The Economics of International Environmental Problems

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The Outlook for Climate Change

1. Introduction

The problem of climate change is one of the most challenging environmental problems facing humankind. The first major attempt to address the problem at the "Earth Summit," the United Nations Conference on the Environment and Development (UNCED) in Rio de Janeiro in 1992, produced the important Framework Convention on Climate Change, but it was not until December 1997 in Kyoto that the signatories of the FCCC agreed to the first concrete mechanisms and targets for limiting greenhouse gas emissions. This has broadened the scope and increased the urgency of climate change research (Hasselmann 1997a).

Despite the agreement on general goals and targets in Kyoto, many questions on the technical details of the implementation and its impacts still need to be resolved (Grubb 1999). Moreover, ratification of the Kyoto protocol by the major nations is still outstanding. It is also not yet widely appreciated that the Kyoto agreement, even if implemented, can represent only a first step towards significantly larger reductions in greenhouse gas emissions during the 21st century if major climate warming is to be averted. In this situation of uncertainty, combined with a widespread realization that we cannot afford to delay action, it is incumbent on the climate research community to provide more accurate assessments of the projected climate change for various greenhouse gas emissions scenarios, and to provide climate models that can be usefully incorporated into integrated assessment studies of the interaction between climate change, the global socioeconomic system, and policy instruments.

In the following, I review briefly our present understanding of anthropogenic climate change and present some examples of the application of climate models in integrated assessment studies.

2. The Climate System

We have only one Earth. It is therefore not possible to study the dynamics of the Earth using systematic experiments, and our only available tool for predicting future climate change, whether due to natural climate fluctuations or induced by human activities, is model simulations. However, the construction of realistic climate models that are capable of reproducing both the present climate state and observed changes in past climate is a nontrivial task. Although we experience climate mainly through processes in the atmosphere, the dynamics of the climate system are governed not only by the atmosphere, but also by interaction with the oceans, the cryosphere (snow and ice fields), the biosphere, land-surface processes, and biogeochemical cycles (see Figure 1 and Washington and Parkinson [1986]). The description of biogeochemical cycles alone, which determine the concentrations of greenhouse gases and other important substances in the climate system, encompasses more than a hundred complex chemical and biological interactions between a similar number of biochemical substances distributed throughout the various climate subsystems.

Thus, climate is considerably more complex than weather. Short-term weather fluctuations are controlled mainly by processes in the atmosphere, so that for purposes of weather prediction it is sufficient to consider only changes in the atmosphere, treating the other components of the climate system as fixed. However, to study changes in climate, we need to consider also the slowly varying components of the climate system.[1] This not only increases the complexity of climate models, as compared with weather models, but also imposes severe restrictions on the spatial resolution achievable with climate models. While a global weather forecast for, say, ten days can be made with an atmospheric model on a modern supercomputer at a spatial resolution of 50 km, a climate change simulation over a period of 100 years or longer can be carried out only at a resolution of 200 km (see Figure 2). The resolution limitations are more striking when viewed on a regional scale (Figure 2): it is not possible to resolve the details of predicted climate change with present global climate models at the scale of individual countries, for example, within Europe. Global climate change predictions can be meaningfully interpreted only at scales larger than about 1,000 km. Moreover, even at these larger scales, the simulations suffer from the basic shortcoming that important processes, such as the formation of clouds, convective mixing within the atmosphere, or the formation of deep water through the sinking of unstably stratified water in the high-latitude oceans, cannot be explicitly resolved and must be approximated through so-called parameterizations.

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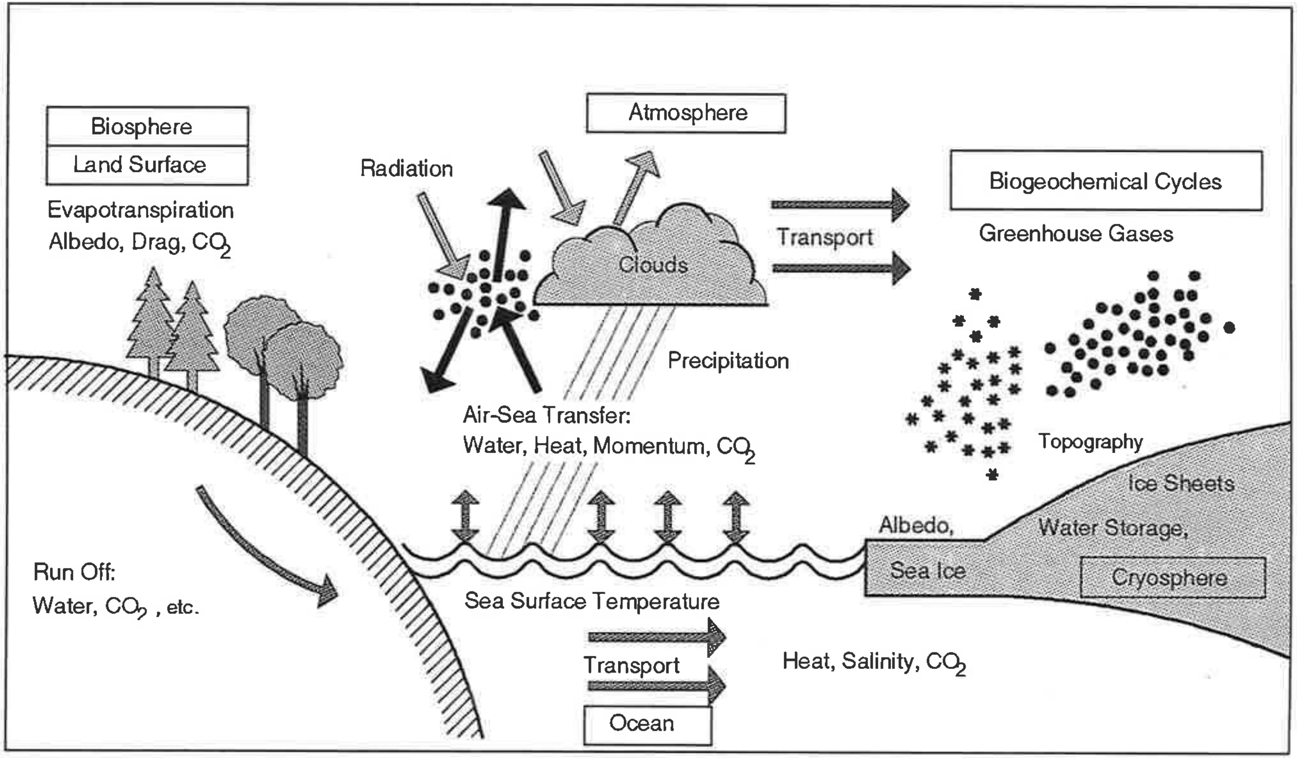
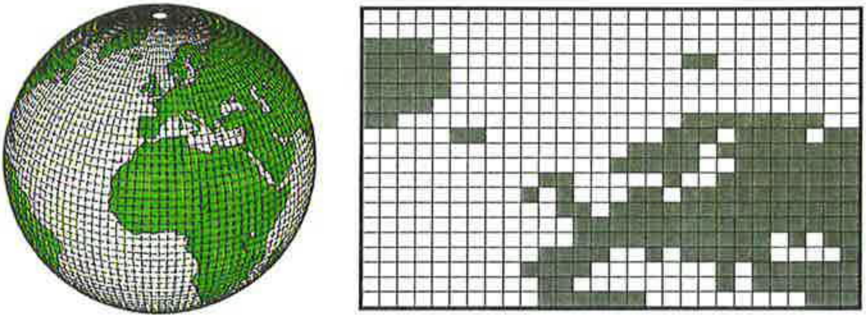
[1] Traditionally, climate was defined as 30-year weather averages. The modern dynamical definition encompasses all time sales, from weeks to millions of years, beyond the theoretical limit of weather prediction.

