THE ABCs OF GLOBAL WARMING

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Reducing carbon emissions will begin to have very significant implications for almost every economic activity in the near future and as such is likely to be one of the most important considerations in shaping the future work programmes of all the sectoral divisions of the UNECE over the next several decades. However, it is not just the UNECE or the United Nations Secretariat and the World Meteorological Organization that will be affected; climate change will be a major theme shaping programme activities for decades in almost all international organizations, including WTO, the World Intellectual Property Organization and the World Health Organization (WHO). It is therefore essential that we all understand the geophysical process that is occurring and its implications for the world's biological and economic systems. In this essay, I attempt to outline what the major variables are regarding this issue and how they are related. How to appropriately address climate change raises a number of fundamental and perplexing economic questions regarding efficiency and equity that will be extremely difficult to address politically. The scientific and technological challenges will be equally difficult to solve. However, after examining all these very difficult challenges, the conclusion I draw is that we are not looking into an abyss or one of CERN's black holes: if the correct political policy choices are made and technological progress continues along historical patterns, we can be reasonably confident that the problem can be properly addressed at reasonable costs. Nevertheless, there remains considerable uncertainty and a wide dispersion of views about most of the important relationships discussed here. Since it is beyond the scope of this essay or even a major book to fully discuss all these complexities and controversies, instead I will try to simplify and present what I consider to be the key variables regarding climate change and some best estimates for the quantitative relationships between them.

THE CHANGING CLIMATE OF THE EARTH

Changes in the temperature of the Earth are determined mainly by the relationship between the amount of solar radiation entering the Earth and the amount of solar and infrared radiation leaving the Earth. Changes in the amount of solar radiation hitting the Earth can vary owing to fluctuations in the intensity of the sun, such as with sun spot cycles or variations in the distance of the Earth's orbit. Changes in the Earth's surface, such as the size of the polar ice caps or in the amount of cloud cover, can affect how much solar radiation is reflected back into space. The sun-warmed surface of the Earth gives off infrared radiation, and as it leaves the planet some of it is absorbed by certain gases in the atmosphere, causing them to warm up. Changes in the abundance of these gases is a major determinant of how much of this radiation is absorbed and this then affects the Earth's surface temperature. For almost 150 years, scientists have known how atmospheric gases trap radiation and how this affects global temperatures. The various causes of climate change can be conceptually separated into either those due to (a) exogenous factors such as changes in the sun's intensity or changes in atmospheric gases due to volcanoes, or (b) endogenous processes whereby ongoing climate change affects the size of the polar ice caps, the amount of cloud cover or the intensity of biological processes, which then feed back to affect atmospheric gas concentrations or the reflectivity of the planet and thus global temperatures. It is thought that these endogenous feedback effects and thus climate variability are greater on a fluid-covered planet such as Earth than they would be on a dry one.

Since the creation of the Earth 4.5 billion years ago, there have been constant fluctuations in the amount of solar radiation hitting the Earth and changes in the composition of the atmosphere. As a result, the surface temperature of the Earth has been in constant flux. For example, the Sahara desert has come and gone over the centuries and much of it was essentially green and populated with animals and humans as recently as 3000 B.C. There was no Northern ice cap 100,000 years ago; but as recently as 20,000 years ago it extended all the way down to where New York City or Berlin are today. Going back even further, the temperature extremes were even larger. For example, in the time of the dinosaurs, the poles of the Earth were almost as warm as at the equator today.

The average temperature of the Earth is now 16˚C (60 ºF) which is 0.75˚C degrees warmer than in pre-industrial times (generally taken to be about 1750). Over this period, although there is a clear longer-run trend, there has been much fluctuation from year to year and there have been fairly extended periods, such as between 1945 and 1975, when temperatures trended downward. In addition, this temperature increase since 1750 has not been uniform across the planet. The land temperature (up 1.3˚C) has risen more than the ocean temperature (up 0.6˚C) and for that reason the northern latitudes (1 ºC) have warmed more than the southern ones (0.6˚C). The higher latitudes have warmed more than the equator, the surface temperature has increased more than the higher atmosphere, and nighttime minimum temperatures have increased more than daytime maximum temperatures. More locally and over a shorter period, the water temperature at the bottom of Lake Geneva has risen by 1 ˚C over the last 40 years. In addition to changes in temperature, precipitation patterns have changed as well and have not been uniform, as some areas have gotten more and some have gotten less. Unfortunately, the dry areas seem to have become drier and the wet areas wetter as precipitation has increased in the high latitudes and declined near the equator. On 12 September 2008, when the Arctic ice cap dropped to its minimum (1.74 million sq. miles) for the year it was a significant 9.4 per cent larger than in 2007 but still 33 per cent below the average since 1979 when satellites began measuring it. Thus, there is no question that the Earth's temperature has always changed and is changing now; the challenge is to determine how much of it is being caused by mankind's activities and, if so, what to do about it.

GREENHOUSE GASES

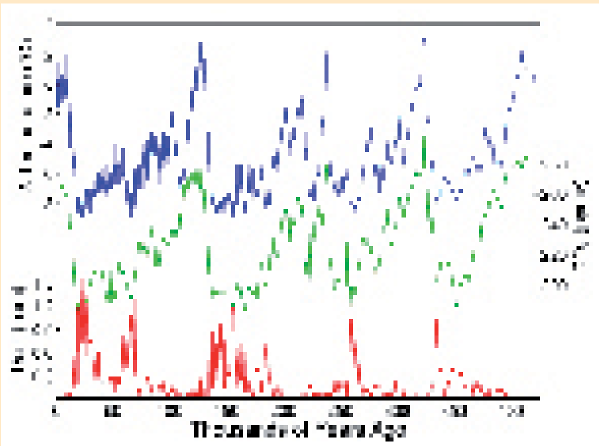
A greenhouse gas is any compound in the atmosphere that warms by absorbing the (mostly long-wave) radiation that is emitted from the Earth after the surface has absorbed the radiation from the sun. A number of compounds do this; interestingly, the most important one is water vapour, which accounts for between one third and two thirds of all the heat absorbed by the atmosphere. CO_2 is the second most important compound, accounting for between 10 and 25 per cent of greenhouse warming. Many additional compounds absorb this radiation, including methane (the major component of natural gas), nitrous oxide (also known as laughing gas), sulphur hexafluoride, chlorofluorocarbons and ozone. All these radiation-absorbing gases are collectively referred to as GHGs; officially, the Kyoto Protocol included only six of these gases in its definition of GHGs, and did not include water vapour since man's activities do not appear to significantly affect its levels.

