principles, and must be based on model conjectures.
3. Model conjectures are not, in themselves, evidence of the size of the overall environmental effect of CO_2. They must be tested against data.
4. The available data varies in quality and length. The longest data series tend to be of lower quality and vice versa. But some of the highest-quality data series are now of sufficient length to provide meaningful tests of model conjectures.
5. There are some statistically (and climatologically) significant discrepancies between the projections of climate models and observations that indicate feedbacks are smaller than conjectured in climate models.
6. The monitoring systems now in place will provide enough high-quality data over the next decade to resolve the lingering questions about the effect of CO_2 on the earth's climate.

The following sections discuss these points.

3.1. CO_2–induced warming and feedbacks

Solar energy warms the land and ocean surface. In order to maintain energy balance, the earth must emit the same amount of energy back to space as it receives from the sun. Energy is drained from the earth's land and water surfaces in two ways: radiation and convection. Radiation is the emission of infrared energy upwards into the atmosphere. Convection involves of the exchange of warm air at the surface for cool air from above, leading to the formation of major air circulation patterns, wind systems, cloud and storm formation and other features of the earth's weather system (Held and Soden 2000, Houghton 1997, Essex 1991).

Emissions of CO_2 and other greenhouse gases makes the air more opaque in the infrared, making the atmosphere less efficient at radiating energy to space. To maintain emission intensity requires an increase in atmospheric temperatures and changes in the convection activity. While the change in temperature is typically considered to be relatively predictable, the changes in convection and circulation activity involve problems of turbulence and cannot be predicted from first principles. For this reason, numerical climate models, or General Circulation Models (GCMs), are used. The current scheme, as embodied in the models used for the 2007 IPCC Report, is that a doubling of CO_2 levels in the atmosphere would lead to a relatively small increase in the average temperature (about 1 ^{o}C, see Held and Soden 2000) which would then be at least doubled by water vapour feedback, leading to a two to four degree warming once the feedback processes, chiefly water vapour accumulation, are included. Much of the concern about CO_2 as a policy matter arises from the magnitude of the potential feedback effects, rather than the effects of CO_2 itself.

Climate models do not simply compute the formulas representing the underlying physical theory because the equations of motion apply to the local scale, such as in parcels of ideal gases or isolated volumes, and do not necessarily integrate up to the planetary scale in a known form. For that reason models rely on simplified representations, called "parameterizations," which involve simple approximations using coefficients derived empirically or through some approximating process. (Knutti 2008)

For example, cloud formation is governed by the formation of droplets at the molecular scale. Since the equations that describe droplet formation cannot be used to predict the large scale average cloud cover, the modeler must develop an empirical approximation which uses other conditions in the atmosphere over a region, including temperature, wind patterns, atmospheric chemistry and so forth, to predict the average cloud cover over vast regions and long time periods. Variations in how models represent cloud behaviour account for some of the largest differences among models (Kiehl 2007, CCSP 2008, p. 41), and even small variations in the strength of feedback processes can lead to large variations in the simulated climate sensitivity to greenhouse gases.

Since many of the processes fundamental to the size of the feedback are based on empirical approximation, testing of GCM outputs against observed data is essential for validating or refuting the hypotheses embedded in GCMs in the form of parameterizations. Model runs cannot serve as tests of the validity of models, nor can the similarity of model runs across multiple modeling groups serve as proof of the validity of models, since they may all share the same errors. Models must be tested against observational data.

3.2. Climatic data

In order to say anything at all about potential damages due to global warming, it is necessary to measure the changing state of the climate. This section will discuss the data sources in common use.[2]

Land surface data

There are three major global land surface temperature series. The Climatic Research Unit at the University of East Anglia produces the CRUTEM data products, which are described in Jones et al. (1999), with updates CRUTEM2 (Jones and Moberg 2003) and CRUTEM3 (Brohan et al. 2006). The variance-adjusted version is denoted CRUTEM3v. The Goddard Institute of Space Studies GISS) at NASA produces another series, and the third is from the US National Oceanic and Atmospheric Administration (NOAA). All three rely on an archive of weather station data known as GHCN – the Global Historical Climatology Network.[3]

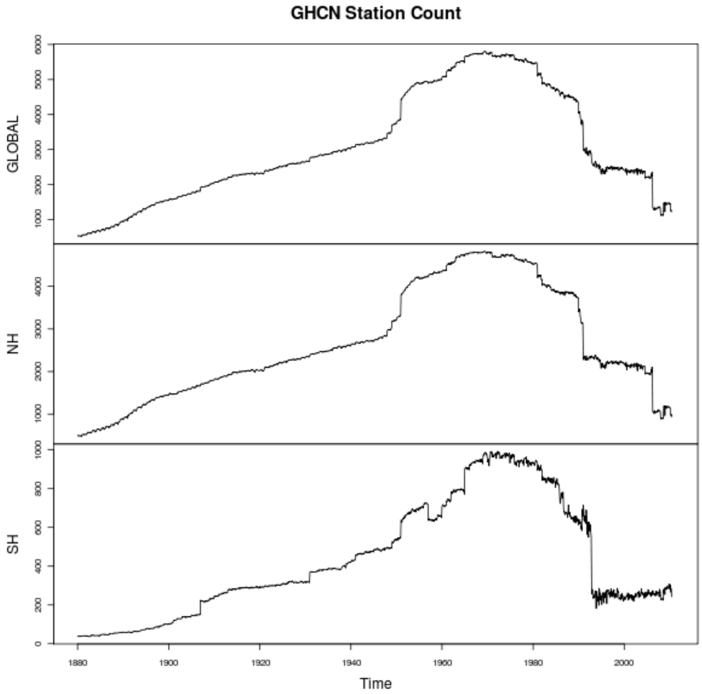

FIGURE 5: GHCN Station Count.
Top: global; middle: Northern Hemisphere; bottom: Southern Hemisphere.
Data source: GHCN. See McKitrick (2010d) for calculation details.

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[2] This section makes use of material previously released in McKitrick (2010d).

[3] The GHCN Website is http://www.ncdc.noaa.gov/oa/climate/ghcn-monthly/index.php. Sources are listed at http://www.ncdc.noaa.gov/oa/climate/ghcn-monthly/source-table1.html.

The GHCN began as a collaboration in the early 1990s between the Carbon Dioxide Information and Analysis Center (CDIAC) and the National Climatic Data Center (NCDC). Its aim was to assemble a more comprehensive temperature data archive than was then available from the CRU or other research units. The first version was released in 1992 (Vose et al. 1992) on an 'as-is' basis with no corrections for inhomogeneities.[4] The second version (GHCN v2) was released in 1997. The construction of GHCN v2 is described in Peterson and Vose (1997) and the quality control methods are described in Peterson et al. (1998). During the preparation of GHCN v2 the authors applied corrections for inhomogeneities and added metadata to the station records, such as nearby population and precise information about each station's location, so that users would better understand the source quality better.

As shown in Figure 5, there are about five times as many weather records from the northern hemisphere as from the southern hemisphere. The total number of weather station records in GHCN peaked in the 1960s and 1970s and has fallen dramatically since then in both hemispheres. Notice that the drop not only continued after 1989 but became precipitous in 2005. The second and third panels show, respectively, the northern and southern hemispheres, confirming that the station loss has been global. The sample size has fallen by about 75% from its peak in the early 1970s, and is now smaller than at any time since 1919. As of the present, the GHCN samples fewer temperature records than it did at the end of WWI.