Figure 1: Climate Subsystems



Despite these limitations, however, modern climate models reproduce the principal large-scale features of the present climate rather well. These include the main atmospheric climate regimes, such as the tropical trade winds, the mid-latitude west-wind belts, precipitation patterns, monsoons, and the seasonal cycle of these features; the major near-surface and deep-ocean currents, and the vertical temperature and salinity distributions in the ocean; the sea-ice fields; the distributions of snow, ice, and vegetation on land; and the concentrations of greenhouse gases and other important substances in the different climate subsystems.

Figure 2: Climate Model Resolutions: A Global and European View



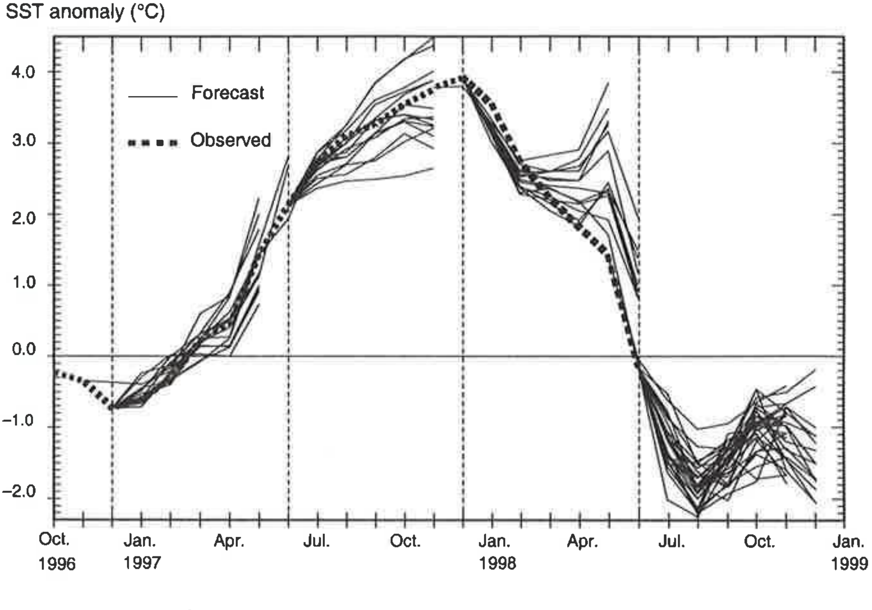
Note: The grid corresponds to an intermediate resolution of about 400 km.

Source: Washington and Parkinson (1986).

A further important test of climate models is whether they are able to simulate and predict natural short-term climate variations on time scales of months to years. The largest such fluctuation is the well-known El Niño phenomenon, a major disturbance of the climate system that occurs irregularly every few years, lasts for 1–2 years, and affects the entire tropical belt, as well as many regions at higher latitudes, such as North America (Latif et al. 1998; Neelin and Latif 1998). El Niño can be reliably predicted today with state-of-the-art climate models for about six months ahead (Stockdale et al. 1998). Figure 3 shows the successful prediction by the European Centre for Medium-Range Weather Forecasts of the recent record 1997/98 El Niño and the following climate anomaly of opposite sign (La Niña), at an estimated savings for California alone of $150 billion.

The validation of climate models against the present climate and short-term climate variations provides some confidence that the models can also be used for medium-term predictions of climate change induced by human activities. However, when the models for predictions of anthropogenic climate change are applied over decades to centuries, it should be cautioned that many features of climate variations on longer time scales from hundreds to hundred thousands of years, as inferred from paleoclimate records of deep ocean sediment cores, ice cores, geological data on land, etc., are not yet well understood and cannot be simulated by present state-of-the-art climate models. It is generally assumed that the additional processes needed to explain the observed longer-term climate variations, which are apparently missing in present climate models, are not critical for the shorter time scales relevant to anthropogenic climate change. However, this hypothesis needs to be tested more carefully in future research.

Figure 3: El Niño (January 1997–June 1998) and La Niña (July–December 1998) Forecasts



Note: Forecasts of the European Centre for Medium-Range Weather Forecasts are carried out monthly, but are shown here for clarity only every sixth month. Each monthly forecast consists of an ensemble of individual forecasts with slightly modified initial values that are averaged to provide a mean forecast. The spread of the individual forecasts provides a measure of the forecast reliability. Shown is the sea surface temperature in the equatorial mid-Pacific, which is highly correlated with other El Niño anomalies, such as the patterns of precipitation, surface winds, pressure, etc.

