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Introduction

The discussion of possible climatic effects of man-made emissions to the atmosphere, in particular of carbon dioxide (CO_2), goes back to early in the previous century. Hundred years ago Arrhenius (1896) made the first quantitative estimate of the possible warming due to excess emissions of CO_2. However, it is only during the last 10 - 20 years that the problem has been focused by the scientific community and it has been on the political agenda for an even shorter period. The Intergovernmental Panel of Climate Change (IPCC) published its first extensive report in 1990 with updated reports in 1992 and 1994. The last report is now (May 96) in press (IPCC, 1996).

In this paper we will very briefly review the present knowledge of climate change, mainly based on IPCC (1996), then mention some studies on costs of reducing emissions. Finally we will propose a strategy taking into account that most measures that will reduce emissions of CO_2, will also reduce other damage caused by pollution, e.g. to human health, materials and vegetation. Although an integrated approach is likely to give much more realistic results in a benefit-cost analysis, there are few studies of this kind. Dixon et al. (1996), in their otherwise interesting paper on strategies, barely mention the positive effects measures may have in addition to mitigate climate change.

Climate change - what are the uncertainties?

The composition of the atmosphere is decisive for the earth's climate. The surface is warmed by short-wave radiation from the sun and emits radiation with longer wave lengths. Some of this infrared radiation is absorbed by gasses and clouds in the atmosphere and part of this energy is returned to the surface causing a natural greenhouse effect. Water vapour is the most important gas in this connection, but CO_2, methane (CH_4), nitrous oxide (N_2O), and ozone also contribute. Without this natural greenhouse effect, the temperature at the earth's surface would have been about 33 °C lower. Except for water vapour, man-made emissions of greenhouse gasses (GHGs) may directly increase the concentrations in the atmosphere. Substantial increases have been observed since pre-industrial times, for CO_2 and CH_4 about 30 % and 145 %, respectively. (Present concentrations are about 360 ppm and 1.7 ppm.) In addition, man has caused emissions of GHGs not occurring naturally, i.e. chlorofluorocarbons. These canges have lead to an *enhanced* greenhouse effect. The role of airborne particles (e.g. sulphate aerosols), which generally have a cooling effect, has become evident in recent years (cf. Andreae, 1996). The contributions to the radiative forcing, which is the change in the energy balance of the earth-atmosphere system and easier to determine than the final temperature change, are shown in Fig. 1 (from IPCC, 1996). Note that the cooling effect of sulphate aerosols is likely to be quite important, but the uncertainties are still large. The understanding of the indirect aerosol effect, arising from the induced change in cloud properties, is still very limited and no mid-range estimate is given.