While GHCN v2 has at least some data from most places in the world, continuous coverage for the whole of the 20th century is largely limited to the US, southern Canada, Europe and a few other locations. Global coverage with complete daily records (including maximum, minimum and average readings) is very incomplete back to 1900. Apart from the United States, southern Canada and coastal Australia, there are only a few such records, with large continental interiors in South America, Africa, Europe and Asia devoid of observations (Peterson and Vose 1997 Figures 3 and 4).

Of the 31 data sources used for GHCN, regular monthly updates are available for only three. Of these, two are US networks and one is a 1500-station network that automatically reports weather data through the so-called CLIMAT network.

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[4] The term 'inhomogeneity' when applied to temperature data is rather loosely defined. Its usual meaning is a measurement discontinuity due to a change in equipment, change in the time of observation, relocation of a weather station, etc. Some authors also use it to cover trend biases due to urbanization, land use change and other non-climatic effects, though many authors use different terms for these latter effects. For this reason, when we speak of an archive like GHCN being "corrected for inhomogeneities" this can be interpreted to mean "corrected for measurement discontinuities", but not necessarily corrected for biases due to local non-climatic effects.

The change in the sample was not uniform with respect to source type. For instance it has biased the sample towards airport locations. A problem with airports is that they are often in urban or suburban locations that have been built up in the past few decades, and the increase in global air travel has led to increased traffic, pavement, buildings and waste heat, all of which are difficult to remove from the temperature record. As shown in Figure 6, the fraction of observations coming from airports increased as a result of the station losses shown above. Most regions were high to begin with: 40 percent or more as of 1980. Now half or more of the measurements from many regions come from airports, up from just over 20 percent in the late 1920s.

The CRUTEM data product is almost entirely based on GHCN. In response to a Freedom of Information request in 2007[5], CRU officials stated that the station data used by CRU were taken from two sources: GHCN, and the US National Center for Atmospheric Research (NCAR) in the form of data sets ds540.0 and ds570.0. At the NCAR website, ds540.0 is just a mirror of GHCNv2 (http://dss.ucar.edu/datasets/ds564.0/). ds570.0 is the World Monthly Surface Station Climatology (http://dss.ucar.edu/datasets/ds570.0/), which is the largest single component of the GHCNv2 archive (Peterson and Vose (1997) Table 1). In a further elaboration, CRU stated that about 98 percent of the CRU data are from these sources.

The global temperature data product from the Goddard Institute of Space Studies at NASA uses three input archives: GHCNv2 for the world outside USA and Antarctica, the US Historical Climatology Network (USHCN, also an NCDC product), and an archive of Antarctic stations from the Scientific Committee on Antarctic Research.[6] The USHCN is the largest US input to the GHCN, but the USHCN also applies its own quality control adjustments.

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[5] Correspondence archived online at http://climateaudit.files.wordpress.com/2008/05/cru.correspondence.pdf.

[6] http://data.giss.nasa.gov/gistemp/sources/gistemp.html.

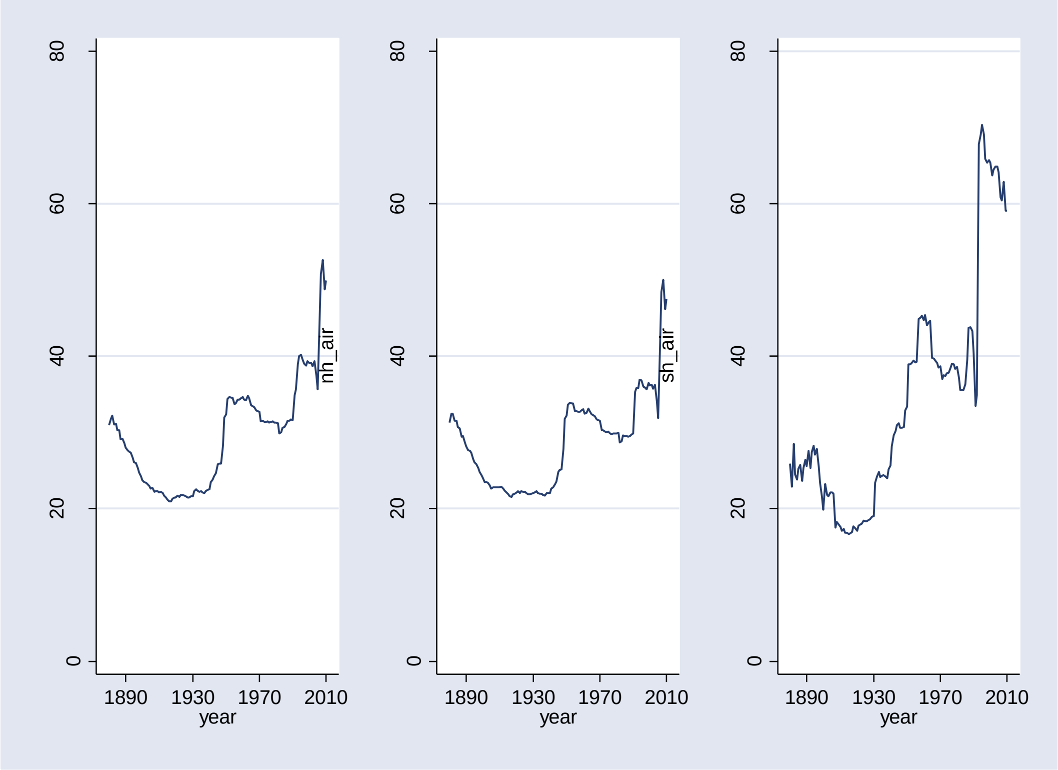

FIGURE 6: Percent GHCN stations located at airports, 1890-2009.
Left: global; middle: NH, right: SH.
Data source: GHCN. See McKitrick (2010d) for calculation details.

NOAA publishes a monthly global temperature anomaly record (http://www.ncdc.noaa.gov/cmb-faq/anomalies.html). They indicate on the NOAA website that the land record is taken from the GHCN archive, and no other sources are listed. Hence all three major gridded global temperature anomaly products rely exclusively or nearly exclusively on the GHCN archive. Problems with GHCN, such as sampling discontinuities and contamination from urbanization and other forms of land use change, therefore affect CRU, GISS, and NOAA. Decreasing quality of GHCN data over time implies decreasing quality of CRU, GISS and NOAA data products, and increased influence of data adjustments to try and remove biases.

Sea Surface Data

All historical Sea Surface Temperature (SST) products are derived from the International Comprehensive Ocean-Atmosphere Data Set (ICOADS, http://icoads.noaa.gov/) or one of its predecessors. ICOADS combines about 125 million SST records from ship logs and a further 60 million readings from buoys and other sources (Woodruff et al. 2005). ICOADS draws upon a massive collection of input data, but it should be noted that there are serious problems arising from changes in spatial coverage, observational instruments and measurement times, ship size and speed, and so forth. ICOADS is, in effect, a very large collection of problematic data.

