B48 2002-3

LECTURES December 10, 12

GLOBAL WARMING

A brief sketch of the science of global warming

But for the greenhouse effect, life on earth would not exist. The sun emits radiation to the earth. If we could imagine a flat surface at the top of the atmosphere, that radiation is about 340 watts per square metre (written 340 W m^{-2}). Just over 100 W m^{-2} is reflected out again by atmospheric aerosols and clouds and the earth's surface, leaving some 240 W m^{-2} which heats up the surface of the earth. The system must be in balance – energy 'in' must equal energy 'out' - so the earth needs to re-radiate this amount back into the atmosphere. But the amount actually re-radiated depends on the earth's surface temperature: the hotter the surface is the more it will emit radiation. The outgoing radiation takes the form of 'long wave' infra-red thermal radiation. If the system balanced 'naturally', then the earth's surface would have a temperature of about *minus* 19^{o}C since at this temperature 240 W m^{-2} would be emitted. Obviously, something else must be happening because at such low average temperatures life would not exist. The earth's surface is very much warmer than this 'natural' level (around +15^{o} C) and hence far more radiation is emitted than the 240 W m^{-2}. What happens is that a lot of the earth's re-radiation bounces back to the earth's surface because it gets absorbed mainly by water vapour and carbon dioxide in the atmosphere. Water vapour, CO_2 and a few other minor gases act like a 'blanket'. The balance is secured as follows:

Incoming solar radiation:	+ 340 W m^{-2}
Reflected from clouds, earth's surface etc	- 100 W m^{-2}
Net incoming radiation absorbed by earth=	+ 240 W m^{-2}
Outgoing radiation:	- 420 W m^{-2}
Greenhouse effect	+ 180 W m^{-2}
Net outgoing (thermal) radiation	- 240 W m^{-2}

The way the system balances, then, is that the earth's surface warms up compared to what would happen if we could imagine an earth not surrounded the blanket of 'greenhouse gases.'

Anthropogenic greenhouse gases

So far nothing is amiss. Indeed, the greenhouse effect is a 'good thing' for life on earth. The problem arises because humankind is *adding* to the effect by increasing the amounts of CO_2 and a few other gases in the atmosphere (notably methane – CH_4 – and nitrous oxides - N_2O). This results in the *enhanced greenhouse effect*, or *global warming*. Since the concentration of water vapour tends to be fixed (it is determined by the oceans) imagine what would happen if the atmospheric concentrations of CO_2 were increased. The effect would be to increase the radiation 'bouncing back' to the earth and reducing the radiation leaving the top of the atmosphere. For a doubling in CO_2 concentrations, the reducing atmospheric radiation would be about 4 W m^{-2}. But the system is now out of balance: 240 W m^{-2} are coming in, but 240 - 4 = 236 W m^{-2} are going out. In order to balance, something must change and what changes is the temperature of the earth's surface. Recall that if it increases, outwards radiation will increase. This will happen until the 240:240 balance is restored. But while the balance is restored, the earth has basically got hotter. For each doubling of CO_2 concentration, the temperature increase is expected to be about 1.2^oC. Various complicating factors intervene to enhance or reduce this figure. Water vapour might increase and this would make the enhanced greenhouse effect stronger still. Other factors of relevance are changes in cloud formation, changes in surface vegetation, melting of the tundra (which would release another greenhouse gas (CH_4), changes in ocean circulation, cooling effects of sulphur aerosols, and so on. The end result is some uncertainty about projected climate change but an average temperature change of about 2^oC by 2100 might be expected.

Where do the greenhouse gases come from? The fact that they come from economic activities that are so pervasive to human society largely explains why global warming control is so complicated and so controversial. CO_2 is emitted from the burning of fossil fuels, so that most electricity production and most industrial activity contribute to global warming. Since gasoline, kerosene and diesel are fossil fuels, they too contribute, which means that the entire transport sector is implicated. Methane (CH_4) is also emitted from fossil fuel burning but also from gas pipeline leaks and from decomposing vegetation. Methane emissions are therefore associated with livestock and with rice growing. Nitrous oxide (N_2O) comes from fossil burning and fertilisers. The burning of forests also contributes significantly to CO_2 emissions.