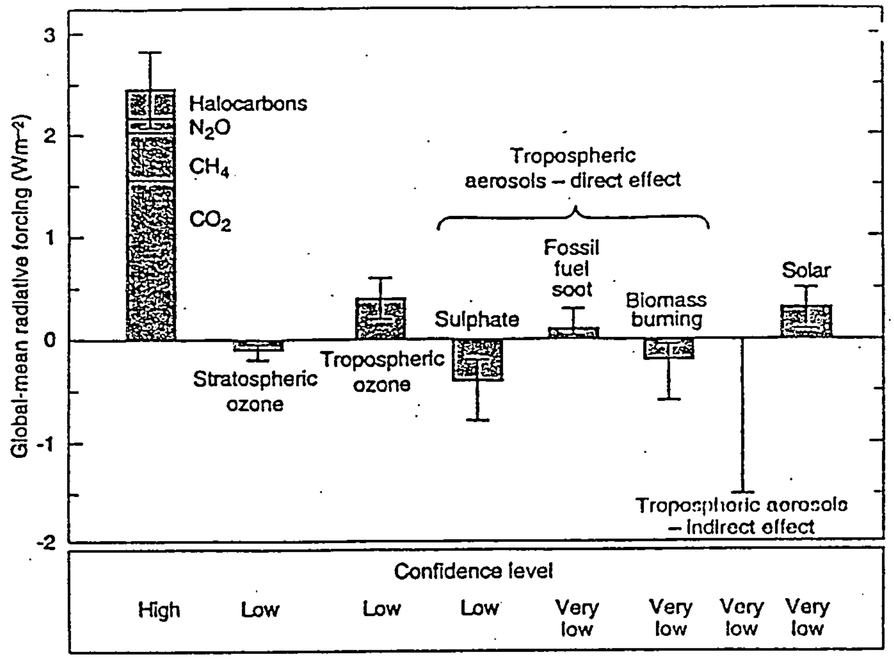

Fig. 1. Estimates of the globally averaged radiative forcing due to changes in greenhouse gasses and aerosols from pre-industrial times to the present day and changes in solar variability from 1850 (IPCC, 1996). The height of the bar indicates a mid-range estimate of the forcing whilst the lines show the possible range of values. Note that while the CO_2 concentration shows little geographical variation, the concentrations of some of the other species (e.g. sulphate aerosols) vary greatly.

It is now close to consensus that the increase in global average temperature seen in the last decades (Fig. 2) is not likely to be solely due to natural variations. IPCC (1996) states: "Global mean surface temperature has increased by between 0.3 and 0.6 °C since the late 19th century, a change that is unlikely to be entirely natural in origin. The balance of evidence, from changes in global mean surface air temperature and from changes in geographical, seasonal and vertical patterns of atmospheric temperature, suggests a discernible human influence on global climate. There are uncertainties in key factors, including the magnitude and patterns of long-term natural variability." (See also MacCracken, 1995). Some recent studies show remarkable correlations between variations in solar irradiance and global temperatures. It has been suggested that about one third of the warming since 1970 may be due to increase in this irradiation (see Kerr, 1996a).

The models used to estimate changes in the temperature and other climate variables (e.g. precipitation) for future emission scenarios, have recently been greatly improved. Equilibrium calculations with climate models, often used to estimate changes for a doubling of CO_2, gave very large temperature increases in polar regions. Improved models, including aerosols and with a gradual change in atmospheric concentrations, give results in better agreement with observations.

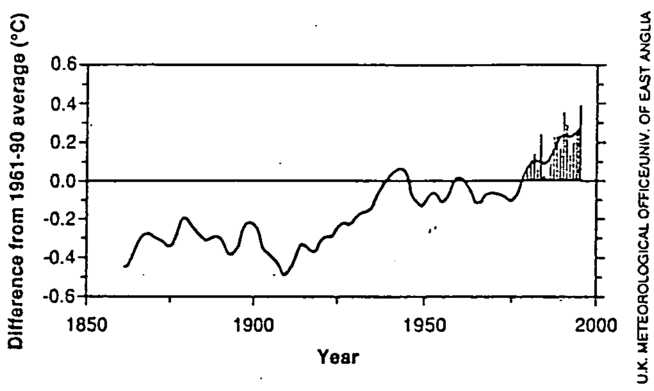

Fig. 2. Observed mean global temperature from 1860 to 1995 as difference from the 1961 - 90 mean (Kerr, 1996b).

IPCC (1996) used a number of emission scenarios. In the mid-range scenario (IS92a) the CO_2 concentration increases from the present 7 GtC/yr to about 20 GtC/yr in the year 2100. The corresponding CO_2 concentration in the year 2100 is ca 700 ppm, i.e. about twice the present value. The emissions in the year 2100 for the low and high scenarios are approximately 5 and 35 GtC/yr, respectively. The estimated corresponding increases in global temperature and rise in sea level are:

Global temp. increase:	2.0 (1 - 3.5) °C
Rise in sea level:	49 (15 - 95) cm

The high and low estimates given in parentheses include uncertainties in emissions as well as in climate sensitivity[1].

Because of the thermal inertia of the oceans, only 50 - 90% of the eventual equilibrium temperature change would be realized by 2100 and the temperature and sea level would continue to increase beyond 2100 even if concentrations of GHGs were stabilized at that time.

Some other important conclusions from IPCC (1996) are given below:

- Confidence is higher in hemispheric-to-continental scale projections of coupled atmosphere-ocean climate models than in regional projections. There is more confidence in temperature projections than hydrological changes.
- A general warming is expected to lead to an increase in the occurrence of extremely hot days and a decrease in the occurrence of extremely cold days.
- Warmer temperatures will lead to a more vigorous hydrological cycle; this translates into prospects of more severe droughts and/or floods in some places and less severe droughts and/or floods in other places. Several models indicate an increase in precipitation intensity, suggesting a possibility for more extreme rainfall events. Knowledge is currently insufficient

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[1] In IPCC reports, climate sensitivity usually refers to the long-term change in global surface temperature following a doubling of atmospheric CO_2 concentration.

to say whether there will be any changes in the occurrence or geographical distribution of severe storms, e.g., tropical cyclones.