Sometimes it is useful to aggregate the amounts of these various gases to create one comprehensive number; the most common is referred to as a carbon dioxide equivalent (CO_2e). In calculating the CO_2e, not all the gases are treated equally since some absorb more radiation than others. For example, methane absorbs much more radiation than CO_2 so it is weighted more heavily. And as some gases remain in the atmosphere longer than others, there are some additional measures that consider this aspect as well. Nevertheless, given the abundance of CO_2 relative to the others, CO_2e or any of the alternative measures of GHGs are quantitatively composed mostly of CO_2.

These GHGs are an amazingly small component of the atmosphere, with water vapour accounting for one per cent and CO_2 only 0.038 of a per cent; there are only trace amounts of the others. It is noteworthy that the two most plentiful gases, nitrogen (N_2) and oxygen (O_2), which account for almost 99 per cent of the Earth's atmosphere, are not GHGs at all; N_2 accounts for 78 per cent and O_2 21 per cent.

The amount of CO_2 in the atmosphere has fluctuated between about 0.018 per cent or 180 parts per million (ppm) and 300 ppm in roughly 100,000 year cycles going back as far as can be estimated. These historical levels of the amount of CO_2 can be determined from ice cores from Antarctica. The temperature of the Earth has also fluctuated in similar 100,000 year cycles, with the higher temperatures highly correlated to the level of CO_2 (see figure 1). The average temperature of the Earth has fluctuated in a range of about 12 ˚C during these cycles. Within this longer-run cycle, the Earth has been for the last several thousand years close to the peak phase of both the temperature and CO_2 cycle.

Figure 1 Global temperature and carbon dioxide concentrations



Source: Wikipedia

However, over the last 250 years CO_2 has increased from 278 ppm to about 384 ppm today, and is currently increasing at about 2.2 ppm a year. In percentage terms, current levels are 37 per cent higher than pre-industrial levels and are increasing above the latter level by approximately one percentage point a year. Existing levels are considerably above those that have occurred naturally over the last million years; however, these levels are not completely new. During the dinosaur period about 100 million years ago, CO_2 levels were 3,600 ppm or over 9 times today's level. Some of the other GHGs have increased even more since pre-industrial times. For example, the level of methane has more than doubled. Combining all the GHGs, the current level of CO_2e is estimated to be about 430 ppm.

Natural ecological processes such as animal respiration and plant decay release CO_2 into the atmosphere and plant respiration reabsorbs it. Man's activities are responsible for only about 5 per cent of the CO_2 released into the atmosphere, yet it is more than the earth's plant life can absorb. Currently, about one half of man's CO_2 emissions are being re absorbed by biological activity (one fourth by plants on land and one fourth by plants in the ocean) and the other half is accumulating in the atmosphere. Owing to several factors such as acidification, which itself is due to the higher CO_2 level, the ability of the oceans to absorb CO_2 is slowly declining. Although most of the CO_2 absorbed from the atmosphere is due to biological activity, there is some chemical "weathering" in that the CO_2 in rainwater combines with chemicals on the Earth's surface to make new minerals. The other GHGs are slowly decomposed by chemical reactions in the atmosphere and generally have a shorter half-life than CO_2. If mankind were to immediately stop adding CO_2 to the atmosphere, the CO_2 level would return to its "natural" level in about 100 years.

MAN'S ACTIVITIES AND THE CHANGING LEVELS OF GREENHOUSE GASES

Although there has been a debate about whether the recent 37 per cent increase in CO_2 is due to man's activities or just part of the natural cycle, a consensus has generally concluded that man's activities explain this increase. The case for its being a manmade phenomenon rests primarily on the observations that (a) current CO_2 levels are significantly above recorded natural levels over the last half million years (but not before that); (b) the changing levels have occurred much faster than during the natural cycles; and (c) perhaps most damning and obvious is the fact that man puts a lot of CO_2 into the atmosphere.

To understand the science behind climate change, we need to understand the relationships between the following variables. The first is the relationship between the yearly flow of CO_2e emissions into the atmosphere and its effect on the long-term level of CO_2e in the atmosphere. The second is the relationship between this atmospheric level and the global temperature. After these relationships are understood, the next step is to determine the implications of the temperature increase for geological, biological and economic systems. Understanding these relationships is complicated by the fact that changes in the Earth's temperature can feed back and induce secondary channels that affect CO_2e levels. For example, higher temperatures can release methane currently captured in the permafrost.

Currently, mankind is releasing about 49 Gt[3] of CO_2e into the atmosphere each year[4]. Since 1990, emissions have been growing by about 1.7 per cent a year; this is the result of an average yearly increase in gross domestic product (GDP) of 3.4 per cent (broken up into a 2.0 per cent increase in GDP per capita and a population increase of 1.4 per cent) and reduced by an average annual decrease in emissions per unit of GDP of 1.6 per cent due to improved energy efficiency, shifts in consumer demand towards less energy-intensive items, and the shift from fossil fuels to other energy sources. The latter, due largely to nuclear power has reduced emissions by about 2 Gt.