The impacts of warming

The next issue is to predict what would happen if these temperature changes are allowed to happen. The science of climate change impact assessment is very uncertain, not least because humans have the capacity to adapt to some of the expected change. There are two stages to impact assessment: predicting what the consequences will be for ecosystem change and human health, and assessing how important those changes will be. The context to all this assessment is uncertainty, not least because the *rate of change* of temperature and the *levels* of temperature change together place some of the change outside human experience. That is, we have little idea how environments and humans will respond if the worst case scenarios occur. An additional complication is that impacts will vary region by region, not just because of different susceptibilities but because there will be regional variations in temperature change, in precipitation and in 'extreme' events such as hurricanes. Summer monsoons in Asia could become heavier, but summer rains in Southern Europe could become less.

The kinds of impacts that would seem to be important are as follows. Sea-levels will rise due to the thermal expansion of the oceans. Low lying areas, such as the coastal regions of Bangladesh, and many small islands, could be seriously affected unless adequate sea defences are built and maintained. Fresh water resources could affected by saline intrusion as sea levels change. Existing dryland regions may become drier still, resulting in a greater likelihood of 'desertified' regions. Agricultural output may change adversely in some regions, due to reduced rainfall, but may increase in other areas because CO_2 also have a 'fertilising' effect on crops. While most of the work on impacts has been carried out on the agricultural sector, it is not clear that world food supply will be significantly affected: some regions will lose and some will gain. But the regions suffering losses may be some of the poorest in the world. In terms of human health there are similar ambivalent effects: if winter temperatures rise, there may be less premature deaths due to winter cold. But if summer temperatures also rise, there may be added deaths from heat stress. The pattern of the world's diseases may also change – diseases such as malaria, eradicated from Europe, could return to some areas. Perhaps the most important effects are the ones we know least about. Ecosystems change in response to climate change but, in general, past changes have occurred slowly as temperatures varied over long periods. A rise of 1 or 2^{o}C in just a century is a very fast rate of temperature change and some ecosystems may not be able to adjust. Even more speculative are the effects of extreme events: for example, the worsening of El Nino, potential effects on ocean currents and hence marine productivity.

Measuring the economic importance of global warming

How much does it all matter? Listing possible impacts is one thing. Saying how important they are, is another. Yet some idea of the collective magnitude of the impacts is essential because the measures needed to reduce rates of warming will not be cheap. Early economic studies suggested a fairly uniform measure of damage of about 1-2% of the world's entire economic output. But this is a figure relating to '2 x CO_2', i.e. for a doubling of carbon dioxide concentrations in the atmosphere. It is a benchmark widely used for economic and scientific analysis, but global warming will not stop there if unchecked, so the damages in the very far future could be very much higher. Table 1 shows some estimates of damage (*note: these estimates come from a survey paper, D.W.Pearce, The Social Cost of Carbon, which is available on the B48 website. The papers deals with many, quite technical issues, so it is only worth looking at if you find the issue of 'valuing' global warming interesting. DWP*)

Table 1 Aggregate social cost of global warming (% of world GNP)

Benchmark temperature increase for $2xCO_2$ (?)	**Pearce et al. 1996** 2.5^{o}C	**Mendelsohn et al, 1996** 1.5^{o}C 2.5^{o}C	**Nordhaus and Boyer, 2000** 2.5^{o}C	**Tol, 2002a** 1.0^{o}C
DCs	n.a	+0.12 +0.03	- 0.5 to +0.4	
LDCs	n.a	+0.05 - 0.17	- 0.2 to - 4.9	
World	-1.5 to -2.0	+0.10	-1.5	+2.3

Source: cited studies and Tol et al. (2000)
Note: + indicates a benefit, - a cost (damage)

Note that more recent studies either confirm the 1-2% figure or give lower figures. The lower figures arise because the models allow for adaptation. The easiest way to see why adaptive measures would lower damage is to think of the 'dumb farmer' syndrome. A farmer watching his crops being damaged each year would not stand idly by and let the damage be repeated year after year. He would invest in drought-resistant crops, irrigation, fertiliser etc. So, damage to adapted crops would be less than damage to the unadapted ones.

Marginal damage cost

Another way of thinking about the economic scale of the damage is to translate it back into the economic damage done by the release of one additional tonne of carbon-equivalent now[1]. Since this is the extra damage incurred for the world as a whole from releasing one extra tonne of carbon-equivalent, it can be compared directly with the costs of reducing that tonne of carbon emission. As long as the cost of control is less than the damage done, it will pay the world as a whole to take action. This is the essence of the *cost-benefit analysis* approach to global warming policy. Figure 1 shows how it would look.