The UK Hadley Centre produces two gridded sea surface data sets: HADSST2 and HADISST (descriptions are available at www.hadobs.org). HADSST2 are combined with the CRUTEM land data to produce the so-called HADCRU global data set. HADSST2 methods are presented in Rayner et al. (2006). Up to 1997 HADSST2 used the ICOADS data, then as of 1998 it switched to a subset of ICOADS called the Near Real-Time (NRT) Marine Observations system (http://icoads.noaa.gov/nrt.html). ICOADS itself cautions that the two are not fully consistent (see http://icoads.noaa.gov/products.html). The NRT system will be phased out at the end of 2010 since the ICOADS system is now sufficiently automated to allow continuous updating, so Hadley will likely switch back to the ICOADS source.

HADSST2 has gaps in surface coverage where data are sparse. HADISST provides globally "complete" coverage, or in other words, numbers for every grid cell, using interpolation methods. The main data source is the UK Met Office's Marine Data Bank, supplemented with ICOADS data up to 1995. A numerical method based on principal components analysis is used for infilling missing grids cells. After 1982 they use satellite data in the interpolation algorithm.

NOAA uses ICOADS data to produce the so-called Extended Reconstruction Sea Surface Temperature, or ERSST. NOAA used Advanced Very High Resolution Radiometer (AVHRR) satellite observations after 1985 to supplement coverage in polar areas. However they noted that it reduced the trend slightly and deemed this effect a cold bias, so the satellite data were subsequently removed (see http://www.ncdc.noaa.gov/oa/climate/research/sst/ersstv3.php).

GISS uses another NOAA product, the Reynolds et al. (2008) Optimal Interpolation version 2 (OI.v2) data base. This is based on ICOADS up to 1998. Thereafter, like Hadley, they switched to a continuously-updated subset, a step which caused a sudden loss of about 20 percent of the sample. The updated subset is weighted towards buoy data since many shipping records are provided in hard copy. OI.v2 also uses AVHRR satellite retrievals to improve the interpolation for unsampled regions. Unlike the ERSST data set the satellite input is still used in OI.v2.

Up to the 1930s, oceanic data coverage was limited to shipping areas. This meant that most locations in the Southern Pacific region, roughly south of a straight line joining the Baja peninsula to the southern tip of Africa, had fewer than 99 observations per decade, with many areas completely blank. By the 1970s coverage was globally nearly complete, except for the oceans south of Australia, South America and Africa. Today coverage is complete except for some polar regions (Woodruff et al. 2008, see their Figure 5).

Pre-1978 data are almost exclusively derived from shipping records. After 1978 the predominant source became drifting and moored buoys (Woodruff et al. 2008). Ships and buoys are referred to as *in situ* measurements. Another source in recent decades has been satellite observations of the ocean surface, which are used to extend coverage outside the *in situ* zones. However, as Rayner et al. (2003) point out, satellite systems themselves have problems. Satellite measurements of sea surface temperatures become inaccurate in the presence of cloud cover and variations in atmospheric dust and aerosols. Infrared data from the AVHRR system can measure SST accurately but need to be calibrated to the existing SST records in order to avoid instrument bias, and they are unreliable in the presence of low cloud cover and heavy aerosol loadings. In the past few years, new satellite platforms (Tropical Rainfall Measuring Mission or TRMM, and the Advanced Microwave Scanning Radiometer or AMSR-E) have enabled more accurate data collection through cloud and aerosol conditions.

Shipping data are bedeviled by the fact that two different types of measurements are mixed together. The older method for measuring SST was to draw a bucket of water from the sea surface to the deck of the ship and insert a thermometer. Different kinds of buckets (wooden or Met Office-issued canvas buckets, for instance) could generate different readings, and were often biased cool relative to the actual temperature (Thompson et al. 2008). Beginning in the 20th century, as wind-propulsion gave way to engines, readings began to come from sensors monitoring the temperature of water drawn into the engine cooling system. These readings typically have a warm bias compared to the actual SST (Thompson et al. 2008). US vessels are believed to have switched to engine intake readings fairly quickly, whereas UK ships retained the bucket approach much longer. More recently some ships have reported temperatures using hull sensors. In addition, changing ship size introduced artificial trends into ICOADS data (Kent et al. 2007).

Up until recently it was believed that there was an abrupt transition from the use of uninsulated or partially insulated buckets to the use of engine inlets in December 1941, coinciding with the entry of the US into WWII (Folland and Parker 1995). Consequently, the Hadley Centre adjusts pre-1941 SST record upwards, on the assumption that use of bucket-measurements also ended at that point. Recently Kent et al. (2007) compiled ship metadata and found bucket-measurements still accounted for about half the known methods for ship-derived ICOADS data as of 1980.

Thompson et al. (2008) used the Kent data and found a further problem with SST data at the 1945-46 transition. From 1940 to 1945, the fraction of data coming from US ships rose sharply to comprise over 80% of the sample, but with the end of WWII there was a jump in UK data and a drop in US data, with UK contributions going from about 0% to about 50% of the total within one year. At the same time the ICOADS average fell by about 0.5 ^{o}C, a large, spurious change which is visible in published global temperature series. Thompson et al. note that the impact of fixing this "blip" may be substantial in the mid-century. If the discontinuity is resolved by raising the post-1945 data so that it becomes continuous with the pre-1945 series, then the series will become flat, implying no warming, from about 1940 to the late 1990s, substantially changing the current understanding of 20th century global warming. If, on the other hand, the discontinuity is resolved by lowering the pre-1945 series so that it joins the post-1945 series, it will imply a much larger, and unbroken, warming trend through the 20th century than previously supposed. Either way, a large impending revision to the current understanding on global warming will come down to a largely arbitrary decision about how to fix an obscure, recently-discovered discontinuity in SST data series.

A further problem, similar to the land data, is a steady decline in the number of ships willing to supply data for ICOADS in recent years. The new worldwide ARGO float network (www.argo.net) provides, as of 2003, complete global coverage of the oceans to a depth of 2000 meters, for measurements of temperature, salinity and currents. However it cannot make up for the declining ship data since it does not measure SST directly. Instead its profiling begins at a depth of 10 meters below sea level, and its intake pumps switch off at 8 m below sea level.

A further challenge is posed by sea ice. Ice-covered regions are hazardous for shipping so data are sparse prior to the satellite era (circa 1978). Historical sea-ice concentration charts for the Northern Hemisphere span 1901-1995 but only the margins can be observed and coverage beyond them must be assumed uniform (Rayner et al. 2003). Also there are no data at all for fall and winter months (September—March) from 1901 to 1956, so sea ice concentration in the marginal zones must be estimated based on summertime data. Data on sea ice extent around Antarctica only became available via satellite observations beginning in 1973. Prior to that there were some observations based on research expeditions. HadISST uses a German record for 1929-1939, repeating it backwards in time to 1871. A Russian research record is used for the 1947-1962 interval. Other years were interpolated until satellite measures became available.

When producing global records, SST is combined with GHCN land data on the assumption that the two together create an average of near-surface air temperature. Marine air temperature records (as opposed to SST) are very sparse and have been affected by the growth in ship height over the century, meaning that air temperatures are not strictly comparable over time except in the cases where they are measured at a consistent height. There have been few tests of the match between SST and air temperature trends. Christy et. al. (2001) focused on locations where they could directly compare air and SST readings in the same places. They examined 1979-1999 SST and Marine Air Temperature (MAT) data from ships, as well as data from weather satellites, weather balloons and a network of buoys in the tropical Pacific. The buoy network data are especially useful since they measure temperatures at one meter below the surface and three meters above it in the same location. In all comparisons of SST and air temperature they found that the ocean has been warming relative to the air, indicating that SST overstated air temperature trends. Moreover, three of the air temperature data sets (satellite, balloon and reanalysis) indicate marine air temperatures just above the ocean surface had been *cooling* throughout the tropics at an average rate of between 0.01 and 0.06 ^{o}C per decade since 1979, even while the SST data showed *warming*. The authors re-calculated 1979-1999 global average temperatures over intervals where air temperature data were available instead of SST, and the global trend was reduced by 0.05 ^{o}C per decade.