Of these 49 Gt, approximately one fourth is composed of GHGs other than CO_2: mainly methane (7 Gt) and nitrous oxide (4 Gt), which result from waste decomposition and agricultural activities. Thus, about 38 Gt of CO_2 are currently being released and 28 Gt is the result of the burning of fossil fuels; of this, 35 per cent comes from burning coal, 36 per cent from oil and 20 per cent from natural gas. These percentages have been relatively stable over time but the share accounted for by coal and gas has been increasing and that of oil decreasing. An additional 1 Gt (or 2 per cent of the total) comes from the production of cement (which was discovered by the ancient Romans). Cement is made by heating naturally occurring limestone (or calcium carbonate, which is what antacids are made of) causing it to decompose into CO_2 and calcium oxide or lime ($CaCO_3 \rightarrow CO_2 + CaO$), the latter being the main ingredient in cement. The remaining 9 Gt come from biomass decay and land-use changes such as deforestation. Also note that human respiration from 6.5 billion humans adds 2 Gt, but that is not normally counted.

[3] *1 Gigaton = 1 billion metric tons.*

[4] *Somewhat confusingly, some studies report the weight of the carbon released while others give the weight of the CO_2 (or its equivalent); CO_2 weighs 3.67 times its carbon component, so this number can be used to convert one measure to the other.*

Although current human activity is not thought to directly affect the level of water vapour in the atmosphere, it could do so indirectly by altering CO_2 and global temperatures.

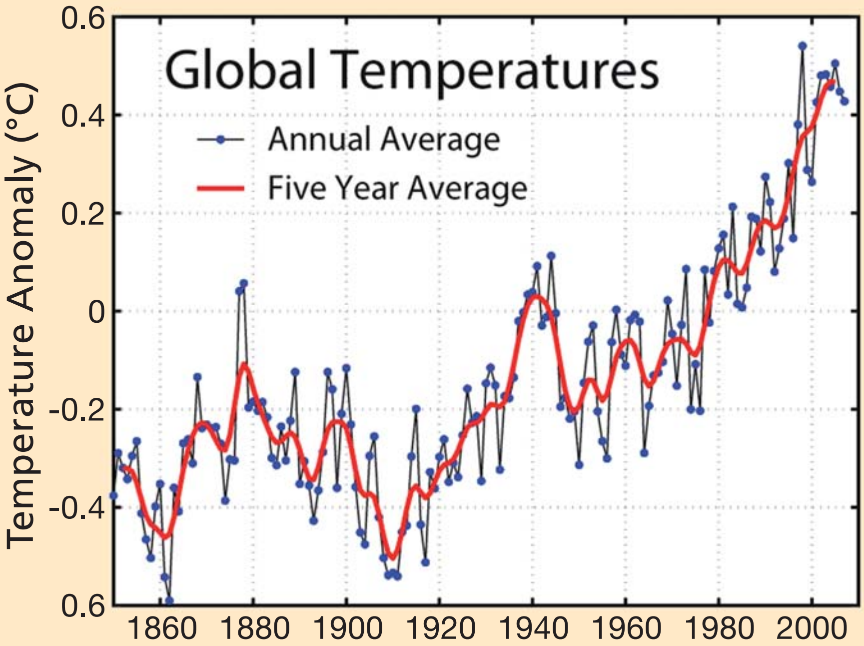
If yearly emissions could be capped at their current level, the CO_2e level would continue to increase from 430 ppm today and would ultimately stabilize at around 600 ppm, which is over twice the pre-industrial level. At such a level, global temperatures would rise by about 3 to 4 ˚C above the pre-industrial level. It is generally believed that anything over this level would result in "catastrophic" climate change. The Earth would then be warmer than at any time since man evolved from the apes. If, instead, the objective were to stabilize atmospheric CO_2e at its current level, yearly emissions would need to be reduced to about one half their current level (or to 25 Gt) but because of lagged effects global temperatures would still increase by a least another degree. A "business as usual" approach where the world continues to rely on fossil fuels (without any attempt at carbon capture) will likely result in CO_2e levels rising above 800 ppm (or almost three times the pre-industrial level) by the end of the century, resulting in a temperature increase of about 5 ˚C. Such an increase would melt much of the Earth's ice at the poles and in the Himalayas (and also Mont Blanc), would cause the sea to rise 10 metres (Copenhagen would just be a memory), and eliminate around one half of the world's plant and animal species. This was about the temperature of the Earth 40 million years ago. However, it would still be less than the 10-degree higher temperatures that existed when the dinosaurs roamed the world.

Unfortunately, because of the delay in addressing this problem, the accumulated GHGs will have increasingly significant impacts over the next two decades and regardless of what is done now it is simply too late to altogether avoid many undesirable consequences of global warming. However, the more and the faster that emissions can be reduced the more limited the consequences will be even further down the road.

THE EFFECTS OF GLOBAL WARMING

There is a tendency for the public to underestimate or under-appreciate the extent of the possible environmental changes by focusing on the estimated temperature increases because the numbers of these increases appear to be so small. When told that global temperatures might rise by two or three degrees, the typical person is likely to be unimpressed because in everyday life two or three degrees is not all that much. A difference of that magnitude is hardly likely to alter whether you wear a short-sleeved or long-sleeved shirt or whether you wear a sweater or not. In finance they talk in terms of basis points, with each one-hundredth of a percentage point being a basis point. If global warming adopted some similar terminology and it was stated that the temperature increase may be 300 basis points, perhaps it could garner more attention. The significance of a numerically small temperature increase can best be appreciated by observing what has already happened considering that the global temperature has only increased by three-quarters of a degree, or 75 basis points. Locally, here in Switzerland, a number of glaciers have disappeared or severely contracted owing to this small decline. The less than one half of a degree change since 1979 has caused the northern polar ice cap to decline by 33 per cent; and another one degree increase might cause it to disappear entirely. (This is currently being forecast to happen sometime between 2013 and 2030). The global temperature during the ice ages was only about five degrees cooler than today. Thus small numerical changes in the global temperature result in big environmental changes.