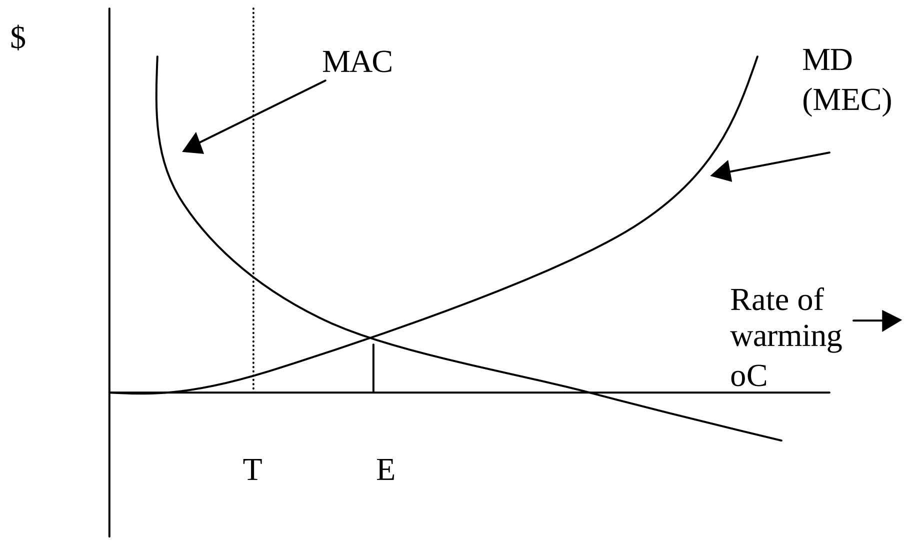

Figure 1 CBA and global warming control

Figure 1 is quite familiar as it is the standard 'abatement cost, damage cost' diagram. MAC is the marginal abatement cost and is best read from right to left. We see that as we aim to lower the rate of warming, the extra cost of doing so rises sharply. The MD curve is the marginal damage curve, which you know well as the marginal external cost (MEC) curve. The economic optimum – the solution produced by cost-benefit analysis – would be at E. But this need not coincide with the desirable level of warming if we use other paradigms. For example, many scientists think we should opt for some level of warming consistent with 'ecological safety'. They argue that

[1] 'Carbon-equivalent' refers to the fact that the different greenhouse gases can be expressed in terms of their equivalence in terms of the warming impact of a tonne of CO_2.

humankind has no experience of rates of warming above about 0.1 degree centigrade per decade. Above this, anything might happen. So, they would argue for a rate given by the vertical line at T. Note that this involves far higher costs of control (the area under the MAC curve) than the CBA solution.

Finally, note that MAC begins below the axis. This is because many people think there are negative costs of control in the early stages – they argue that things like energy conservation pay for themselves. This is a much disputed issue.

Estimating marginal damage

Estimates of the marginal damage of climate change vary significantly (see the paper by D W Pearce, if you need detail). The issue is further complicated by 'equity weighting'. Recall the discussion about SWFs and distribution. If we measure MD by WTP to avoid climate change, the answer will depend in part on income levels. It seems unfair to base climate policy on WTP if incomes in rich countries are 10-15 times those in poor countries. So, the solution is to convert the WTP estimates to utility estimates by weighting by the marginal utility of income.

$$D_{WORLD} = D_R \cdot \left[\frac{\bar{Y}}{Y_R}\right]^e + D_P \cdot \left[\frac{\bar{Y}}{Y_P}\right]^e$$

where D is damage, R = rich and P = poor, Y is income Y-bar is average world income. Epsilon is the 'elasticity of the marginal utility of income' introduced in previous lectures. It is often argued that this has a value of unity. Crude estimates of the relevant magnitudes are D_R = \$216 billion and D_P = \$106 billion, for 2 x CO_2; Y_R = \$10,000, and Y_P= \$1110; and Y-bar = \$3333[2]. This produces estimates of world damage of

unweighted	\$ 322 billion
weighted, e = 1	\$ 390 billion

So, while equity weighting increases world damage (which means we take more, not less, action to control warming), in this particular case it has not had a dramatic effect.