Satellite measurements of air temperature

An alternative to surface data became available when Spencer and Christy (1990) published a new climatic data series based on an analysis of data retrieved from the Tiros-N weather satellites launched by the US National Oceanographic and Atmospheric Administration (NOAA) in 1979. The satellites carry microwave sounding units (MSU) that measure radiation emerging from oxygen molecules at different layers of the atmosphere, taking a near-complete sample of the entire troposphere and stratosphere each day. Each reading can be interpreted as a proxy for the bulk average of the air temperature.

The advantage of the MSU series is that, by calibrating the MSU data against atmospheric temperature measurements from a global network of radiosondes,[7] Spencer and Christy were able to provide the first global mean temperature

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[7] Radiosondes are thermometers mounted on weather balloons that transmit temperature readings by altitude to monitors on the ground. A global sample is obtained from a network of meteorological stations.

series based on a consistent sampling method that covered the entire atmosphere, especially the all-important tropospheric region. The disadvantages include the following.

- The series only goes back to 1979. While it currently provides a 30-year sample that corresponds with the strongest period of surface warming, it cannot be used to resolve questions about mid-century warming patterns.
- At several points in the series, satellites were replaced, and the calibration over the breakpoints can affect the trend.

The Spencer-Christy data are usually referred to as the UAH series, denoting the University of Alabama-Huntsville, where the authors are located. An independent algorithm for analysing the MSU data was developed by Remote Sensing Systems (RSS) in California (Mears et al 2003). The two versions are very similar outside the tropics, but over the tropics the RSS series has a noticeably higher trend, which appears to be associated with a step-like increase around 1992 coinciding with a satellite changeover (Christy et al. 2010). The RSS data have been shown to have a post-1993 warm shift relative to weather balloon data (Randall and Herman 2008) and reanalysis data[8] (Bengtsson and Hodges 2010), as well as some other regional data sets (Christy et al. 2010).

A concern that RSS brought to attention was the possibility that spurious cooling trends might arise due to a loss of altitude over time as satellite orbits decay. Both the UAH and RSS teams have developed historical corrections for this effect. After 2002 the UAH team began incorporating MSU data from the so-called AQUA satellite system, which has on-board propulsion allowing it to maintain a constant altitude. RSS does not use the AQUA data.

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[8] Reanalysis data is obtained using 6- and 12-hour ahead weather forecasts. The weather models are initialized with observations and provide complete spatial outputs at various atmospheric layers. Since the short-horizon forecasts are the most accurate, this provides a good source of data for comparing against direct observations.

Concluding comments

My impression of the different data sets available for measuring global climate change is that the longest series, namely the land and sea surface records, have serious sampling, continuity and quality problems, making the long continuity of the data something of an illusion. The sampling problems of the land series have grown worse over recent decades. Also, it is invalid to claim that the agreement of the three global series against each other comprises a quality control test, since they all draw from the same underlying archives, implying a lack of independence. The MSU satellite data series is shorter, but has clear advantages in terms of consistency and completeness of the sample, quality of the instrumentation, and validation against independent observational platforms. For policymaking purposes I consider the MSU data the most appropriate system.

3.3. Model-data comparisons

Since parameterizations are unavoidable in models, it is important that climate models be tested against data in order to assess the quality of the empirical approximations. It is common to see simple univariate comparisons of the model-generated global average temperature to observation-based global averages over the 20th century (e.g. Knutson et al. 2006, CCSP 2008). But the global average is dominated by a slow, steady upward trend, and it is not difficult to create a model that can generate a simple upward trend. Since there are many conflicting hypotheses that can generate such a shape, observing a match between observations and models for the global average is not proof of much. For instance Knutti (2008), CCSP (2008, p. 44), Knutti and Hegerl (2008), Kiehl (2007), Hegerl et al. (2007 p. 678), Schwartz et al. (2007) and others have noted that the observed global average trend can be consistent with stronger or weaker assumptions about sensitivity to greenhouse gas-induced warming if paired with offsetting assumptions about aerosol-induced cooling, oceanic heat uptake or other mechanisms. In practice, models with stronger sensitivity to greenhouse gases tend to have stronger offsetting cooling mechanisms, to an extent that does not seem coincidental (Kiehl 2007).

GCM evaluation, as reviewed in Chapter 8 of the Fourth Intergovernmental Panel on Climate Change (IPCC) report (Randall et al. 2007) primarily consists of static reproduction tests, i.e. the ability to reproduce the distribution of mean temperature and precipitation levels, but not trends, around the world; and *a priori* process checks, i.e. whether certain known meteorological processes are coded into the models. The IPCC notes that relatively few studies have looked at whether empirical fidelity between model simulations of historical periods and observations improves the accuracy of climate trend forecasts (Randall et al. 2007 p. 594). Methods for ranking models based on the ability to capture different trend patterns across space are needed. On this, Berk et al. (2001) noted that quantitative comparison of model outputs to observed data was rare and "relies very heavily on eyeball assessments" (Berk et al p. 126). The situation has not progressed much since 2001. Neither the Climate Change Science Program review of GCMs (CCSP 2008) nor the most recent report of the IPCC provides a statistical test of how well climate models reproduce the spatial pattern of temperature trends in recent decades; instead they rely on "eyeball assessments." Chapter 9 of the IPCC report (Hegerl et al. 2007) presents a diagram and accompanying discussion (Figure 9.6, pp. 684-686) of the averaged output from 58 GCM runs and the spatial pattern of temperature trends over land from 1979-2005, comparing model runs under the assumption that greenhouse gases do not warm the climate versus runs that assume they do. It is asserted that the latter fits the data better, but no quantitative evidence is provided. CCSP (2008) presents a visual comparison of the fit between observed trend patterns over 1979-2003 and those generated by the GISS ModelE. Again the discussion is entirely qualitative—readers are not even given a correlation coefficient, much less a suite of significance tests.

One of the key tests of GCM quality is the ability to correctly represent the behaviour of the vast tropical region. The general circulation of the atmosphere is driven by the difference in heating between the equator and the poles.[9] Intense solar heating near the equator causes ascension of hot, moist air, which cools and transfers polewards about 30 degrees latitude in each direction, at which point it descends and joins a return flow towards the equator near the surface. Some of the descending air bifurcates and joins a poleward flow, with separate loops ending at the poles. Global atmospheric models must represent these processes on a rotating sphere with appropriate distributions of moisture, momentum and energy. In experiments using these models, it has consistently turned out that the strongest and earliest warming due to greenhouse gas accumulation is in the tropical troposphere. Held and Soden (2000, p. 464) report that models assign about 60 percent of the global atmospheric water vapour feedback to the upper troposphere over the tropics from 30 N to 30 S, while only about 40 percent occurs at all other latitudes.[10]

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[9] A simple schematic description of the general circulation is in Lockwood (1979) Ch. 4.