Figure 2 Global temperature since 1850



Source: Wikipedia

Global warming is expected to slightly raise sea levels, by half a metre (1.6 feet), by 2100. Approximately one half of this is due to melting ice, and the other half is due to the fact that water expands when it is heated so the volume of the oceans will increase as they get warmer. The melting of the northern ice cap will have only a minor impact since most of that ice floats on water. And as demonstrated in ancient Greece by Archimedes (287-212 B.C.), when ice melts the volume of the water created is exactly equal to the volume of the water displaced by the floating ice. Thus, the melting of ice on water does not affect the level of the water. However, some of the northern ice is on land, such as Greenland, and most of the ice in Antarctica is on land; therefore, when it melts the ocean rises. If all the ice in Greenland were to melt, the sea would rise by 7 metres and if all the ice in Antarctica were to melt, the sea would rise by 70 metres (230 feet)! In the latter case, most of the coastal cities of Europe and even many inland ones such as London and Rome would be completely flooded. In fact, 100 million years ago the seas were at these levels. Luckily, no one is projecting temperature increases large enough to melt all the ice in Antarctica during the next century even if there are no emissions reductions.

The ecological impact of global warming is thought to be greater in the tropical regions and the ice caps than in the more temperate regions. Tropical biological species are more sensitive to temperature changes than those in the middle latitudes. This is because they experience limited temperature changes throughout the year and thus have evolved to exist within a small temperature band. For example, the average daytime temperature of the coldest and warmest months in Manaus on the Amazon River only varies by 1.6˚C, whereas in Geneva, Switzerland, it varies by 19.3˚C. In addition, the day and night temperatures vary less in the tropics. Thus a plant or animal in the Amazon is specialized to live within a very small temperature range while a (non-migratory) species in Geneva must be able to tolerate significant temperature changes. The Geneva species is therefore more likely to be able to adapt to a warming climate. Another factor is that with global warming the latitude range of a given species moves closer to the poles; at the middle latitude ranges, a given species may disappear but it may be replaced by one that previously lived nearer the equator and is better able to handle the heat. In the tropics, however, there are no existing species to move into the newly created ecological niche. Therefore, any newer species would have to evolve through evolution. There is little question that this will happen, but the new species is unlikely to just take the place of the old one. It will interact with the other species differently so there is likely to be a total disruption of the ecological system. At the poles, there is no place for existing species to go so they may become extinct. Thus, for example, the polar bear was recently placed on the United States Endangered Species List since its existing habitat has been rapidly disappearing and it has no place to go. Although these ecological adjustments are quite complex and difficult to make and involve a lot more than discussed here, the basic point remains that the ecological systems at the equator are far more sensitive to temperature changes and are likely to be more severely impacted while the species at the poles may become extinct.

Besides the issue of temperature change, the increasing levels of CO_2 directly affect biological systems. Carbon dioxide is of course an input into the process of photosynthesis by which sunlight energy is transformed into chemical energy in the form of sugar. If there is more CO_2 in the atmosphere does that translate into plants being able to convert more of it into plant material? The answer is a slight yes; however, it turns out that there are really three different biochemical mechanisms that result in photosynthesis and that the mechanism (C4 carbon fixation) used by tropical plants does not benefit from higher CO_2 concentrations as does the mechanism (C3 carbon fixation) used by temperate plants. Thus, this boost to plant productivity that will occur in the temperate regions will largely be absent in the tropics.

For mankind, the greater disruption of the tropical biological systems will be compounded by the fact that those living in the tropics have less ability to adapt to these changes primarily because they depend more on agriculture for a living and because they are poor. These farmers do not have the resources to extensively use irrigation to solve water shortages or to increase their use of fertilizer to take advantage of the increased CO_2 in the atmosphere. There are no crops from even warmer regions that can be substituted if current local varieties can no longer survive. In addition, tropical farmers will not benefit from a longer growing season as will temperate farmers. Agriculture production in the equatorial countries will also decline from lower precipitation; for instance it is hypothesized that South Asia's monsoon pattern, which is quite sensitive to global warming, is likely to be disrupted.

The sum total of all the environmental consequences for mankind from global warming can be summarized conveniently by estimating their implications for world GDP. A very crude rule of thumb is that global GDP will decline by one per cent for each one degree increase in global temperatures. Thus the five-degree temperature increase estimated by 2100 under a "business as usual" scenario implies that GDP in 2100 would be 5 per cent less than it would be without climate change[5]. However, these GDP declines will be much greater, perhaps by a factor of four or five, in poor equatorial countries in Africa or India relative to Europe or the United States. A few countries, such as Canada or the Russian Federation, could actually gain from rising temperatures. A significant contributor to Africa's large GDP decline is the expected deterioration in human health resulting from the increased spread of tropical diseases. More generally, the poorer countries have more limited technological capability, which will hinder their ability to innovate solutions to their particular problems. Thus, one of the most important fundamental conclusions regarding the economic effects of global warming is that the world's poor, who are generally situated in the tropical regions, will likely be the ones most negatively impacted by global warming. The irony, of course, is that they are not the ones who are causing it.

WHO IS ACTUALLY PRODUCING GHG EMISSIONS?

Currently about half of fossil fuel carbon emissions are from the advanced economies, and the other half are from developing economies; however, by mid-century the developing countries' share will increase to 70 per cent. The United States and China are now the largest emitters of GHGs, each accounting for about one fifth of the world total. The 56 UNECE member States are responsible for about 49.5 per cent of the world total; they currently account for 53.5 per cent of world GDP (on a purchasing power parity (PPP) basis). In making these calculations, it probably makes sense to also include countries' land-use policies; those that are increasing their forest cover get the additional absorption capacity being created subtracted from their emissions, while those that are destroying their forest get the loss of absorption capacity added on to their emissions. This makes a big difference for some countries: for example, Brazil's emissions more than double when land-use policies are included. Another issue that has been raised is whether the responsibility for emissions should be charged to those who consume items instead of those who produce them. For example, much of China's GHG-intensive output is in fact consumed in the advanced economies, so maybe it is the latter who are the responsible parties.