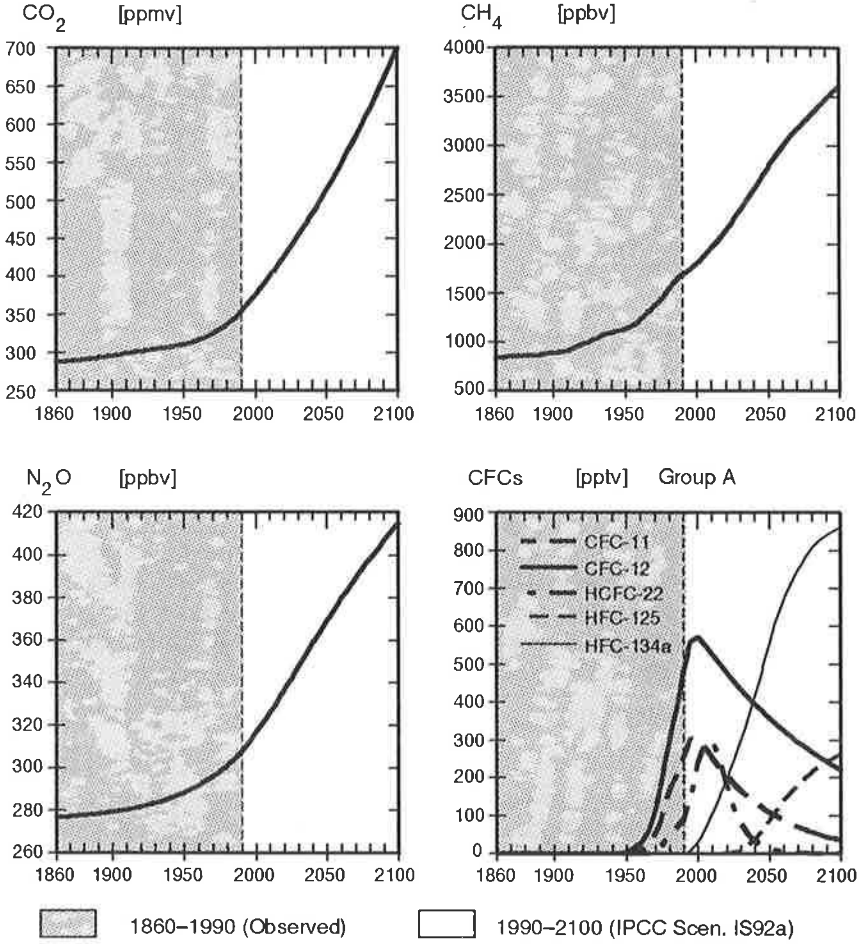
3. Climate Change Predictions

Predictions of future anthropogenic climate change are necessarily based on prescribed scenarios of assumed future greenhouse gas emissions. Figure 4 shows typical "business-as-usual" (BAU) projections of the future concentrations of greenhouse gases, assuming that the global economy continues to grow without climate regulation restrictions (Houghton et al. 1996). The relative contributions of the individual greenhouse gases to the net climate change are shown in Figure 5, together with other climate change factors such as the depletion of stratospheric ozone, the increase in tropospheric ozone, enhanced sulphate aerosol concentrations due to the emission of SO_2 (mainly through the burning of coal), and fluctuations in the solar radiation. The climate change impacts are expressed in terms of the effective "radiative forcing," the changes in the fluxes of solar and infrared radiation that drive the climate system. The largest impact is through the greenhouse gases, but greenhouse warming is reduced by about 20–30 percent as a result of increased aerosol concentrations. The effect of variations in solar forcing is small compared with the anthropogenic impacts.

The net radiative forcing of all greenhouse gases is usually summarized in terms of an equivalent CO_2 concentration change. The upper panel of Figure 6 shows the increase in global-mean, near-surface temperature predicted by a number of different climate models for a 1 percent annual increase in equivalent CO_2 concentration, corresponding approximately to the BAU projections of Figure 4 (Cubasch [personal communication]; see also Houghton et al. [1996]). The lower panel shows the corresponding temperature change when the cooling effect of sulphate aerosols is included. The associated spatial temperature-change patterns, averaged over the two decades 2010–2039, are shown in Figure 7. Figures 7 and 8 provide an impression of the considerable uncertainties in present climate predictions. However, despite significant differences in the details, the orders of magnitude and general spatial structures of the warming patterns are reasonably consistent. The temperature increases are significantly higher over the continents than over the oceans, which lag the warming over land due to the thermal inertia associated with the large heat storage capacity of the oceans. Higher warming is also found in the polar regions due to a positive feedback mechanism induced by the high reflectivity of snow and ice relative to ocean or land surfaces: a reduction in the areas of snow and ice leads to an increased absorption of solar radiation, resulting in stronger warming and further melting.

The fluctuations seen in the temperature curves of Figure 6 are not artefacts of the model, but represent realistic natural climate variations which are also found in observations. They are produced by large-scale ocean-atmosphere interactions, triggered by random weather fluctuations in the atmosphere. The pre-

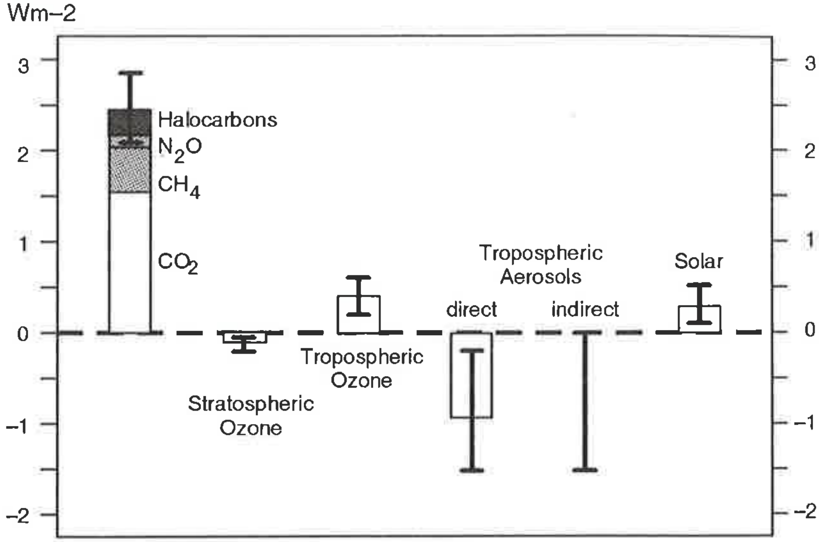
Figure 4: Observed (1860–1990) and Projected Greenhouse Gas Emission Concentrations (1990–2100)



Note: Projected emission concentrations are given for the business-as-usual scenario IS92a of the Intergovernmental Panel in Climate Change (IPCC). CFC concentrations (bottom right) decrease in the future due to the Montreal protocol, but hydrolyzed substitutes are seen to grow rapidly. Although these no longer endanger the stratospheric ozone layer, they are nonetheless effective greenhouse gases.

Source: Houghton et al. (1996).

Figure 5: Contributions of Different Anthropogenic Factors to the Radiative Forcing in the Atmosphere