[10] These proportions refer to the 'free atmosphere' or troposphere above the boundary layer (the lowest 1—2km). Ten percent of the global effect occurs in the boundary layer, so the total tropospheric proportions are 55% tropics and 35% extra-tropics.

All climate models predict exceptionally strong and rapid greenhouse warming in the troposphere (altitude 1—16 km) over the tropics. This is shown in Figure 10.7 of the IPCC Working Group I Report, online at http://www.ipcc.ch/graphics/ar4-wg1/jpg/fig-10-7.jpg. Twelve IPCC climate model forecasts for the Fourth Assessment Report were originally archived by the IPCC, though the web page has since been removed.[11] These model experiments follow the 'A1B' emissions scenario, a medium-range emissions trajectory out to 2100. The global average surface warming as of the end of the century for the GISS model is about 2.3 C.[12] The tropospheric average is twice that, reaching 5 C, and the focal pattern in the tropical troposphere emerges at the beginning of the forecast period. The pattern was clear in all 12 climate model simulations done for the 2007 IPCC report.

Also in the 2007 IPCC Report Figure 9.1[13] a 'hindcast' is presented examining model-generated climate patterns for the interval 1890 to 1999. The same pattern shows up, implying that a strong warming trend in the tropical troposphere ought to be underway already and should be the dominant pattern of change in comparison with all other forcings.

This pattern is also shown in a model-generated 'hindcast' that simulates climatic changes from 1958 to 1999 under the assumption of strong GHG-warming, which was done for the US Climate Change Science Program Report (2006), Figure 1.3 Panels A and F, page 25, available online at http://www.climatescience.gov/Library/sap/sap1-1/finalreport/default.htm. Again, the bright disc in the tropical troposphere is the dominant feature of the diagram.

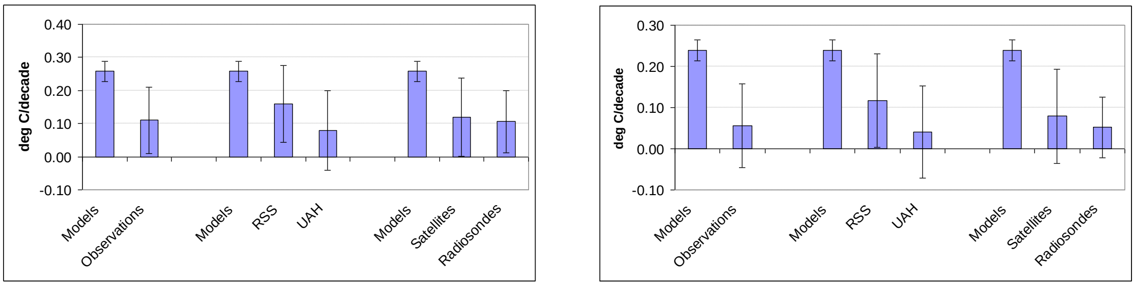

FIGURE 7: Comparison of observed and modeled temperature trends 1979-2009 in tropical troposphere.
Left: Lower troposphere. Right: Mid troposphere. Source: McKitrick, McIntyre and Herman (2010).

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[11] An incomplete archived version is available on the Wayback Machine at http://web.archive.org/web/20070925231825/http://ipcc-wg1.ucar.edu/wg1/Report/suppl/Ch10/Ch10_indiv-maps.html.

[12] IPCC Fourth Assessment Report (Working Group I) Chapter 10 Fig. 10.5.

[13] Online at http://www.ipcc.ch/graphics/ar4-wg1/jpg/fig-9-1.jpg.

Taken together the models are unanimous in implying that a pattern of strong tropical tropospheric warming should already be observed, if GHG warming is the dominant long-term effect on our climate, and will dominate the future changes to the climate. The models are unanimous that the upper troposphere warming will be stronger in the tropics than the rest of the whole troposphere, and stronger aloft than at the surface.

However, the expected tropical tropospheric pattern is not observed in the data. The discrepancies take two forms.

- At the lower- and mid-troposphere levels over the tropics, climate models predict between two and four times more warming than has been observed over the 1979-2009 interval (see Figure 7). While earlier studies examining samples ending in 1999 had claimed that while models over-predict warming the models and observations could be reconciled due to wide confidence intervals, McKitrick et al (2010) showed, on data extending to the end of 2009, that models strongly over-predict warming, and using robust parametric and non-parametric tests they showed the differences between models and data are statistically significant at the 99 percent significance level. This was based on multivariate comparisons using all available climate models, and both satellite and weather balloon data sets.
- Models also predict that warming in the troposphere should be stronger aloft (in the troposphere) than at the surface, with the ratio of trends at about 1.4:1. But Christy et al. (2010) have shown, across a wide range of observational data sets, that the observed warming aloft is *less* than that at the surface in the tropics, with the observed ratio around 0.8. This points to a serious inconsistency between models and data.

In other words, in the tropics, models consistently predict more warming aloft, and a stronger amplification factor than is observed.

This problem was noted back in 2006 by the US Climate Change Science Program (CCSP 2006). The models predict a vertical pattern for the tropical troposphere that runs opposite to what was found in 7 out of the 8 comparisons examined by the CCSP[14] (the 8th was inconclusive); moreover none of the available tropospheric data series showed a statistically significant warming of the troposphere. With reference to the equatorial region from 20 N to 20 S, page 2 of the Executive Summary states the following:

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[14] See report page 111, Figure 5.4 panel G.

Although the majority of observational data sets show more warming at the surface than in the troposphere, some observational data sets show the opposite behavior. Almost all model simulations show more warming in the troposphere than at the surface. This difference between models and observations may arise from errors that are common to all models, from errors in the observational data sets, or from a combination of these factors. The second explanation is favored, but the issue is still open.

To summarize, climate models that embed an assumption of a strong positive feedback to greenhouse warming unanimously predict that a strong warming trend of at least 0.2 degrees per decade should be observable in the tropical troposphere. Temperatures in this region of the atmosphere are monitored by weather satellites and weather balloons. The evidence does not support such a prediction. While the RSS satellite series shows a significant warming trend, it may reflect a warm bias due to a satellite calibration problem. The other series (UAH and radiosodes) agree, showing trends of 0.1 C per decade or less, in most cases insignificant. Also, the expected vertical pattern is not observed: warming aloft is not amplified relative to surface warming. Overall, we are justified in saying that the current data indicates CO_2-induced greenhouse warming is on the low end of the range of projections. Consequently, economic damages attributable to CO_2 are likely on the low end of the published range.

3.4. Economic models of MD

There have been many studies of the marginal damages of greenhouse gases, computed on the assumption that climate model projections can be taken at face value. Tol (2005) canvassed over 100 such estimates. While there was variability regarding the methodologies and assumptions, the studies had in common that they took climate forecasts and attached dollar values to the global consequences of emissions. They differed in how they valued those effects, but the overall results were nevertheless surprisingly clustered.