- ...most simulations show a reduction in the strength of the north Atlantic thermohaline circulation[2] and a widespread reduction in diurnal range of temperatures.
- future climate changes may involve "surprises" due to the non-linear behaviour of the climate system.

IPCC (1996) points out a number of areas where more work is needed to reduce the uncertainties, such as representation of climate processes in models, especially feedbacks associated with clouds, oceans, sea ice and vegetation.

The effects on terrestrial ecosystems are not well predicted. Higher CO_2 concentrations seem to increase the yield of many agricultural species (Culotta, E., 1995). For natural systems the situation is more complex. Since different plant species react differently, the balance in the ecosystem may be seriously disturbed, and the outcome is difficult to predict. Extreme weather conditions may certainly take its toll, but plants may be more resistant to drought when the CO_2 concentration is high (Culotta, E., 1995). Increased temperature may increase spread and frequency of many diseases (Stone, 1995; Sprigg, 1996).

Costs of mitigation vs costs of damage

A further increase in the atmospheric CO_2 concentration is inevitable. According to IPCC (1996) the CO_2 emissions must be reduced to less than 2 $GtCyr^{-1}$ to stabilize the concentration at 450 ppm. This is a formidable task. The very large variation in energy use in different regions must be kept in mind. Comparing the two countries with the largest CO_2 emissions, USA and China, the per capita emission is nearly 10 times greater in the former. With the rapid industrial growth in China and some other developing countries, often based on coal as the dominant energy source, a substantial increase in CO_2 emissions in these countries must be expected.

In the economic literature on climate change there are several attempts to evaluate climate policies. Most of them analyze the costs and benefits of introducing carbon taxes in order to reduce the emissions of CO_2. While there seems to be some consensus about the cost of climate policies, the studies exhibit highly variable estimates of monetized benefits. These estimates are usually based on anticipated damages appearing in a present economy exposed to a doubling of GHG concentrations compared with pre-industrial level.

A comprehensive benefit-cost calculation requires monetization also of goods with no market price. In one often applied approach - the contingent valuation method - people are asked what they are willing to pay for a benefit (e.g. a specific improvement in the environment) or what they would accept as a compensation to tolerate an environmental deterioration. There are clearly a number of problems related to this method, e.g. the people questioned will usually know that they will not actually have to pay (Seip and Strand, 1992). Studies indicate that the answers often more reflect a willingness to pay for environmental goods in general, than for the specific case in question. Moreover, these methods do not provide information about how the value of environmental qualities may change over time. However, the method is being refined and useful information may be obtained.

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[2] The large scale density-driven circulation of the ocean, driven by differences in temperature and salinity.

Other explanations for differences in the valuation of damage may be varying assumptions regarding temperature sensitivity and extent of damage of individual effects. The effect on mortality is clearly difficult to evaluate in benefit- cost analyses. For instance, Nordhaus (1991) and Tol (1993) estimate the annual cost of enhanced mortality in the US to between 35 and 40 bill. US$, which is about 7 times higher than suggested by Cline (1992), and three to four times higher than Fankhauser's (1995) estimate. "The value of a person" is usually defined as the social willingness to pay for a reduction in the marginal risk of dying ("the value of a statistical life"). This may be difficult to arrive at, and when it comes to global policies, the measure is highly controversial, because the willingness to pay for reducing the risk of dying is sensitive to income, thus making the value of e.g. an American significantly higher than that of an African.

The methods for making assessments of the value of damage from climate change are clearly incomplete. Ethical aspects and equity considerations are generally dealt with in an arbitrary manner, and the damage estimates are based on highly uncertain, sometimes speculative, assessments of physical effects of climate change. On the other hand, it would be misleading to put all the blame on the economist for making ethical conflicts and controversies of equity visible. To shoot "the piano player" could only contribute to hide the fact that mitigation of climate change is a highly controversial topic.