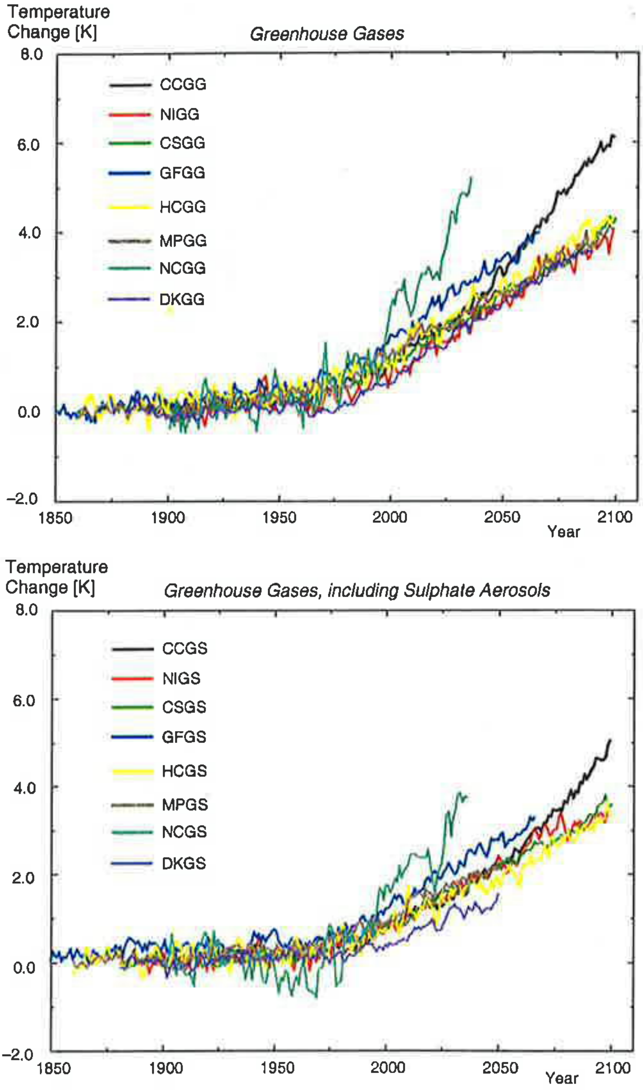


Note: Also shown is the impact of natural variations in solar radiation, which is small, however, compared with anthropogenic impacts. Tropospheric aerosols tend to cool the atmosphere by reflecting incoming sunlight (direct effect) and by modifying clouds (indirect effect).

Source: Houghton et al. (1996).

dictions of anthropogenic mean climate change are necessarily uncertain due to these superimposed natural climate fluctuations. However, the major uncertainty of climate predictions, as evidenced particularly by the differences in the predicted temperature change patterns of Figure 7, must be sought in the inaccuracies of the climate models themselves. These inaccuracies are associated primarily with the uncertainties in the parameterizations of the subgrid-scale processes mentioned above that cannot be resolved by the models. Estimates of predicted anthropogenic global warming are therefore normally presented in the reports of the Intergovernmental Panel on Climate Change (Houghton et al. 1996) with uncertainty bounds of 50 percent. Nevertheless, there exists a general consensus within the climate modeling community that, within these bounds, the orders of magnitude and general structure of the predicted climate change patterns are realistic.

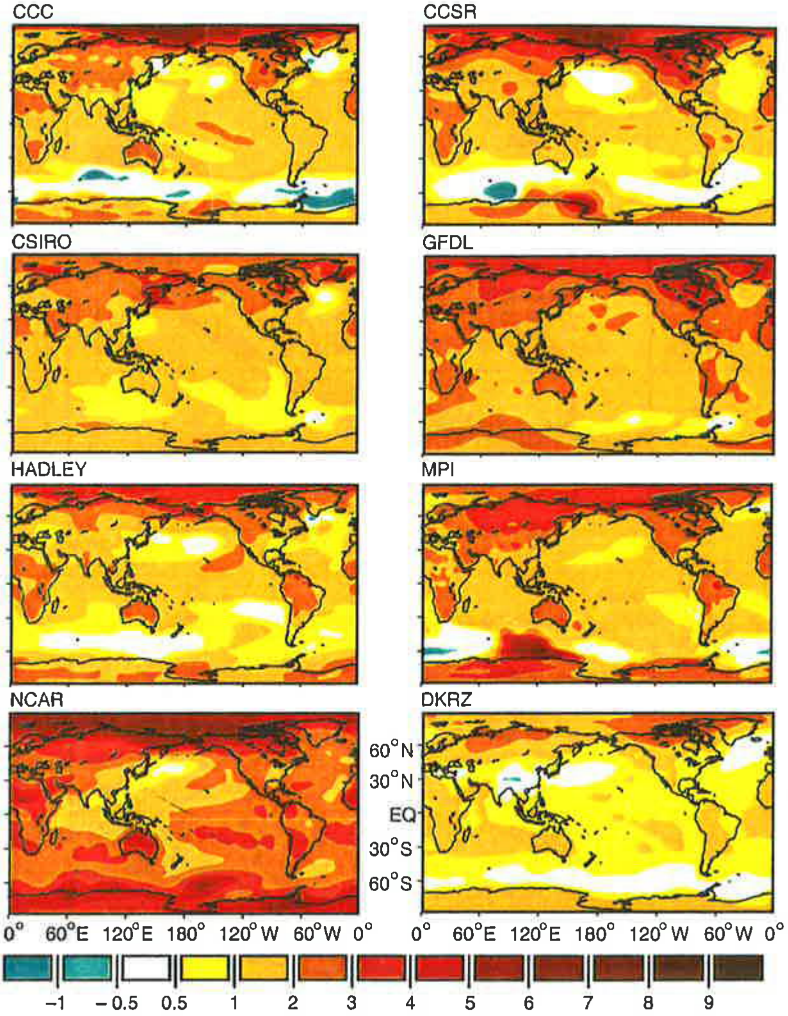
Figure 6: Temperature Change due to Increasing Greenhouse Gas Concentrations, with and without Inclusion of Areosols



Note: Global mean near-surface temperature computed with various climate models for a 1 percent annual increase in equivalent CO_2 concentrations (upper panel) and including aerosols (lower panel).

Source: Cubasch (personal communication); see also Houghton et al. (1996).

Figure 7: Spatial Patterns of Near-Surface Temperature Changes



Note: The changes correspond to the global mean temperature shown in Figure 6, averaged over the two decades 2010–2039. The models are indicated in the top left of each panel.

Source: Cubasch (personal communication).