Besides the actual volume of emissions by country, there are two other useful country level measures. Emissions per capita are likely to be a highly used measure because there is some moral basis for believing that each person on Earth has an equal entitlement to their share of the atmosphere. On this basis, currently the average person in the world is responsible for about 7.5 tons of CO_2e per year (49 Gt/6.5 billion). However, in the United States and Canada, emissions (about 23 CO_2e tons per capita) are about four times greater than those of China, and about twice that of Western Europe or the Russian Federation.

The other measure is CO_2e per dollar of GDP (on a PPP basis), which is a useful measure for gauging the efficiency of a country's economic structure. However, there are a number of other factors such as the country's production mix, the availability of natural resource alternatives such as hydropower, and energy pricing that could also significantly affect this

[5] *Some have estimated that a business as usual approach could result in GDP reduction of 15 per cent by 2200.*

measure. Generally as per capita income increases, this measure tends to fall. This reduction mostly reflects a richer country's better use of technology that allows items to be produced using less energy (as well as other materials). However, perhaps equally important is the shift in consumer demand; as people get richer they shift their consumption from items that are energy intensive towards service sectors such as information and communications, health, and entertainment that use less energy. A slightly alternative measure that is sometimes used, that of CO_2e per dollar of GDP (using market-based exchange rates), is a meaningless concept that has the effect of grossly exaggerating the inefficiency of developing countries' energy use.

WHAT SHOULD BE DONE?

Once it is acknowledged that human activity is causing global warming and that the consequences are very serious, the most fundamental question is whether it makes sense to attempt to stop its progression by alternating the activities that are causing it, or if mankind should concentrate on adapting to the changing climate. Almost every study that has seriously examined this question has concluded that the cost of mitigating a significant percentage of the GHGs currently being produced is a much cheaper option than the cost of adapting to the changing temperatures. An analysis by the Stern Commission[6] concluded as a best guess that abatement to a reasonable level could be achieved by yearly investing about 1 or 2 per cent of global GDP, whereas adaptation would ultimately result in the yearly loss of about 5 per cent of global GDP. Still there are various degrees to each option; it is not really an either/or question but a question of where to draw the line and at what points in time activities should be undertaken.

This question of where and when to draw the line is a very important one and the answer depends on a number of normative value judgments about which there is considerable disagreement. The basic problem is that mitigation requires that mankind start to undertake actions that require considerable costs now but the benefits will be spread out far into the future and will accrue to a different group of people, many of whom will be much richer than those living today. If something costs \$1 million today, does it make sense to invest now if the benefits will be \$5 million in 2050? Obviously five is greater than one, but things are not that simple. Even if the \$5 million is inflation adjusted, three fundamental factors still need to be considered. The first factor is time; a dollar today is generally considered worth more than a dollar in the future. This is because if you had a dollar today you could invest it and make interest on it and it would be worth more in the future (assuming, of course, that there are no global financial crises with collapsing banking systems). If the interest rate was five per cent, then \$1 next year is really just worth 95 cents today and \$1 in 2050 is worth just 13.5 cents today. Thus, since the \$5 million in 2050 is worth just \$680 thousand today, it appears that the costs of the \$1 million project are greater than the benefits and the project should not be undertaken. Basically, the higher the interest rate the less weight on future benefits. A procedure similar to this is generally used to evaluate long-term projects undertaken by Governments. Currently, the British Government uses a 3.5 per cent interest rate to evaluate a project and the United States Government uses 7 per cent. Regarding what this interest rate should be, some argue that it should be the actual market interest rate but others disagree. Nicholas Stern in his highly cited study used an interest rate of 1.4 per cent. However, many have argued that this is much too low and that as a result Stern significantly overestimated the future benefits of emissions mitigation.

There are others, however, that have argued that there should be no discounting of future benefits at all. With an interest rate of 3 per cent, someone born today will be valued twice as much as someone born in 2031. To them, it is not clear ethically how this can be justified. If we are thinking of providing benefits to an individual it certainly makes a lot of sense to discount the future since an individual is impatient and would admit to preferring a dollar today to slightly more than a dollar next year. However, in a long-term situation such as climate change, where the individuals getting the benefits may be largely different from the individuals paying the costs, it is less clear that the same procedure as applied to an individual should be applied to a society.

In addition to the time dimension, a second important consideration deals with the expected future income of the world's residents. As a result of technological change and the accumulation of capital, the per capita income of the world has been increasing by about 2 per cent a year. If this were to continue into the future, it means that mankind would be more than twice as rich in 2050 as today. Although there is some debate about this, many contend that a person with twice the income of someone else does not get the same additional pleasure from an extra dollar as the poorer person. Therefore, since future generations will be richer than we are today, some argue that future benefits to them should be discounted because a dollar will not give them the same level of enjoyment that we could get from that dollar today. In effect, the argument is basically, why should poor people be asked to sacrifice today so that richer people in the future can be even richer. There is obviously

[6] *Nicholas Stern, The economies of climate change: the Stern Review, United Kingdom HM Treasury, 2006.*