Note that these are total damage estimates, not marginal damage estimates. To go from one to the other is not simple and we simply report some of the available estimates. They range from a few dollars per tonne of carbon to over \$100 per tonne carbon. Roughly speaking, equity weighting increases the marginal damage costs by a factor of 1-4, with doubling seeming to be about right. The other reasons for the variation are (a) different models have different geographical distributions of damage, and (b) they vary in the extent to which they account for adaptation, (c) they vary in the extent to which they account for 'surprises' (like major hurricanes). Pearce (Social Costs of Carbon) suggests a reasonable equity weighted number is about £16 tC (about \$25 tC) whereas the UK government is using a figure of £70 tC (about \$110).

[2] We take rich countries to be OECD countries, poor to be everyone else.

Some issues

As with virtually all aspects of the global warming debate, there are many complications. First, it seems likely that the costs of controlling carbon emissions now is fairly low for the first 'tranche' of emissions, but as more and more reduction occurs it will become increasingly expensive to reduce emissions. Many of the economic models used to 'simulate' policies estimate control costs of over $100 per tonne of carbon, well above the damage figure and suggesting it may not be economically justified to take drastic action to control global warming. Second, recent economic analyses have suggested that the incorporation of *human adaptation* into the calculations of damage would greatly reduce the damage figures, although there appears to be limited adaptation possibilities to some of the major ecosystem impacts. Third, and offsetting the argument about reduced damage, the control of CO_2 emissions brings with it many other benefits. For example, CO_2 emissions from the transport sector might be controlled by having more fuel efficient cars and by traffic restraint programmes. This will bring with it benefits in the form of reduced conventional pollutants that harm human health, such as particulate matter, and traffic restraint will reduce congestion, noise and perhaps reduce accidents. Estimates of these *ancillary benefits* are very uncertain but may actually double the marginal damage figure, so that it will pay to spend up to $2 to reduce a tonne of carbon emissions in order to save $1 of avoided global warming damage. Fourth, failure to control global warming now simply shifts the problem forward on to future generations who are likely to face larger damage costs still. It can be argued that the current generation should incur costs now that are greater than the marginal damage per tonne benefit figure in order to be fair to future generations. Others disagree: why use valuable resources now to protect future generations who are likely to be richer anyway when the same resources could be used to reduce poverty now?

The international response to global warming

These widely varying views also explain the differences of opinion about the adequacy of the actions already taken. It does not benefit any single nation to take action unless it can be assured others will act likewise. The disadvantages of being a 'first mover' explain why the subject has to be dealt with at the international level, initially through the Framework Convention on Climate Change (FCCC) in 1992 in Rio de Janeiro, and subsequently at the Conference of parties in Kyoto in 1997. The 'Kyoto Protocol' is the first agreement under the FCCC with greenhouse gas emission reduction targets which will be binding in international law. The FCCC itself set voluntary targets for industrialised nations such that their CO_2 emissions should be no higher in 2000 than they were in 1990. Developing countries argued that they had no responsibilities to cut emissions because the industrialised countries were the main emitters of greenhouse gases. As it happens, no nation met the FCCC targets by design. The UK achieved its reduction by privatising the electricity industry (the purpose of which was to introduce competition, not to help the environment). This gave electricity generators the freedom to choose the fuel they wanted – gas- rather than coal which had been protected by the government. Germany met its target through the reunification of Germany which meant closing down many inefficient companies in the old East Germany. And Easter Europe and Russia met their target through the collapse of communism.

The Kyoto Protocol sought a 5.2% reduction in overall (carbon-equivalent) greenhouse gas emissions by about 2010 relative to 1990. This target applies collectively to industrialised economies only. Once again, developing countries have no mandatory targets. The target is differentiated between industrialised countries. The European Union as a whole must achieve an 8% reduction, the United States 7%, Japan 6%. Within the European Union a separate agreement allocates the 8% cut between Member States.

The details are set out below. Note that the actual reductions negotiated under the Kyoto Protocol were changed in subsequent negotiations and are now smaller than the 5.2% originally agreed. In addition, the USA has refused to ratify the treaty.