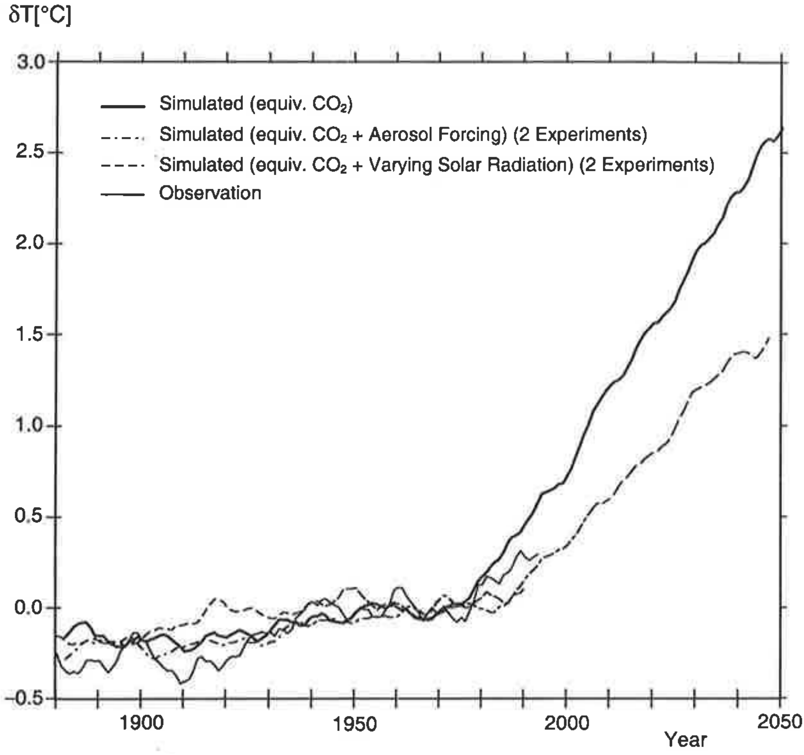
This is subject, however, to an important caveat: it is assumed that the climate system does not enter an unstable regime. In this case, the future climate state is basically unpredictable and can differ significantly from the climate change predicted with current models. A number of potential instabilities have been discussed in the literature. One of the more serious contenders, which has been observed in paleoclimatic records and simulated in models, is a breakdown of the Atlantic circulation (Maier-Reimer and Mikolajewicz 1989; Rahmstorf and Willebrand 1995; Rahmstorf 1995; Schiller et al. 1997). This can be triggered by a warming and/or freshening of North Atlantic surface waters. The surface water is then no longer dense enough to sink to sufficient depth to drive the deep ocean circulation, which is coupled with the Gulf Stream as the balancing return flow. A breakdown of the Gulf Stream, which is responsible for a 6°C warmer climate in Europe relative to the latitudinal mean, would clearly have dramatic consequences for the climate of Europe. Other potentially catastrophic instabilities are a sudden melting of the West-Antarctic ice sheet, which would result in a global sea level rise of 6 m, or a runaway greenhouse warming caused by the release of large quantities of methane (a very effective greenhouse gas) that are currently trapped in the permafrost regions of Siberia and in hydrates in the deep ocean.

4. Detection of Anthropogenic Climate Change

The computed present global warming due to anthropogenic greenhouse gas emissions is of the order of 0.7°C. This is comparable to the observed warming in the 20th century (Figure 8). However, it is not obvious that the observed temperature increase can be attributed to human influences, since natural climate variations of comparable magnitude over similar time periods have been observed in the past. Nevertheless, detailed statistical analyses of the global patterns of the observed and predicted temperature change using sophisticated, so-called fingerprint methods indicate that the probability that the observed warming can be attributed to natural climate variability lies below 5 percent (Hegerl et al. 1996, 1997; Hasselmann 1997b, 1998; Barnett et al. 1999). However, the detection of an anthropogenic climate signal can necessarily be expressed only in statistical terms and cannot be established with scientific certainty. This is well captured in the cautious, much-quoted statement of the Intergovernmental Panel on Climate Change in its latest report: "The balance of evidence suggests a discernible human influence on climate" (Houghton et al. 1996, p. 4).

Although the detection issue has received considerable attention in the media, it appears of secondary importance compared with the concern of scientists re-

Figure 8: Changes in Observed and Computed Global Mean Near-Surface Temperatures



Note: The computations were made with the Hamburg model for the observed greenhouse gas concentrations, with and without the inclusion of aerosols, and for estimated variations in the incident solar radiation.

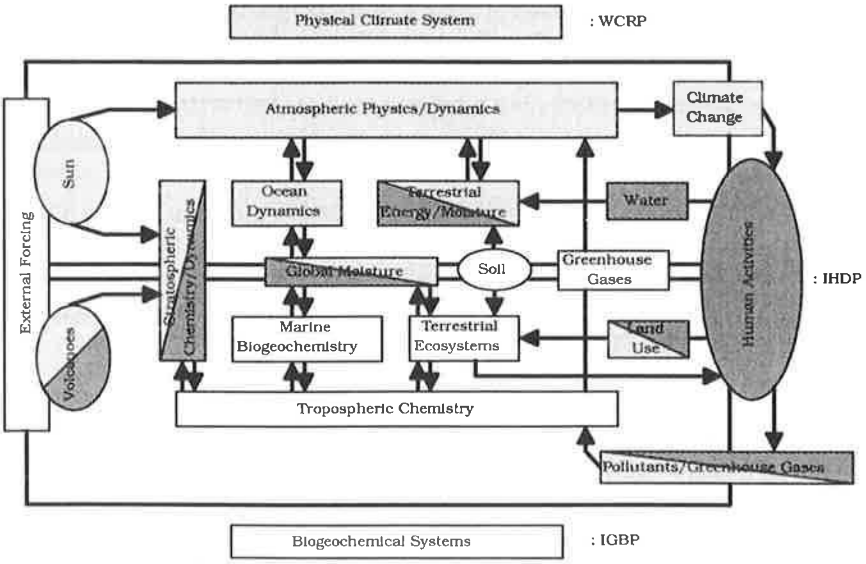
Source: Hegerl et al. (1997).

garding the significantly greater climate change predicted by models for the 21st and following centuries should the emissions of greenhouse gases continue to increase unabated. The confidence of climate modelers in the order-of-magnitude reliability of their climate change predictions is based primarily on the validation of their climate models against present climate data, rather than on the answer to the statistically complex question of whether the relatively small present anthropogenic climate change signal can be detected in the presence of natural climate variations of comparable magnitude. We can clearly not afford to wait until the statistical level of detection has reached near-certainty levels; the longer we delay taking action, the more difficult and expensive will it become to carry out effective mitigation measures. The challenge to climate protection policies is to implement optimized mitigation measures while accepting the unavoidable uncertainties of both predicted future climate change and the technological and global economic development.

5. Application of Climate Models in Integrated Assessment Studies

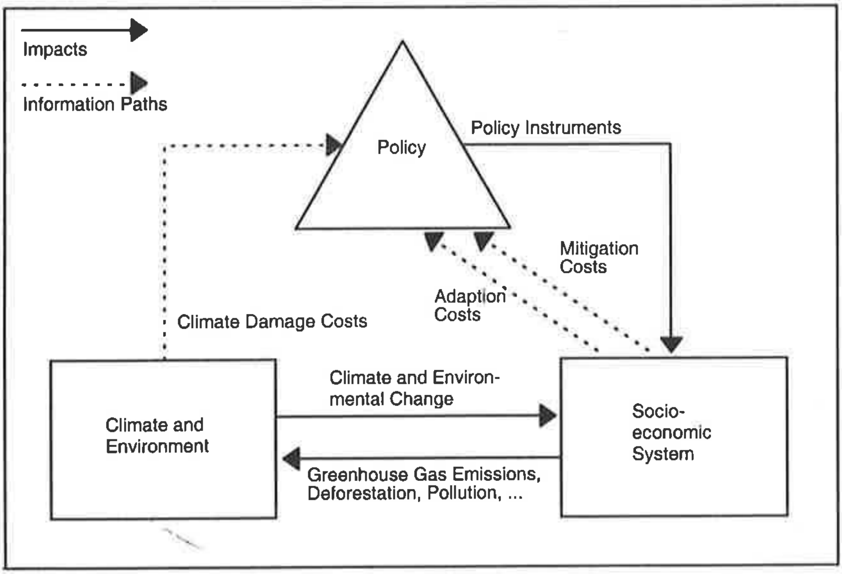
The physical climate models discussed above represent only one component of the Earth system. A realistic representation of the Earth system needs to combine three basic components: the physical climate system, the biochemical system, and the socioeconomic system (Figure 9). Research in these three areas is coordinated internationally through the Global Change Program, comprising the World Climate Research Program (WCRP), the International Geosphere-Biosphere Program (IGBP), and the International Human Dimensions Program (IHDP).