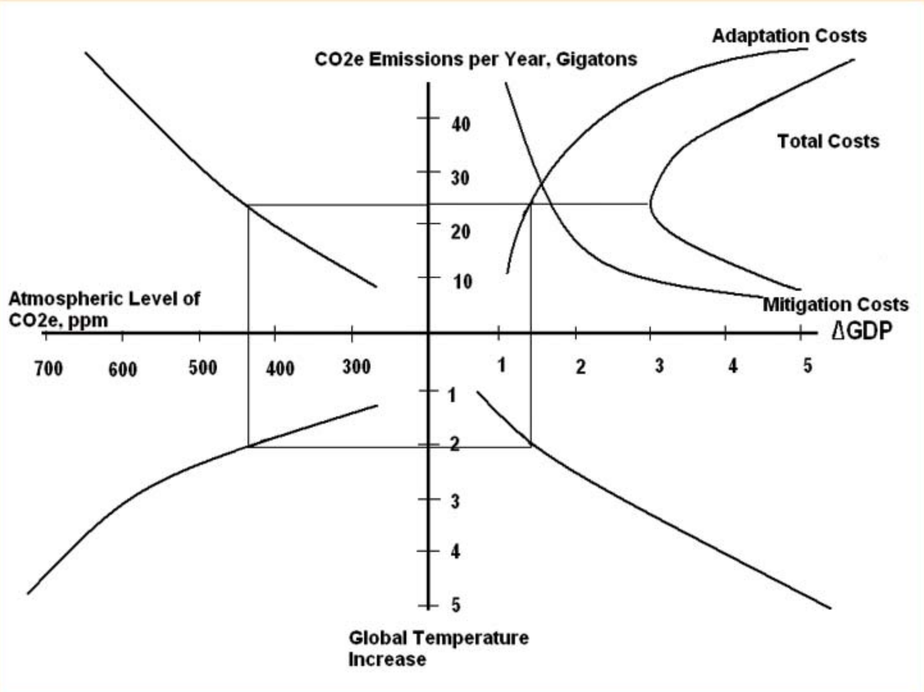
some validity to this if we are asking Europeans today to sacrifice for much richer Europeans decades in the future; however, asking Europeans today to sacrifice for even poorer Africans in the future is a different matter.

This brings up the third issue concerning distribution. If the benefits are going to accrue to people other than those paying the costs, then those footing the bill might not be that altruistic and might not be willing to endure a great sacrifice so that someone on the other side of the world can be better off. Unfortunately, it is clear from tragedies such as Darfur that people are not generally willing to make a great sacrifice for strangers far away. This is likely to be even truer if the beneficiaries are future generations that have yet to be born. Inevitably, there will be other value judgements that will have to be made. For example, if global warming increases disease and mortality, some value will have to be placed on the lives lost.

Thus, in attempting to make the most sensible economic decisions, there are three fundamental issues of time, income level and distribution that require normative value judgements. Basically, there is no way to scientifically make these assessments, they are philosophical judgments. Therefore, even if we knew for certain the science of global warming and knew exactly what would cause what, some very difficult economic judgments need to be made, and reasonable people could disagree about what the correct choices are because they weigh these three factors differently. Thus, we face a fundamental problem in making any purely objective assessment of how to address global warming. Nevertheless, we have no alternative but to make these judgements and proceed. Once the climatologists have estimated what is going to happen in the future under various scenarios, economists must assign some economic value to them and then translate those future values into present values after adjusting for time, income and distribution.

This is starting to get complicated. However, since economists love graphs as a way to simplify things, I have come up with a nifty graph that puts what we have discussed into one neat little picture. In figure 3, in the upper-left corner panel the relationship between annual CO_2e emissions is plotted against the atmospheric level of CO_2e that would result. As we saw, to maintain the current atmospheric level of 430 ppm requires that annual emissions be reduced to about 25 Gt. The lower-left panel shows that at that atmospheric level, global temperatures will rise by about two degrees (above the pre-industrial level). The lower-right panel shows that economists have calculated that a two-degree increase will reduce global GDP by about one and a half per cent. Next, the circle can be closed by plotting in the upper-right panel the relationship between each level of annual emissions and the corresponding adaptation costs. For example, 25 Gt correspond to adaptation costs equal to a loss of one and a half per cent of GDP.

Figure 3 The key relationships in determining the optimal response to climate change



In addition to estimating the future adaptation costs, there has to be an economic calculation of what the mitigation costs are going to be. Essentially, this requires an assessment of the cheapest method of reducing carbon emissions to each level. For example, if the yearly CO_2e emissions are to be reduced by half to 25 Gt, what will it cost? The costs of all the various activities, such as using solar instead of coal to generate electricity, have to be evaluated. Once all the options are considered, it is possible to come up with an estimate of the least cost of reducing emissions to any given level. Some initial projections of this have now been made and their economic costs can be translated into a percentage of GDP and this can also be plotted in the upper-right panel of figure 3.

Given today's technology, improving energy efficiency appears to be the least costly way to begin to reduce emissions. In fact, there are currently many ways such as improving building insulation or using phosphorescent light bulbs that have actual negative long-run costs. Nevertheless, the marginal costs will increase as emissions are reduced further; thus, the mitigation curve is not only downward sloping but convex. Essentially, emission-reduction options can be grouped into several categories; these include (a) shifting to activities with lower energy consumption; (b) improving the energy efficiency of producing a given item; (c) shifting to non-fossil fuels such as hydro, solar, wind, geothermal or nuclear; (d) shifting to biofuels; (e) shifting to less carbon-emitting fossil fuels (e.g. to gas from coal); and (f) capturing the carbon that is released by burning fossil fuels so that it does not enter the atmosphere.

This last option, referred to as carbon capture or sequestration, is still an unproven technology but the Intergovernmental Panel on Climate Change (IPCC) (which shared the Nobel Peace Prize with Al Gore) believes it has tremendous potential and has estimated it will account for between a tenth and a half of all mitigation over the next century. There are still a large number of competing technologies regarding this, but essentially the CO_2 is removed from the combustion gas, compressed (sometimes into a liquid) and stored underground in specially selected geological sites, including spent oil and gas fields. Although one might think that the CO_2 would easily escape, those developing this technology believe that leakage for the first 1,000 years can be limited to one per cent. The process, however, may increase the costs of electricity by up to 50 per cent.

The degree to which mankind will be able to make these mitigation adjustments in the future will depend considerably on unknowable technological advances. However, what is apparent from the above list is that despite the enormity of the task there are many options; and each option can be achieved in dozens of ways. For example, even now there are any number of competing solar technologies that could produce energy at a reasonable price. And even if some prove to be a dead end it is unlikely that they will all turn out as such.