There was a large modal concentration between \$0 and \$10 (US) per tonne of carbon.[15] The mode was \$2/tonne of carbon, the median was \$14/tonne and the mean was \$93/tonne. Tol initially included some gray literature in his sample, with cost estimates up to \$800 per tonne. If we only consider peer-reviewed literature, the mean falls to \$43 and the mode falls to \$1.50 per tonne; Tol reports

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[15] The terminology needs to be clarified here. Damages associated with warming are due to carbon dioxide, as opposed to “carbon” (a term which can include soot particles and aerosols). However, emissions and costs are typically expressed in terms of tonnes of carbon, rather than carbon dioxide. The ratio between the two is 11/3: one tonne of carbon corresponds to 3 2/3 tonnes of CO_2. Thus a \$37/tonne carbon tax would imply approximately a \$10 per tonne carbon dioxide tax.

the latter number is robust to many configurations of quality-weighting. Removing papers that apply a pure rate of time preference below 3% the median falls to about $6/tonne (Tol, 2005, Fig. 5). In other words, half the peer-reviewed studies that use conventional discounting put the costs at or below $6/tonne.

Tol (2007) presented an updated survey, this time drawing on over 200 studies of the social costs of CO_2 emissions (in carbon equivalent). Among all studies, including both peer-reviewed and gray literature, the mean estimate of the marginal damages was $127 per tonne. Of the studies that were peer-reviewed, the mean and mode were $71 and $20, respectively. Of the studies that applied a 3 percent pure rate of time preference, the mean was $24 per tonne and the mode was $14 per tonne. Tol also noted that the mean damage estimate has been declining over time, with the mean of post-2001 studies less than half that of studies published before 1996.

So even if we ignore the fundamental uncertainty about the effect of CO_2 on the climate, there is not a lot of uncertainty about the marginal damages of carbon. The social cost of carbon, at the global level, is almost certainly less than $50/tonne, and likely less than $20/tonne. A price of, say, $15/tonne of carbon (US) would be a reasonable starting point for a carbon tax, given current damage estimates, if CO_2 really does cause global warming.

3.5. Summary of the challenges

At present, if we take climate models at face value, we could justify a low carbon tax on the understanding that it would not reduce emissions by much, instead it would merely serve to internalize an external cost. Since emissions would hardly be reduced we might ask, why bother?—a valid question. Still, there remains a fear that the global warming issue might involve an acceleration of damages in the future, or unexpectedly severe consequences that are not presently foreseen. That possibility is the reason for continued calls for sharp emission reductions. But since it is merely a possibility, and one that is not supported in current data, it does not provide a compelling basis for incurring the high costs of large-scale CO_2 emission reductions.

Nevertheless, over the next few years there may be new information, in the form of better climatic data or new technological innovations, that indicate emission reductions would be very beneficial. What is needed, therefore, is a policy mechanism that automatically incorporates new information as it becomes available and adjusts the stringency of climate policy up or down accordingly. The current policy regime involves repetitive announcements of fixed emission targets far in the future. Apart from the fact that such targets are rarely acted upon, the problem is that announcing a fixed target for ten or twenty years hence assumes that we will learn nothing in the meantime of relevance to the setting of optimal policy. But that is simply untrue. Amidst all the uncertainties of climate, we can be certain of this: there is much more to learn, and relevant new information will become available over the coming months and years.

In the final section I discuss how the prospect of new information ought to be taken into account when setting climate policy.

4. Incorporating new information in future emission pricing

4.1. Integrated assessment models and pseudo-optimal solutions

There have been several types of solutions to the problem of dynamic uncertainty in climate policymaking.[16] The integrated assessment model (IAM) approach of Nordhaus (2007) and coauthors assumes knowledge of key parameters in the functions describing the economy and the climate, yielding a smooth policy "ramp" in the form of an escalating tax on CO_2 emissions over time. This solution can only be considered optimal if we assume the model parameters are correct. But these things are, in reality, very uncertain. The proposed policy ramp is therefore only *pseudo-optimal* in the sense that it only applies under strong assumptions about key functional forms and parameters that are not put to the test by implementation of the policy.

4.2. Bayesian learning models

Kelly and Kolstand (1999) and Leach (2007) framed the problem differently by investigating the possibility of observing the response of the climate to policy innovations, and incorporating such information into a Bayesian learning routine. The goal of the policy system is to accumulate enough information that the policymaker can test, at 95 percent statistical confidence, the hypothesis that the correct policy is being implemented. In applications to climate change they have found that uncertainty about even one or two key structural parameters is sufficient to delay for hundreds of years the identification of an expected-optimal policy rule. Leach (2007) presented a model similar to Nordhaus', in which the policymaker uses all new information about the climate system's response to policy-induced emission changes. The question posed was how long it would take (given various assumed priors), before enough information is available to reject at 95 percent significance a false null hypothesis about the severity of the underlying problem. With only two model parameters subject to uncertainty, the learning time ranges from several hundred to several thousand years, depending on the base case emissions growth rate. An expanded version of the model, incorporating simple production and an intertemporal capital investment structure, not only yields a time-to-learn measured in centuries, even when most model parameters are assumed known, but depending on which of several climate data sets are used to form the priors, the policy path may never converge on the correct target.

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[16] This section makes use of material presented in McKitrick (2010b).

This result appears to be overly pessimistic because the policy maker has to wait centuries before finding out whether the chosen path was correct: in effect the answer comes too late to be relevant. But it is not the case that the IAM, or pseudo-optimal approach, is better. The real difference between them is that in the Bayesian approach we eventually learn if we are on the wrong path and in the IAM approach we never do.

4.3. Insurance and fat tails

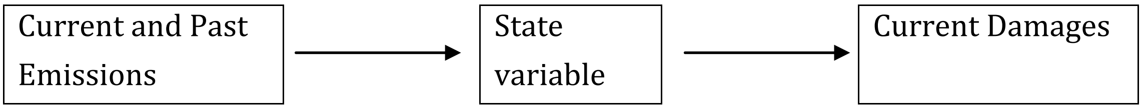
Weitzman (2009) looked at the global warming problem as one of trying to price an insurance contract when there is a nontrivial probability of extreme damages. Under specific conditions, it is impossible to place a finite value on a full insurance contract. Weitzman's model depends on some specific assumptions, some of which are conventional and some of which are not. One unusual assumption is that there is a possibility of infinite (+ or -) climate sensitivity, or in other words, that while the possibility of an extreme change in the climate (twenty degrees or more) may be small, it cannot be ruled out, no matter how large. There are also assumptions about how changes in temperature affect changes in income, and so forth. Based on this set-up, Weitzman applies financial analysis to derive the cost of fully insuring against the risk of climate disaster. The expression turns out to coincide with an equation from mathematical statistics called the moment generating function of a t distribution. Statistics textbooks caution that this expression has no finite solution. Weitzman interprets this to mean that the solution is infinite, which means the present day society should be willing to spend all current income to insure against a possible catastrophe in the future. Within the framework of this model, in order to get around this unrealistic implication, it is necessary to assume the distribution of possible climate sensitivity values is truncated, or that it has "thin tails." But, Weitzman points out, this implies that the optimal insurance policy depends on assumptions about the distribution of possible climatic changes in regions where there are too few observations to know for sure. As things stand, the Weitzman 'Dismal Theorem' does not so much prescribe an infinitely large insurance premium as point to the fact that cost-benefit analysis using IAMs is only pseudo-optimal, and that among the uncertainties assumed away are those associated with the preferences for insurance against extreme events.