Figure 9: Interactions between the Physical Climate, Biogeochemical and Socioeconomic Systems in a Comprehensive Earth System Model



A comprehensive Global Environment and Society (GES) model including all three subsystems has the general structure indicated in Figure 10. A basic difficulty in constructing such models—apart from the inherent complexity of each of the individual subsystems—is the incompatibility of state-of-the-art models of the individual subsystems with the requirements of a single coupled model. Sophisticated General Circulation Models (GCMs) of the atmosphere and ocean used in modern climate models and state-of-the-art General Equilibrium Models (GEMs) of the global economic system involve very large numbers of independent variables and require significant computer resources. This makes it difficult to combine the models (particularly when developed in different coding languages) into a single computationally efficient model with which one can systematically carry out a large number of exploratory simulations, such as sensitivity studies, cost-benefit analyses, or optimal control computations.

Figure 10: Interactions between the Climate and Environment, the Socioeconomic System, and Policy



For applications in integrated assessment studies, the climate and socioeconomic subsystem models need to be reduced in complexity to computationally efficient and analytically transparent modules. For the climate subsystem, this can be achieved by projecting the response properties of the climate system computed with a sophisticated state-of-the-art climate model onto a dynamically equivalent impulse-response model, as discussed in the following section. For the socioeconomic system, the long time scales of the climate system require dynamic multiactor global growth models that include, in addition to climate change impacts, important long-term processes such as endogenous technological development, intergenerational transfers, and risk management.

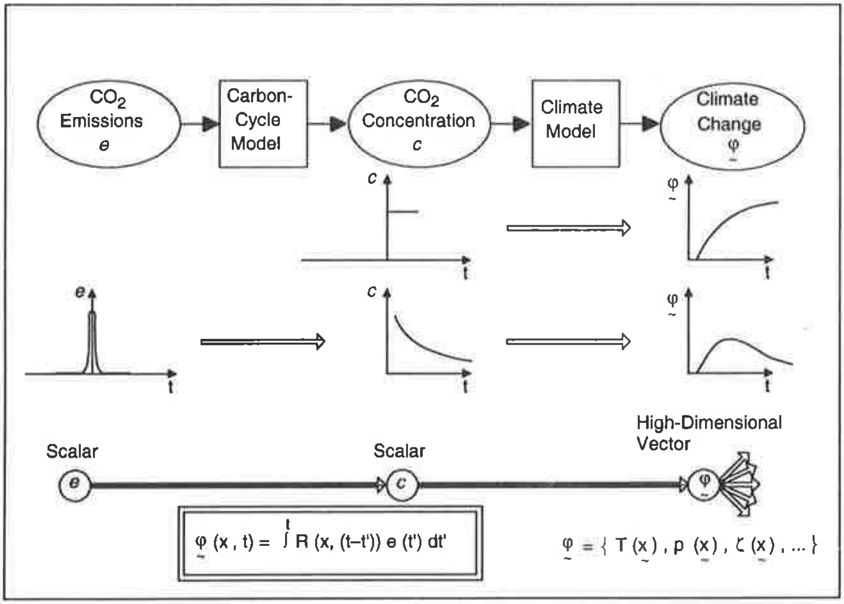
6. Impulse-Response Climate Models

Although the climate system, as noted above, is highly complex and strongly nonlinear, it is nevertheless feasible, for sufficiently small perturbations, to describe the response of the climate system to external influences in terms of a linearized model. The linearization conditions are reasonably satisfied for external forcing due to anthropogenic greenhouse gas emissions, provided the temperature change remains below 2–3°C. Measured in absolute Kelvin units, relative to absolute zero temperature at –273°C, the 15°C global mean temperature of the earth corresponds to 288 K. Thus a 3°C temperature change represents a perturbation of only $3/288 \approx 1$ percent in absolute temperature units (which is the relevant temperature scale governing infrared greenhouse radiation effects), so that climate change can be treated in the linear approximation.

For small perturbations, the relation between the forcing of a system—in the present case, the equivalent CO_2 emissions $e(t)$—and the response—the climate change $\varphi(x, t)$—can be expressed as a general linear response integral in terms of an impulse-response function $R(x, t)$ (see Figure 11). The function $R(x, t)$ can be calibrated against the response of the climate system for a given greenhouse gas emission scenario that has been computed with a fully nonlinear, state-of-the art climate model. The impulse-response model engenders no loss of information compared with the complete model, as the function $R(x, t)$ contains the same number of degrees of freedom in the representation of the climate change signal as the complete climate model against which it is calibrated. Once the impulse-response function $R(x, t)$ has been determined, the climate response can be computed very efficiently for arbitrary emission curves. Coupled with a similarly efficient socioeconomic model, the impulse-response model thus enables a large number of simulations to be performed, as required, for example, for optimal emission path computations or sensitivity studies.

Examples of impulse-response functions are shown in Figure 12 for the carbon cycle, the physical ocean-atmosphere system, and the full coupled carbon-cycle-plus-ocean-atmosphere system. The carbon-cycle response function, R_W,

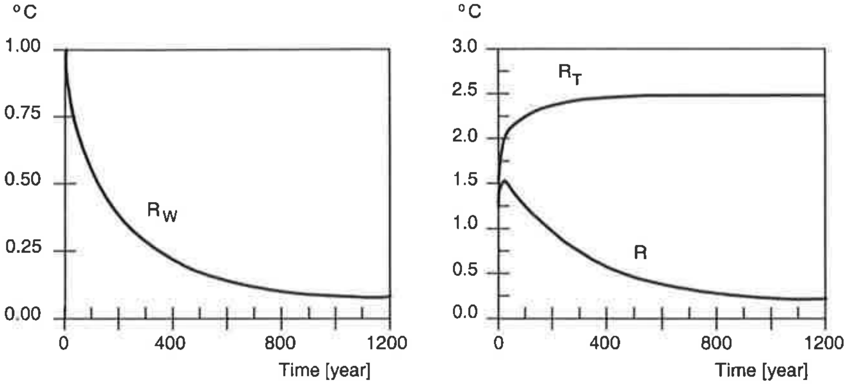
Figure 11: Impulse-Response Climate Model