The total costs of dealing with climate change are the sum of adaptation costs plus mitigation costs; in the diagram the total costs curve is therefore the sum of the horizontal distances of the adaptation and mitigation curves for each level of annual emissions. In theory, the economically optimal level of annual CO_2e emissions is where the total sum of adaptation and mitigation costs is minimized; in figure 3 that occurs with yearly emissions of about 25 Gt. It is likely that the total costs of dealing with climate change may be several percent of world GDP. If the annual emissions level is set higher than the optimal, then mankind would be enduring too much climate change. Setting the annual target too low would mean that mankind was bearing excessive mitigation costs relative to the "minor" environmental damage that would occur. In figure 3 the mitigation costs are greater than adaptation costs at the optimal level, but that is just a guess[7]. Also note that for any given costs of dealing with climate change (say, 4 per cent of GDP) other than the optimal, there are two options or points on the total costs curve: one that over emphasizes mitigation and one that over emphasizes adaptation.

The point of figure 3 is to provide a framework for understanding how to go about determining how aggressive we should be in implementing policies to address climate change. As I have emphasized, there is much dispute about the exact relationships between all these variables, and different assumptions would lead to different slopes for the curves in each panel. Thus, the optimal point would move around as well. The curves that are plotted and the final optimal value derived are my best estimates, but undoubtedly in the coming years the best guess of what these curves look like will shift around considerably. I have also cheated a bit: because of long lags, some of these relationships have a dynamic component that a true policy expert would need to consider, but to simplify things I ignored that dimension.

[7] *The optimal is not where mitigation costs equal adaptation costs, but where the marginal increase in mitigation costs equals the marginal decrease in adaptation costs for each additional reduction in annual emissions; these marginal curves are not drawn on the graph. Also note that the value judgments concerning time, income level and distribution are incorporated into the adaptation and mitigation curves; once these curves are agreed upon, it is possible to say something about the economically optimal level of emissions.*

WHAT GOVERNMENTAL MECHANISMS NEED TO BE ESTABLISHED TO ADDRESS GLOBAL WARMING?

Once there is agreement that GHGs should be controlled, how should this be accomplished procedurally? Global warming as a result of GHG emissions represents an almost classic case of what economists call a "market failure". This is essentially a situation in which the outcome produced by a market system results in an inefficient outcome. As a result, some type of governmental regulatory apparatus is required to address the problem. Given that the problem is global in nature, the solution must also be global. The basic political problem is that there is no global Government that can impose a solution. Intergovernmental cooperation is the remaining option, but a negotiated agreement is less likely to be optimal because each country will assess the costs and benefits differently based on factors such as their geographical position, per capita income and endowment of fossil fuel resources. In addition there is a real possibility that some countries might attempt to opt out of any agreement; some mechanism to "force" compliance or punish "free riders" will need to be considered.

If some targets are established through intergovernmental negotiation, what specific regulatory procedures need to be enacted to ensure that they are achieved? There are several possible approaches with some regulating fossil fuels and others regulating carbon emissions. The regulations of either can take the form of a tax or a physical quota. At some theoretical level the result is the same, but as a practical matter one approach may be preferable because it is less costly to administer or better able to achieve specific objectives. Since fossil fuels have uses other than being burned for energy, and emissions can result from non-energy related activities (e.g. cement production) the emphasis has been on regulating emissions instead of fuel use. There are two basic approaches for regulating emissions – one charges a price (i.e. a tax) for releasing GHGs into the atmosphere, and the other places physical limits or quotas on the release of the emissions. Essentially the first approach directly targets the price of emissions and then allows the quantity to adjust, while the other sets the quantity and allows the price of the quota to adjust. These are generally referred to as either having a carbon tax or having an emission-trading system, respectively. There is nothing new here as these are standard options used by Governments in many different areas. For example, many cities attempt to restrict the number of taxis that can operate; some cities charge a large fee for licences as a way to discourage entry, while some create a fixed number of licences and then anyone who wants to enter the taxi business must buy an existing licence from someone.

A tax on emissions has the advantage of being relatively easy to administer and the financial burden on businesses would be known in advance and could easily be adjusted through time as information or conditions about global warming evolved. The major disadvantage is that Governments do not have a good idea of how much a given tax would reduce emissions and thus they may not be able to meet emission targets accurately. The alternative is to set emission limits that could be distributed in numerous ways (e.g. auctioned, sold, or given to existing polluters). Those that obtained the permits could either use them or sell them to others; a sophisticated market for emission rights could develop. This is sometimes called a "cap and trade" system. The main advantage of this approach is that Governments could set an overall quota on CO_2e emissions and be fairly confident that it would be met. The disadvantage is that the actual costs that businesses would have to pay would not be known in advance.

There is considerable disagreement between not only the experts, but between countries over which of these two approaches would be best. Aside from the administration costs, theoretically the same level of emission reductions at the same costs, which are distributed in the same way, could be roughly achieved by either system. Much of the preference for one approach over the other is due not to a preference for the approach per se but to how agents expect that the approach would be implemented. For example, a given firm might prefer emission quotas instead of a tax because they might expect that the emission rights would be initially given to them but they would have to pay an emissions tax. Another new or growing firm might prefer a tax because they might expect that all their competitors would equally pay the tax but that emissions quotas might be allocated on historical levels, which would put a new or growing firm at a competitive disadvantage. To summarize, a given firm or country cannot tell whether they would be better off under a carbon tax or emission trading regime without knowing the specific details of what would be taxed, at what rates, and how the tax revenue would be distributed versus how emission rights and any revenue from their sale would be distributed. Also practically speaking, there is no reason that a hybrid system combining the two approaches could not be designed.

Note that whether there is a tax on emissions or a market-determined price for emission permits, the amount is generally referred to as a price for carbon. Sometimes it is given in terms of CO_2 and sometimes just for carbon. Since a ton of CO_2 contains a fixed amount of carbon (0.27 ton), a price of $10 a ton for CO_2 is equivalent to $2.70 a ton of carbon. In order to reduce emissions to the desired levels, what will be the necessary price of carbon? Generally, it appears that emissions will have to be slowly reduced over the rest of this century; but at the same time GDP will continue to increase, which would create more emissions, all things being equal. This implies that the price of carbon will need to gradually increase through time. Obviously, the actual price will depend on how much it is decided to reduce emissions. If, for example, the objective was to reduce emissions enough to stabilize CO_2e levels at the current level of about 430 ppm (which implies a further temperature increase of about 1 ˚C owing to lagged effects), it has been estimated by the International Monetary Fund (IMF) that the price of carbon would need to start out at $15 a ton in 2013 and rise to $86 a ton by 2040. This would imply that gasoline would need to be taxed by an extra 5 cents a litre in 2040; this seems remarkably low. However, others have estimated the required price of carbon will be several times greater.