Despite the widely different estimates of values of individual effects of climate change, most economic studies give similar recommendations for a climate policy, namely that it is not economically viable to initiate an aggressive policy to mitigate climate change at present. To some extent high and low values for individual effects in the different studies may cancel in the estimate of total damage, but the main explanatory factor behind the agreement on policy recommendations is the effect of discounting. The choice of a discount factor is usually based on the remuneration on investments in the western economies, approximately 5 percent per year in real terms. To defend investments in climate measures from an economic point of view, a 5 percent annual income is required from the year the investment is made. No wonder most climate measures turn out with a deficit, as the effect of mitigation today is not significant before 25 - 30 years ahead.

The standard argument for the choice of discount rates rests, however, on a theoretical framework similar to that of ordinary economic analyses. This implies that the value of the environment (or climate) is assessed once and for all, and related to what we estimate the value to be today. This is clearly a paradox when analyzing climate change. Such studies ought to examine the effect of a gradual deterioration of the environment, which in economic terms means that the value, or price, of the environment changes over time. Thus, even if we were certain about the physical effects of increased concentrations of greenhouse gasses, the value of these effects may change.

Aaheim (1996) studied the value of climate change in a comprehensive context, where increased concentrations of GHGs affect economic production indirectly. The gross domestic product was allocated to consumption, productive investments and investments in measures against climate change. The marginal value of postponing consumption or abatement must then over time equal the marginal return on investments in productive capital and abatement capital, respectively. Thus the values of these two categories of capital follow the same path only if the value of postponing consumption is equal to the value of postponing abatement. This is not likely to be the case. Figure 3 displays the value per unit of productive capital and capital invested in abatement measures over a 50 years period along the optimal policy path for reasonable assumptions. The values follow widely different paths. This indicates that very different discount rates, defined as the slope of the value-curves with opposite sign, should be used for the two kinds of investments. While the benefits of ordinary investments are to be discounted at a rate between 4.5 percent and 3.5 percent per year, the discount rate for abatement measures is negative the first 25 - 30 years, and slightly positive towards the end of the period.

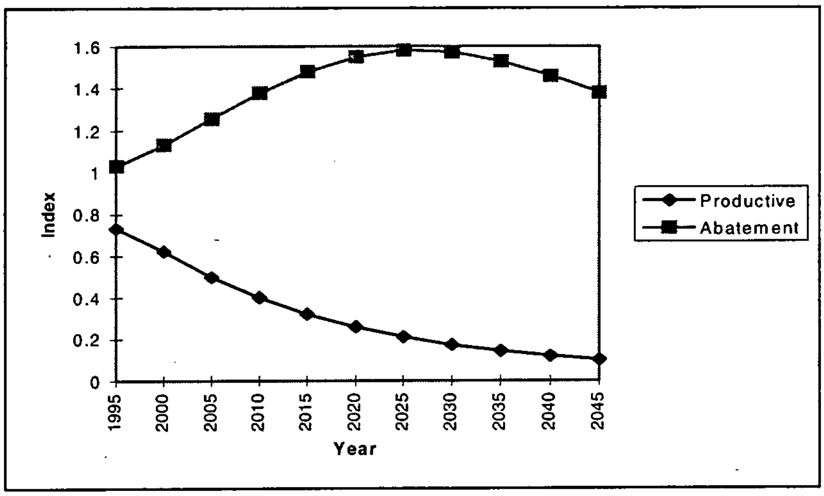

Figure 3. Value of productive capital and abatement capital over a period of 50 years

The study showed further that the optimal policy depended greatly on the assumptions about the costs to initiate a policy for reducing emissions. These so-called adjustment costs are related e.g. to transaction costs, trial and failure due to new technology, and training. Assuming these costs to be high, the profile of optimal investments was found to be quite similar to the profile suggested by an ordinary benefit-cost analysis, except that the level of abatement was somewhat higher. Reducing the initial costs of investing in abatement will lead to more abatement at an early stage and therefore a different profile.

The policy relevance of this result is simply that the advice of what to do with climate change is significantly different from the standard economic advice, which tends to encourage a relaxed attitude (cf. Wigley et al., 1996). The approach presented here indicates that there may be large benefits from directing efforts towards reducing the costs of mitigation measures, and that possible achievements might have immediate impacts on the policy.