Note: Linear relation between the anthropogenic forcing of the climate system through CO_2 emissions $e(t)$ and the climate response $\varphi(x, t)$. The net climate response $R(x, t)$ is determined by the response of the atmospheric CO_2 concentration to the CO_2 emissions and the subsequent response of the physical coupled ocean-atmosphere climate system to the atmospheric CO_2 concentration change. The impulse-response function $R(x, t)$ contains the same spatially dependent climate information (temperature, precipitation, pressure, cloud cover, etc.) as the complete, fully nonlinear climate model against which the impulse-response model is calibrated.

describes the decay of the atmospheric CO_2 concentration following the input of an initial amount of CO_2 into the atmosphere at time $t = 0$; the ocean-atmosphere response, R_T, represents the increase in temperature after the atmospheric CO_2 concentration has been suddenly increased at time $t = 0$ to a constant new level (corresponding in the example shown to a doubling of the CO_2 concentration); the net response, R, finally, shows the resulting temperature change in the complete coupled system to the CO_2 input (a doubling) at time $t = 0$. The important common characteristic of the response functions is their long memory. The decay, R_W, of the atmospheric CO_2 concentration , due to the gradual uptake of CO_2 by the oceans and the terrestrial biosphere, is an extremely slow process extending over several hundred years. Combined with the delayed temperature response, R_T, of the coupled ocean-atmosphere system to a CO_2 increase due to the large thermal inertia of the oceans, the net temperature response, R, of the climate system to CO_2 input persists over several centuries. Thus, in assessing the climate change impacts of human activities, one must consider time horizons far beyond the normal planning horizons of decision makers.

Figure 12: Response Functions for the Carbon Cycle (R_W), for the Physical Ocean-Atmosphere System (R_T), and for the Complete Coupled System (R)



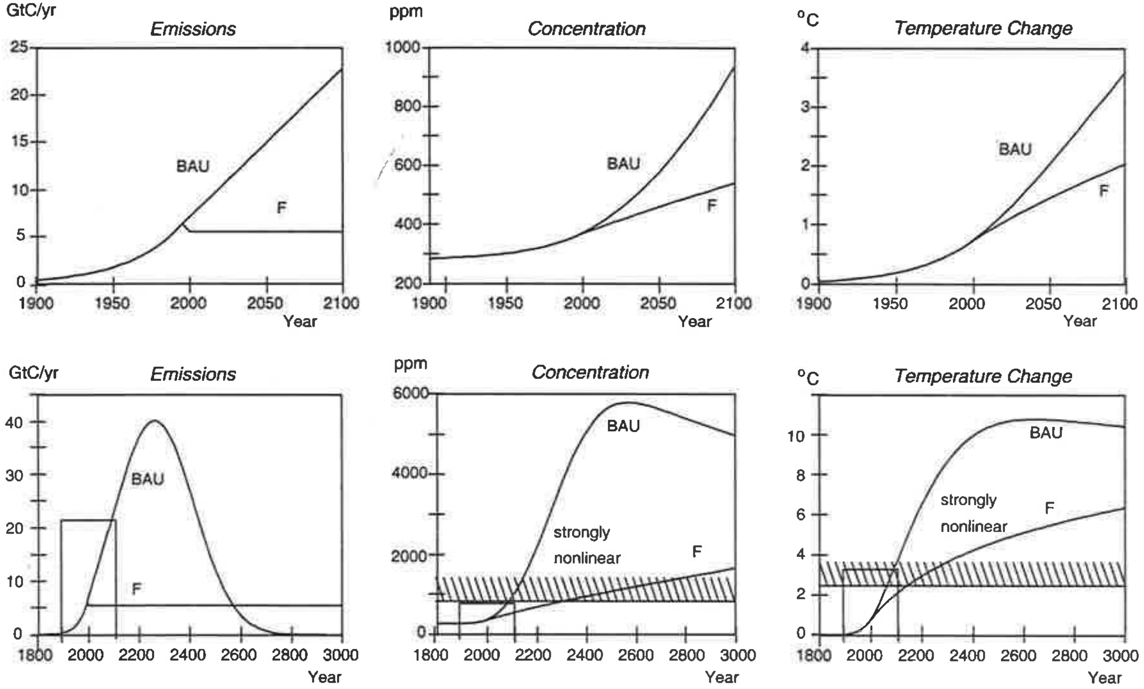
Note: The response functions were calibrated against nonlinear state-of-the-art Hamburg climate models.

Source: Hasselmann et al. (1997).

7. Optimizing CO_2 Emission Paths

The impact of the long memory of the climate system on the climate response to anthropogenic CO_2 emissions is illustrated in Figure 13, which shows the CO_2 emissions, CO_2 concentrations, and temperature change computed for a BAU scenario and an alternative frozen-emissions scenario F. The upper panels show the evolution over the next 100 years, the lower panels the evolution over the next 1,000 years. In the case of the business-as-usual (BAU) scenario, all fossil fuel resources, estimated as 10,000 GtC, are assumed to be exploited within the next 500 to 700 years. The long-term impacts in the lower panel are seen to greatly exceed the climate change over the next 100 years. Although the impulse-response computations are unreliable for large climate changes, the orders of magnitude of the computed warming in the range of 10°C clearly demonstrate the danger of underestimating future climate change impacts by developing climate policy over a period of only a few decades (see also Cline 1992).

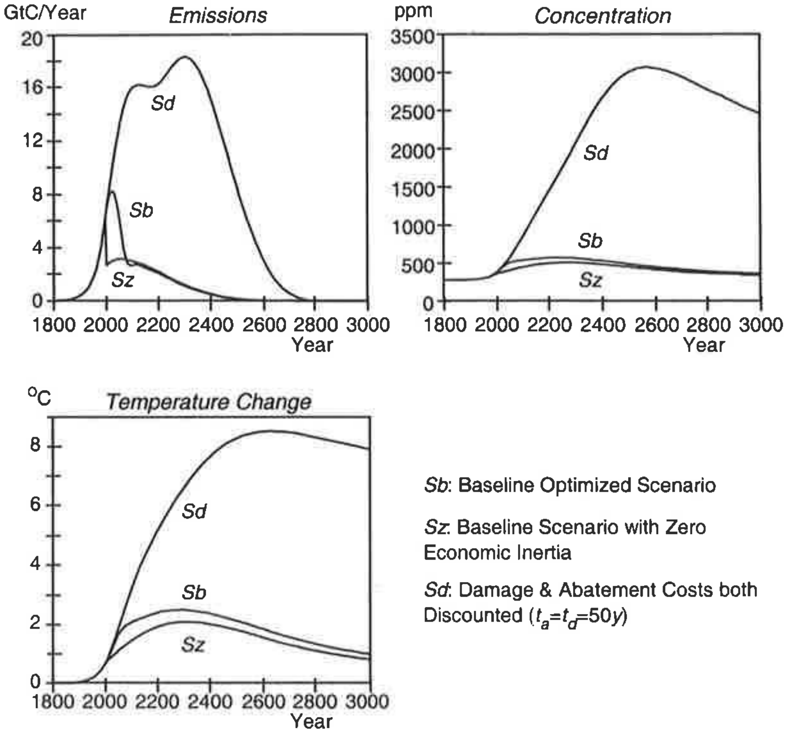
Figure 13: Evolution of Atmospheric CO_2 Concentrations and Global Mean Temperature