Under the Kyoto Protocol (which was signed in December 1997 and came into force in February 2005), which has been signed and ratified by 178 countries including all the major emitters except the largest, the United States,[8] the signatories agreed to reduce six GHGs by an average of 5.2 per cent below their 1990 levels for the 2008-2012 period. However, only 37 countries are actually obligated to meet emission targets, and only 31 are committed to reduce emissions below 1990 levels. The developing countries, including Brazil, China and India, have no limitations at all, and several others, such as Australia, Iceland and Norway, have targets but they are above 1990 levels. The 5 per cent is just an average, as almost all of those 31 committed to reductions have targets greater than 5 per cent; for example the EU agreed to an 8 per cent reduction. The agreement is more progressive than might be apparent, since by 2012 without an agreement emissions would be considerably above the 1990 level due to economic growth, so that as a practical matter countries have agreed to an almost 30 per cent reduction. It is worth pointing out that 30 of the 31 countries that have committed to emission reductions are members of the UNECE, the only non-UNECE country being Japan.

The underlying mechanism governing the Kyoto agreement has been one of emission limitations. Each country is responsible for achieving its own limits but actual national levels can exceed these caps if they purchase emission rights from others. Given that it is typically cheaper to lower GHG emissions in developing countries by upgrading their technology, a substantial market has developed whereby businesses in the advanced economies purchase emission rights by helping to finance emission reduction projects in the developing economies and the countries with economies in transition. During 2007, almost three quarters of these carbon credits came from projects in China. Note that the use of 1990 as the base year has proven to be very fortuitous for the countries with economies in transition since their GDPs have grown quite moderately (and in some cases are negative) over the 1990-2008 period; thus for example, the Russian Federation was able to cut its emissions by 32 per cent between 1990 and 2004 to a large extent because its real GDP fell by 10 per cent. It is actually now being forecast that the Kyoto 5 per cent target will be met despite the fact that some countries such as Canada are way off target because of the large reductions in emissions of the countries with economies in transition due significantly to their poor economic performance.[9] Countries that do not achieve their Kyoto targets are to be penalized in the post 2012 follow-up agreement. It was decided in Bali in 2007 that the follow-up agreement will be negotiated in Copenhagen in 2009.

As in so many economic activities, in designing any system there is likely to be a conflict between the objectives of efficiency and equity. The most efficient outcome would be one where the price of emissions is the same throughout the world. Assuming away all kinds of complicating factors, a country with twice the per capita income of another would end up producing twice the level of emissions. Equity considerations might suggest, though, that the level of emissions per capita should be equalized throughout the world. However, if emissions were allocated on a per capita basis, production in the poorer country would use a less carbon-efficient process, and this would not be economically efficient.

The conflict could potentially be addressed if the revenue raised from a carbon tax or the sale of emission rights were distributed on a per capita basis. An efficient outcome need not be a fair outcome, but nevertheless it may be possible to achieve both objectives with a carefully designed system that puts equal weight on both objectives. Typically, national authorities can disregard equity considerations when designing domestic environmental policy (as with international trade policy) because the Government can deal with equity issues independently through its tax and spending policies. However, since there is no world Government to address international equity concerns, these concerns will need to be addressed within the context of the environmental policy itself.

A "free rider" country that stayed out of the international carbon-control framework might be able to benefit, as its producers would acquire a competitive advantage since they would have lower production costs. As a result its citizens would have a slightly higher standard of living relative to being in the system. Although it is certainly conceivable that there might be a transition period in which some of the developing economies would remain outside the system, ultimately there will have

[8] The fact that the United States has not committed to the Kyoto targets should not be interpreted as meaning that programmes to reduce emissions are not being implemented there. For example, there are regional initiatives such as the Regional Greenhouse Gas Initiative, which is a cap and trade system for the largest power stations and factories in 10 north-east states.
[9] UNECE activities promoting energy efficiency in the countries with economies in transition have also had a significant impact.

to be some mechanism to ensure that all countries are part of the system. There are several options here but a special tax on imports from countries outside the regime may prove to be a sufficient stick to encourage worldwide compliance.[10] An import tax would result in consumers and producers facing the same prices as with a carbon tax, but the Government of the importing country would get the revenue instead of the producer's Government. As a result, the wayward Government would have a strong financial incentive to join the system.

The implementation of a carbon tax will mean that the current producers of fossil fuels will suffer some loss, as the revenue they receive for their commodities will be lower. The tax will mean that fewer of these resources will be demanded (since the prices of goods intensely using them will be higher) and thus there will be a quantity effect with less extracted. There will also be a price effect, since the lower demand will mean that the extraction rent that producers currently receive will be less. Some might argue that these countries should be compensated for this loss by perhaps getting some of the carbon tax but there does not seem to be a solid moral argument for this since they were obtaining the revenue in the first place largely as a result of luck.

In conclusion, the informational, technological and political challenges for addressing climate change are immense. Nevertheless, given the ingenuity of mankind, it seems reasonable to believe that we can overcome them. However, the costs will be substantial and every year that decisions are delayed, possible options are being eliminated. The total costs of dealing with climate change include both adaptation and mitigation costs; most experts believe the focus should be on mitigation with policies attempting to minimize carbon emissions and temperature changes. Hopefully this essay has provided some perspective on the key issues that will need to be addressed and has presented a useful framework for thinking about how to address these challenges.

[10] *For example, the climate change bill that the United States Congress failed to approve in 2008 (but probably will do so in the next year or two) contained such a provision.*