4.4. The state-contingent approach

In light of the failure of previous methods to derive a plausible solution to the long term GHG emission pricing problem, I have proposed a new approach which focuses on developing a dynamic pricing rule, rather than a static long term emissions path. In the standard economic model (as outlined in Section 2 above), current damages are a direct function of current emissions:

But the situation with GHG's has two additional complexities. First, emissions may have lagged effects, and the length of the delay may itself be unknown. So we must be concerned not only with the immediate effects of current emissions, but also with their potential future effects. The other way of looking at this is that we are currently *experiencing* the effects not only of present-day emissions, but also of emissions that may have occurred in the distant past.

Second, emissions do not directly cause damages. Instead they affect some aspect of the environment (such as the average air temperature), and those changes cause damages. CO_2 emissions are not harmful in and of themselves. The harm, if any, arises from changing the state of the climate. In other words, the emissions act on a measurable state variable, and changes in the state variable cause damages. The above diagram should therefore be redrawn as follows.



The influence of current and past emissions on the state variable is complex and uncertain. While this adds to the difficulty of determining how current emissions ought to be priced, we should also note that the state variable contains information about the effect of emissions over time, and this information can be used to reduce uncertainty.

Suppose a tax on CO_2 emissions is implemented, and the amount it changes over time is tied to movements in an observable state variable, for instance, a measure of atmospheric temperature. If current and past emissions have almost no effect on the state variable, then the emissions price will not change. If they have a strong effect, and the temperature goes up, then the emissions price will go up as well. In McKitrick (2010b) I show that a simple formula using current observations on the state variable and emissions data closely approximates the unobservable optimal dynamic emissions tax based on the intertemporal marginal damages function. The formula for the state-contingent tax *t* is

$$t = \gamma \times \frac{e}{\bar{e}} \times s$$

where γ is a constant, *e* represents current emissions, $\bar{e}$ is a moving average of current and past emissions (going as far back in time as you think emissions affect the current state), and *s* is the current observation of the state variable. In this approach, γ can be chosen so that the tax rate *t* starts at a value that seems reasonable to the policymaker as of the present. Thereafter, the evolution of the tax will primarily be driven by the evolution of *s*.

In order to compute the current value of the emissions tax, we only need data on current and past emissions, and the current value of the state variable. In the case of GHG's, emissions data is readily available at the global and national levels. European data are available through Eurostat (http://epp.eurostat.ec.europa.eu) and data for all countries is available (with a lag of several years) through the US Oak Ridge National Lab (Marland et al. 2010, online at http://cdiac.ornl.gov/trends/emis/tre_regn.html).

The choice of state variable *s* must take into account the underlying science and the different quality issues of climatic data. As discussed in Section 3 above, land and ocean surface data have serious quality problems that make it unwise to use them for policy purposes. Satellite systems are more reliable for measuring air temperatures, especially those using the AMSU system for maintenance of constant altitude. With regard to a suitable state variable, I suggest using the mean temperature in the tropical lower- or mid-troposphere, as it is an indicator that all models show to be particularly sensitive to greenhouse gases, and it is continuously monitored.

Since no information about abatement costs are used in deriving the tax *t*, it may seem that it cannot be a complete policy prescription. The tax paths derived in integrated assessment models are solutions to a two-sided optimization problem, with intertemporal damages netted against intertemporal abatement costs. However, it is important to bear in mind that the formula above does not prescribe a policy *path*, it yields a *rule* that ties the tax rate to the environmental state. The actual path of taxes over time will be determined by the evolution of the state variable. The ensuing level of abatement will be determined by emitters who respond to the current and expected future tax rates according to their current and future marginal abatement costs. If the capital stock is variable then firms will respond to emission tax rates as they would to any fluctuating input costs. If capital is fixed and time-to-build lags are long, firms will need to form forecasts of the future values of the tax rate, which in turn will depend on future values of the temperature variable. In this way, imposition of the state-contingent emissions tax will create a market for *accurate* forecasts of the environmental state variable. At present, no such market exists: different parties seem to have incentives to overstate or understate global warming forecasts depending on the policy they wish to influence, or the amount of attention they want to get for their work. But if firms are trying to forecast the actual future tax rate, they will not gain from using inaccurate forecasts, instead they will gain the most from having the most accurate forecasts of the actual future path of *s*. The market will thus weed out worse quality climate models in favour of more accurate ones.

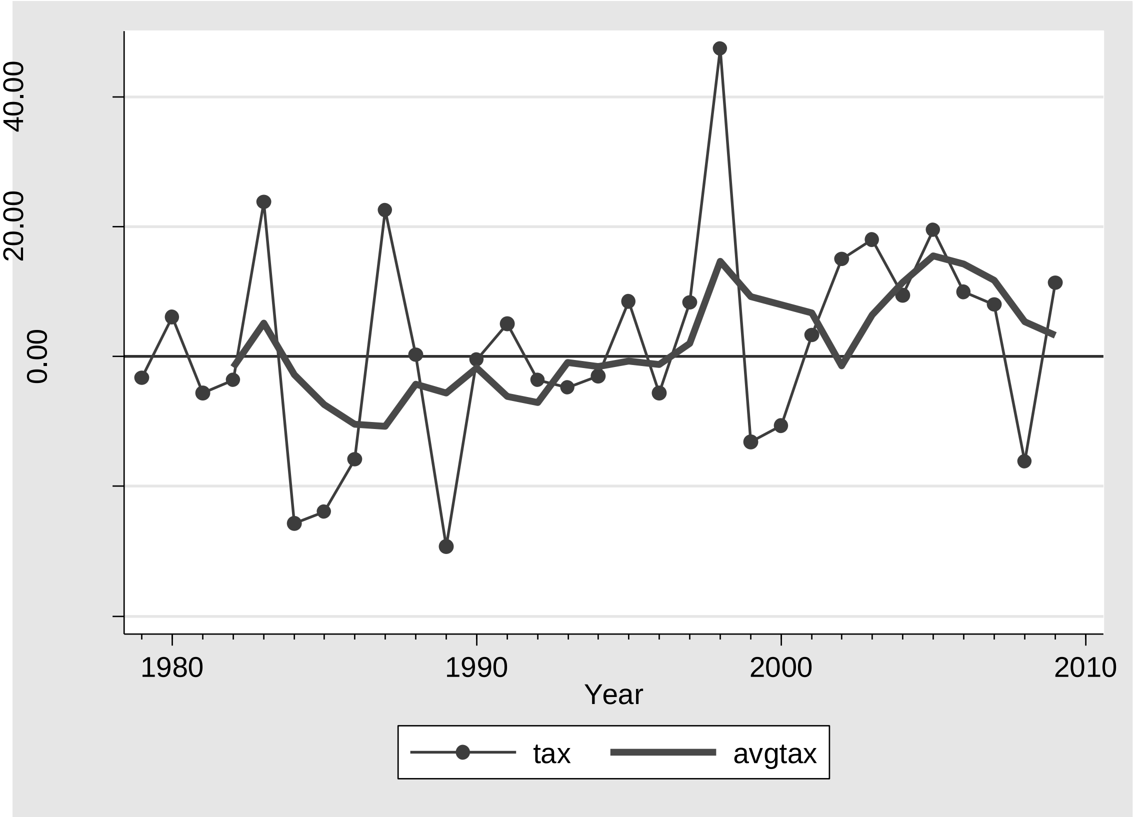


FIGURE 8: Value of state-contingent tax on greenhouse gas emissions since 1979. ‘avgtax’ denotes 3-year moving average. Source: McKitrick (2010d).