Benefit-cost analysis based on an integrated approach

As described above, there are large variations in the estimates of net costs (i.e. costs - benefits) related to reduction in emission of greenhouse gasses. However, there are reasons to believe that most studies exaggerate the net costs of a reduction policy, since the benefits are likely to be underestimated. In most cases only effects of climate changes are considered. Most measures that will reduce emissions of GHGs, will also reduce emissions of several other pollutants, in particular sulphur dioxide, nitrogen oxides and particles. These pollutants have a number of local and/or regional effects. A schematic illustration of steps required to rank a number of abatement measures (or policy strategies) is given in Fig. 4. Each measure may affect a number of pollutants and each pollutant may have several effects. The main problems in many cities and industrial areas of the world are effects on health (e.g. by sulphur dioxide and particles) and on materials (e.g by sulphur dioxide and ozone). On a regional level, sulphur and nitrogen oxides cause acidification, and air pollutants (in particular ozone) may reduce the yield of various crops. Global effects are on the stratospheric ozone layer and on climate. To estimate the benefits of particular measures, it is therefore essential to look at environmental and health problems in an integrated way. It is likely that the population in cities with high pollution levels, as for instance some cities in developing countries, will be much more concerned about the local effects (e.g. on health) than about a change in global climate.

A few examples may illustrate the importance of local and regional effects. Present surface ozone levels seem to reduce the cereal crops by 5 -10 % in large parts of Europe (see Aunan et al., 1995 and references therein). The gain, due to decreased damage to buildings in Europe if the 1994 sulphur protocol were fully implemented, has been estimated to about 9 500 million US$ per year (Cowell and Apsimon, as cited by Kucera and Fitz, 1995). Using dose-response functions for SO_2, estimated annual excess deaths in Chongqing (China), which is heavily polluted, range between 100 and 400 per 100 000 (Fig. 5). It has been estimated that carbon dioxide emissions in Chongqing would increase by a factor of 2.1 from 1992 to 2010 without abatement measures. Two estimates have been made based on measures designed to improve *local and regional* problems. With the present policy plan the factor would be 1.45. With additional measures, as suggested by Task Force of Experts (1995), the factor would reduce to 1.25.

The suggested approach is hampered by a number of difficulties in addition to the problem of monetization of environmental goods discussed above. Present day concentrations of a number of compounds must be known and models must be applied to calculate changes in concentrations corresponding to various measures. In practice we have found that reported concentrations are often very uncertain. Dose-response (or exposure-response) functions (cf. Fig. 4) are often not well known. For example, the effects of pollutants on forests have been intensively studied for about two decades, but still the mechanisms, and thus quantitative relationships, are largely unknown (EC-UNECE, 1995). Health effects of air pollutants (e.g. particles) have been extensively studied in Europe and North America, resulting in dose-response functions of fair accuracy at least for excess mortality. However, to use these functions in, for example, developing countries, entails large uncertainties. Concentrations of other pollutants are likely to differ, and effects of mixtures of pollutants are not well understood. Furthermore, differences in life style in general may strongly modify the effects of pollution.