Note: Evolution computed with the impulse-response climate model, for a BAU scenario and a frozen-emissions scenario, F, over the next 100 years (upper panels) and the next 1,000 years (lower panels). The long-term climate change in the lower right panel is seen to greatly exceed the predicted climate change in the next 100 years (indicated also by boxes in the lower panels). The impulse-response model, from Hooss et al. (2000), was generalized in this example to include also some first-order nonlinear corrections.

The given emission scenarios of Figure 13 may be compared with optimized emission paths, shown in Figure 14, in which the time integral of the total climate change-related costs, composed of the sum of the emission abatement costs and the climate damage costs, has been minimized. The climate module of the elementary Structural Integrated Assessment Model (SIAM, Hasselmann et al. 1997) used in these optimization exercises consisted of an impulse-response model, while the economic module was represented simply by price expressions

Figure 14: Optimized Emission Scenarios and Climate Change



Note: In scenarious *Sb* and *Sz* only the abatement costs were discounted; in scenario *Sd* climate damage costs and CO_2 emission abatement costs were discounted equally. Standard discounting of both costs in the case *Sd* yields a solution close to the BAU case (Figure 13). In scenario *Sz* the economic inertia, characterized in scenarios *Sb* and *Sd* by a time constant of 50 years, was set equal to zero; see also Figure 15.

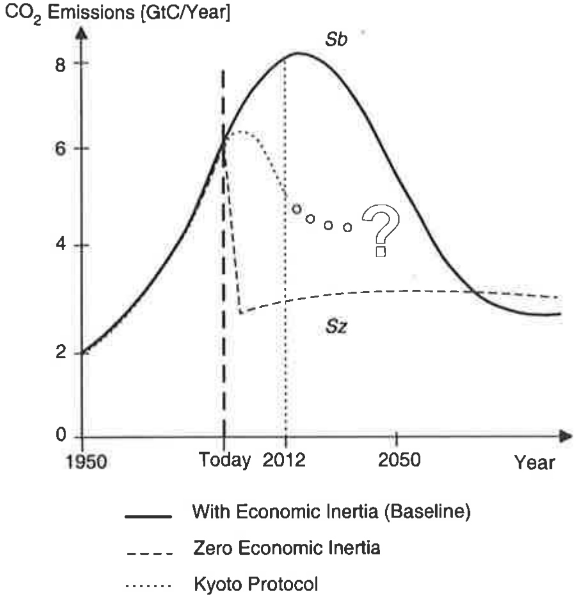
Source: Adapted from Hasselmann et al. (1997) and Hooss et al. (2000).

for the abatement and climate damage costs, including a relaxation parameterization of the effects of economic inertia. Three examples are shown: a baseline case, *Sb*, and two further cases, *Sz* and *Sd*. The scenario *Sz* was identical to the baseline case except that the economic inertia was set equal to zero. Although the cases *Sb* and *Sz* differ significantly in their emission paths in the first few decades, the differences in the long-term climate impact are minor, underlining again that for an effective climate mitigation policy, long-term emission abatements far outweigh the impact of short-term reduction measures. The gradual but complete replacement of carbon-based energy technologies by carbon-free technologies is essential for the prevention of major long-term climate change.

This is further illustrated by Figure 15, which compares the cases *Sb* and *Sz* with the Kyoto protocol for the industrialized countries. The Kyoto curve lies between the cases *Sb* and *Sz* and thus appears acceptable. From the long-term perspective imposed by the memory of the climate system, however, the hard-won Kyoto compromises over emission-reduction percentages appear almost irrelevant compared with the central challenge of establishing an effective long-term post-Kyoto mitigation strategy that will gradually but surely lead to a complete restructuring of the present energy technology away from fossil fuels.

The third case, *Sd*, in Figure 14 illustrates another important point. In the baseline optimal scenario, *Sb*, and the zero-inertia case, *Sz*, the abatement costs (at the relatively low value of 2 percent per year), but not the climate damage costs, were discounted. In contrast, in *Sd* both costs were discounted at the same rate, following standard economic accounting practice. In this case, the optimized emission path leads to a climate "catastrophe" similar to the BAU case shown in Figure 13. The reason for this is simple: since dramatic climate change occurs only after several hundred years, the implied discount factor is very small, and the discounted climate damage costs are negligible. Thus, there is no cost penalty incurred in following the BAU path. The conclusion is clearly that if concern for the welfare of future generations is to be taken seriously, this must be reflected in the discount factors applied to future climate damage costs. However, the appropriate choice of discount factors in cost-benefit analyses of future climate change is still a subject of considerable controversy. In my view, the problem reduces ultimately to an ethical judgment by the present generation on the relative value attached by future generations to a stable climate, compared with the future value of normal market goods, and to a willingness of the present generation to honor this basic ethical judgment through an intergenerational commitment to a sustainable development (see, for example, the discussions in Hasselmann et al. [1997], Nordhaus [1997], Heal [1997], Brown [1997], Hasselmann [1999]).

Figure 15: Optimized Scenarios *Sb* and *Sz*, with and without Economic Inertia, and the Kyoto Protocol for the Industrialized Countries



The computations of optimal emission paths over many centuries presented in these illustrative examples clearly far exceed the horizons over which economic and technological developments can be reasonably predicted. In practice, the translation of such theoretical results into policy recommendations can be meaningfully made only in the context of a continual, iterative process: policy measures need to be continually updated and adapted to new knowledge on climate change and technological and economic developments. However, the basic conclusion of these examples, namely that, in the long term, carbon-based energy technology must be completely replaced by carbon-free technologies in order to avert major climate change, is independent of the details of the transition process. It follows simply from the long time constants of the climate system, which are determined by elementary physics. But the long memory of the climate system also has an important positive aspect: it implies that the transition to carbon-free energy technologies can be carried out gradually over many decades, without causing major dislocations of the economic system. This long-term perspective needs to be kept in focus as an important orientation in the ongoing international negotiations over the goals and means of implementing an effective climate policy.

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