An interesting feature of the state-contingent tax is its potential ability to appeal to a broad coalition of interests. People with conflicting expectations about the future evolution of the state variable will nevertheless each expect to observe his or her preferred policy path. Those who think emissions have no effect on climate will expect low emission taxes to prevail in the future, and those who think they have strong effects will expect the tax to increase rapidly. Since each agent expects to get his or her preferred outcome, it may be easier to get agreement for implementation. One of the challenges of climate policy is the need to get agreement at the global level. Different regions have different views on the urgency of the problem and how it compares to their domestic economic priorities, which makes it all but impossible to get agreement on emission targets, or to ensure compliance with earlier agreements. Asking policymakers around the world to agree on a state-contingent tax might be easier. The tax revenue would stay within each country, reducing the burden of inequality across different nations. And during the negotiations, there would be no reason for countries that took opposing views on the likely future path of temperatures to take opposing views on whether the tax is desirable, since each party will expect to get what they consider to be the "correct" outcome.

What would such a tax have looked like if it was implemented previously? In McKitrick (2010b) I used UAH and RSS data as well as global CO_2 emissions series to compute hypothetical values of a carbon tax tied to the mean temperature of the tropical troposphere. The result for the 1979 to 2009 interval is in Figure 8. The value of γ is set so that the tax rate equals $15 per tonne of carbon in 2002, around the time when the Kyoto Protocol was being ratified. The tax path shows an upward trend of about five dollars per decade, which is slightly below the Nordhaus prescription of an increase of about eight dollars per decade. However the Nordhaus approach calls for a commitment now to a price path over many decades. The state-contingent approach only requires commitment to a rule that yields the new rate each year, or month if desired. If temperatures go up more quickly than expected, so will the tax, and if temperatures do not go up quickly, neither would the tax.

There is a similarity between the state-contingent approach to emission pricing and the mechanisms used in monetary policy. Central bankers do not commit to long term paths of interest rates or monetary growth. Instead they commit to rules that translate current economic conditions into current values of these policy targets. We would not want central bankers to commit to a fixed path of interest rates over a ten- or twenty-year time horizon, because new information will emerge in the future that will indicate what the appropriate interest rates ought to be. In the same way, it makes little sense for policymakers to commit to long term CO_2 emission prices since new information will emerge in the future about the effects of greenhouse gases and the evolution of atmospheric temperatures. It is simply unrealistic to make plans today that assume we will learn nothing in the future about whether those plans are appropriate or not.

Using a state-contingent pricing rule does not mean that we only put a price on emissions after the damage is done. Businesses are forward-looking. They will base their investment plans on the most accurate possible forecasts of the effects of emissions on future climate change. As time passes, these forecasts will be continually improved and updated. Firms that under-estimate the future path of an emissions tax will be placed at a competitive disadvantage to firms that used an accurate forecast. There will be no advantage to over- or under-estimating the emissions tax path. The optimal strategy for firms will be to estimate it accurately. If we are entering an era of rapid greenhouse gas-induced warming, and if we are able to reliably forecast that we are entering such an era, industries will know they face a steeply-increasing emission price, which in turn will lead to emission reductions and investment in the kinds of technologies that can yield deeper emission cuts in the future. But if it cannot credibly be shown that we are entering such an era, firms will only make some investments in abatement options, and await the emergence of better information. These are the appropriate kinds of responses to the dynamic uncertainties currently confronting the world.

5. Conclusions

There is probably no area of public policy in which so much effort, and so many resources, have been invested over twenty years, with such a consistent record of failure. I believe that this state of affairs has arisen because climate policy has long been placed an economically flawed basis. Badly-conceived policies inevitably fail. Satisfactory progress in forming successful climate policy therefore requires fundamentally new thinking.

I have argued that there are four basic flaws in the current approach to climate policy. First, bureaucrats and policymakers have failed to recognize that the CO_2 case is exceptional, and in particular it is not like the problem of sulfur dioxide (SO_2) or chlorofluorocarbon (CFC) emissions. In each of those cases, parties to the various negotiations were able to agree on strategies because the risks were more apparent and solutions were far less expensive. The negotiating mechanisms and policy initiatives that worked in those cases have been copied to the CO_2 case, where they are ill-suited and largely useless.

Second, and directly related to the first, policy advocates have failed to come to terms with the steepness of the marginal abatement cost (MAC) curve: in other words the rate at which abatement options go up in cost as the emission reduction target deepens. Consequently they have embraced policy targets that cannot be achieved without incurring much higher costs than the public is prepared to accept. The reality is that under existing technologies, policies that are mild enough to be affordable have such small effects on the climate as to be pointless. The policies that would be stringent enough to achieve the kinds of emission reduction targets commonly advocated would cost far more than the public has agreed to incur, and far more even than the politicians making the commitment appear to realize. Pursuit of the illusion that subsidies and regulations can create a prosperous “green economy” has only served to amplify the costs, while achieving nothing of significance for the environment.

Third, economic analysis shows that GHG reduction policy should be focused on emission pricing, not emission caps. Yet all the major global initiatives to date, including the Kyoto Protocol and similar instruments, have focused on quantity targets or, worse, indirect regulatory measures aimed at manipulating modes of energy consumption. These policies have been costly, intrusive and often futile. Reorienting the discussion towards pricing mechanisms is the single biggest challenge to putting global climate policy onto a rational basis, but it is essential if the next twenty years are to avoid the costly failures of the past twenty years.

Finally, the deep uncertainties, long planning horizons and the expectation that relevant new information about both the magnitude of the environmental damages of GHG emissions and the costs of abatement will emerge over the coming years, make it necessary for policy primarily to focus on state-contingent (or adaptive) pricing rules, as opposed to fixed, long-term emission cap commitments.

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His research areas include modeling the relationship between economic growth and pollution emissions; regulatory mechanism design; and various aspects of the science and policy of global warming. His economics research has appeared in such peer-reviewed journals as *The Journal of Environmental Economics and Management, Energy Economics, Economic Modeling, The Canadian Journal of Economics, Empirical Economics, The Energy Journal,* and *Environmental and Resource Economics.* His physical science research has appeared in such peer-reviewed journals as *Journal of Geophysical Research, Geophysical Research Letters, Atmospheric Science Letters, The Journal of Non-Equilibrium Thermodynamics* and *Proceedings of the National Academy of Sciences*. He is the author of the advanced textbook *Economic Analysis of Environmental Policy* published by University of Toronto Press. In 2002 he and Christopher Essex of the University of Western Ontario published the book *Taken By Storm: The Troubled Science, Policy and Politics of Global Warming* which was awarded the $10,000 Donner Prize for Best Book on Canadian Public Policy.

Professor McKitrick is widely-cited in Canada and around the world as an expert on global warming and environmental policy issues. He has been interviewed by numerous media including Time, The New York Times, The Wall Street Journal, The National Post, The Globe and Mail, the CBC, BBC, ITV, Fox News, Bloomberg, Global TV, CTV, and others. His commentaries have appeared in many newspapers and magazines, including Newsweek and the Financial Post. His research has been discussed in such places as Nature, Science, The Economist and the Wall Street Journal.

Professor McKitrick has made invited academic presentations in Canada, the US and Europe, and he has testified before the US Congress and the Canadian Parliamentary Finance and Environment Committees. In 2006 he was one of 12 experts from around the world asked to brief a panel of the US National Academy of Sciences on paleoclimate reconstruction methodology.