Table 2 Emission Reduction Commitments under the Kyoto Protocol

(% Reductions 2008-12 relative to 1990, for six greenhouse gases)

Country	Emission Reduction (-) or increase (+)
Australia	+ 8
Canada	-6
Iceland	+10
Japan	-6
New Zealand	0
Norway	+1
Switzerland	-8
USA	-7
European Union (see table 2)	-8
Bulgaria, Czech R, Estonia, Latvia, Lithuania, Romania, Slovakia, Slovenia	-8
Hungary, Poland	-6
Croatia	-5
Russia, Ukraine	0

Table 3 European Union Burden Sharing Agreement
(% Reduction in 6 greenhouse gases 2008-12 compared to 1990)

Country	Emission Reduction %
Austria	-13
Belgium	-7.5
Denmark	-21
Finland	0
France	0
Germany	-21
Greece	+25
Ireland	+13
Italy	-6.5
Luxembourg	-28
Netherlands	-6
Portugal	+27
Spain	+15
Sweden	+4
United Kingdom	-12.5

Table 4 Scale of Emission Reductions for CO2: 2010 targets relative to 2010 'Business as Usual' (million tonnes carbon)

Country	2010 projected CO2	2010 Kyoto target	Scale of emission reduction required
USA	1724	1244	480
Canada	151	110	41
Australia	101	78	23
N Zealand	11	7	4
Japan	311	273	38
Austria	18	14	4
Belgium	34	28	6
Denmark	12	12	0
Finland	21	15	6
France	110	103	7
Germany	244	212	32
Greece	37	25	12
Ireland	12	10	2
Italy	136	109	27
Luxembourg	2	2	0
Netherlands	45	41	4
Portugal	18	15	3
Spain	78	71	7
Sweden	17	18	-1
UK	173	137	36

How much of a breakthrough is the Kyoto Protocol? That there was any agreement at all is an achievement. After all, reducing greenhouse gases affects virtually all aspects of economic activity from electricity generation, industrial activity, agriculture, forestry and transport. By calling for a change to a less ‘carbon intensive’ world, Kyoto signals the need for fundamental change in the way economic activity is organised. A second positive feature is that the agreement enables ‘carbon trading’ to take place in order to help secure emission reduction targets. Carbon trading involves one country cutting emissions of CO_2 (or another greenhouse gas) in another country. This has no deleterious environmental effect overall because a tonne of CO_2 does the same amount of damage wherever it is emitted. But it is known that it is much cheaper to reduce emissions in, say, Eastern Europe than in the USA, so securing the reductions in Eastern Europe could save substantial sums of money for the USA. Keeping these compliance costs down is crucial since the cost of meeting the Protocol targets are the biggest obstacle to further international agreement. Under carbon trading, the USA would pay for the reductions but would secure the paper ‘credit’ for the CO_2 reductions which it can then set against its target. More sophisticated forms of trading are enabled under the Protocol as well.

Why does the Kyoto Protocol achieve so little?

There are lots of reasons why international agreements like the Kyoto Protocol are so ineffective. Economists point to the game theoretic nature of such agreements.

Just like the fishery, cooperation would make everyone better off. But non-cooperative solutions are more likely because (a) each individual believes they are better off by not joining the agreement, and (b) they can free ride if others do agree. This is the standard open access or ‘tragedy of the commons’ outcome.

Figure 2 illustrates. The line MACi shows the marginal abatement curve for one country, i. The MBi curve shows the marginal benefits that country i will get from the actions of everyone in controlling warming. It is important to understand the basis of the two curves. MACi is country i’s own costs. *But the benefits it gets from warming control arise only if all countries take action.* The MBg line shows the sum of the marginal benefits of all countries, ie global marginal benefit. The non-cooperative solution (also known as the Nash equilibrium) is at Q, where i’s own marginal benefit and cost curves cross. But the global, cooperative, solution is at Q* where marginal costs cut the global marginal benefit line. Each country is actually better off with the cooperative solution (it can’t secure any benefit by acting alone).

The gap between Q and Q* depends on the slope of the ‘own’ MAC and ‘own’ MB curves. Call these c and b respectively. Then, the literature has shown that if c/b is ‘large’ or ‘small’, the cooperative and non-cooperative solutions will not vary much. If c is large, and b is small, then cooperation will not achieve much more than countries would do anyway: QQ* is small. If b is high and c is small, on the other hand, countries will abate unilaterally, and Q will already be close to Q*.

The difficulties arise when c/b is neither large nor small. Then the gains from cooperation will be large. But the chances of securing those gains will be small since (a) the bigger the distance QQ* the bigger the incentive countries need to agree, and (b) the more likely it is that countries will free ride.

This is the simplest of game theory models and there are many reasons why countries might cooperate. For example, the model above is a ‘one shot’ game, whereas the real world consisted of ‘repeated games’ and it may pay to join this agreement in order to get others to cooperate on another agreement than one particularly wants. Nonetheless, enough has been said to illustrate why agreement is not easy.