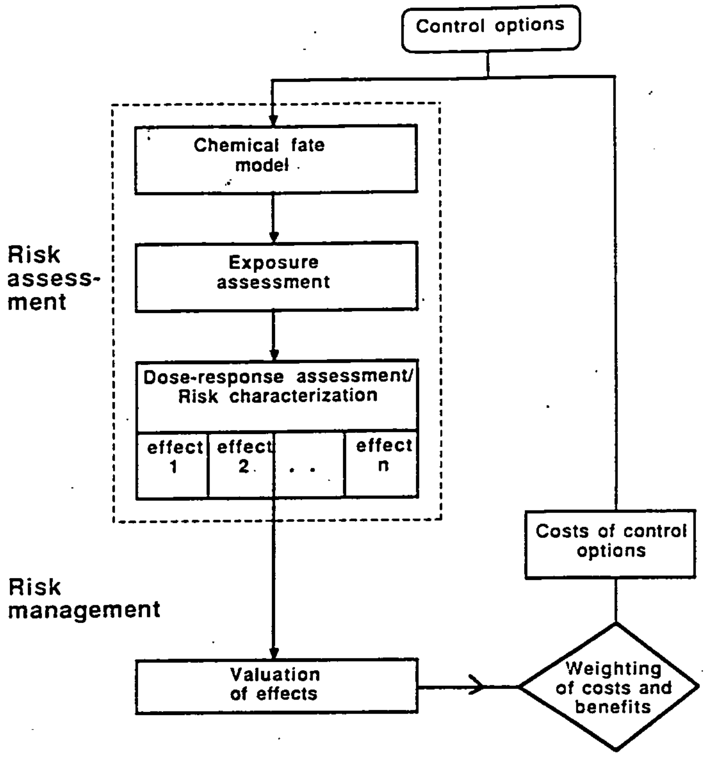

Fig. 4. Components of an analysis for ranking measures to reduce pollution (from Trønnes and Seip, 1988). To estimate exposure of humans and the environment the concentrations of the pollutants must be known. For various measures these must be calculated by a model. Assessment of effects requires some knowledge of the relationship between exposure (or dose) and effect. Changes in the effects caused by the measures must be valuated and compared to the costs of the measures.

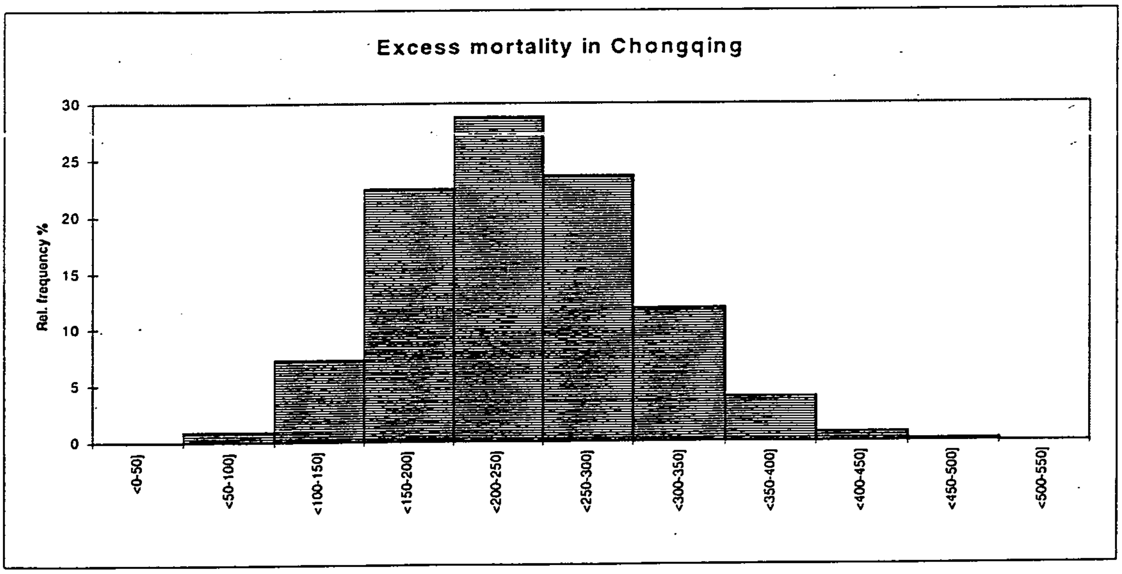

Fig. 5. Probability distribution of excess annual deaths per 100 000 in Chongqing, China, due to air pollution, based on epidemiological studies in Cracow and Beijing. Revised from Aunan and Seip (1995).

Conclusions

- To arrive at the most cost-effective strategies to reduce emissions an integrated approach is necessary. This implies to carry out detailed analyses of harmful effects on human health, materials and the ecosystems.
- By using an integrated approach it may be possible to solve local problems and at the same time reduce the emission of greenhouse gasses. Mitigation of man-made climate changes may therefore turn out to be less expensive than most earlier studies indicate.
- The value of a given environmental quality will vary over time and is likely to increase during economic growth.
- The discount rate for investments in abatement should be different from that used for investments in production. During economic growth the former will in general be lower.
- Legal, institutional, organizational and social constraints to effective control strategies must be considered.
- Close interdisciplinary cooperation is necessary, e.g. between natural scientists, social scientists and economists.

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