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# Assessing and Simulating the Altered Functioning of the Earth System in the Anthropocene

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## ABSTRACT

The current human-dominated era or “Anthropocene” has been a time of unprecedented rates of change within the Earth system. As such the Anthropocene poses a no-analogue situation in which evidence of past Earth system changes cannot, on their own, tell us of how the system will respond in the future. Instead, we need to develop mechanistic and phenomenological models based on robust underlying principles to extrapolate our knowledge of the past Earth system into projections of the future. This requires an entire spectrum of Earth system models that can be related to each other in a more rigorous way than has been achieved to date. It also requires new integrated models of the two-way coupling between the biophysical and human aspects of the Earth system. Only then will we be able to approach all of the paleodata constraints on Earth system dynamics (which requires long simulations), while also providing regionally specific Earth system projections and spatially specific human development paths for policy makers (which requires, in both cases, high-resolution comprehensive models as well as models that can bridge spatial and temporal scales). Such a spectrum of models offers a solution to the tension between “simulation,” which inevitably leads to increasing model complexity, and “understanding,” which often involves reducing the system to its bare necessities.

## INTRODUCTION

As a working definition, we consider the Earth system to be the sum of the components, interactions, and feedbacks that determine the physical, chemical, and biological environment of the planet, as well as its variations in space and time.

The current Anthropocene era is a period of unprecedented rate of change in the Earth system brought about by human activities. Atmospheric CO<sub>2</sub> levels are now higher than they have been for at least 2 million years and probably much

longer (Prentice et al. 2001). Methane concentrations are double what they were in the preindustrial era. Anthropogenic inputs have also almost doubled the amount of available N coming into the global terrestrial ecosystems each year (Vitousek et al. 1997). Throughout human history, land-use change has reduced the global fraction of forests from 45% to 27% (Andreae et al., this volume), and the rate of deforestation has generally accelerated with 16 million ha of tropical forest lost per year through the 1990s (Houghton 2003). An even more significant human perturbation of the Earth system is projected for the next 100 years.

The absence of a past analogue for the Anthropocene implies that we need to extrapolate our knowledge of the functioning of the Earth system into new areas of its phase space. Although purely empirical relationships between variables (e.g., global temperature and CO<sub>2</sub> or energy services and CO<sub>2</sub>) can be used to interpolate data points, they cannot be reliably utilized outside the region for which they were fitted. Instead, mechanistic and phenomenological models are required based on principles that apply to both the past and future Earth system states (in this way, mechanistic and phenomenological models extrapolate mechanisms and the underlying systems dynamics rather than the empirical correlations between variables).

An Earth system model is a numerical representation of the Earth system. The precise definition of such a model depends on the timescale of interest. Much slower processes can be considered as constant boundary conditions (e.g., locations of continents in century-scale projections). Much faster processes can be considered as stochastic forcing of the slower processes (e.g., the impact of weather systems on the deep-ocean circulation). Components of the natural Earth system, along with their characteristic timescales for change, are shown in Table 15.1.

Processes with similar timescales need to be explicitly modeled if they are a sufficiently strongly interacting part of the overall system. Weakly coupled subsystems may, however, be considered as time-varying boundary conditions if they respond little to changes in the system of interest (e.g., variations in solar input).

Earth system models span a massive range of complexities, from conceptual models designed to enhance understanding, to general circulation models (GCMs) developed to predict future climate change. This spectrum of Earth system model complexities reflects a natural tension between the scientist's desire to understand the system and the policy makers' desire for useful predictions. To develop an understanding of the workings of a system, a scientist will tend to simplify and idealize, taking the model of the system away from reality but generating more robust and reproducible findings. The key motivation is often to isolate the dominant factors in the system's behavior rather than to predict its evolution in detail. This driver leads to simpler conceptual models. By contrast, to produce predictions of a system's behavior (e.g., as required by policy makers) requires complex simulation models (e.g., GCMs). These models need to be

**Table 15.1** Components of the Earth system and their characteristic timescales.

Earth System Component	Subcomponent	Timescale of Change
Atmosphere	Boundary layer	Day
	Free atmosphere	Days to months
Ocean	Mixed layer	Months to years
	Deep ocean	100–1000 years
	Sea ice	Days to 100 years
Cryosphere	Snow	Days to years
	Mountain glaciers	100 years
	Ice sheets	10,000 years
Biosphere	Vegetation	10 days to 1000 years
	Soil carbon	1 to 1000s years
Geosphere	Rock weathering	> 10 <sup>5</sup> years
	Plate tectonics	> 10 <sup>7</sup> years
Anthroposphere	Technological change	20–100 years
	Life expectancy	35–75 years
	Doubling of CO <sub>2</sub> emissions	30–40 years (at current rates)
	Doubling of human population	80 years (at current rates)

mechanistic, where they are used to extrapolate into no-analogue situations (e.g., the Anthropocene), and complete so that all plausibly important processes are included.

Table 15.2 shows three classes of models that make up the spectrum of Earth system models. Conceptual models include “box models” in which a substance or quantity (e.g., carbon in vegetation) is often represented by a single compartment (or “box”). Aspects of the coupled Earth system are studied by coupling a number of boxes together through parameterized exchanges. Box models are very economical and thus can be used to study Earth system dynamics on long timescales (billions of years in some cases). Their relative simplicity makes it possible to understand their outputs in terms of the underlying model assumptions; however, they tend to have a high ratio of tunable parameters to internal degrees of freedom.

Comprehensive models attempt to model the key Earth system processes explicitly. For example, GCMs were born of weather forecasting models, which aim to simulate the movement and development of weather systems. Unfortunately, it is not feasible to run very high-resolution models for periods of interest with regard to climate change (10–100 years), and therefore lower-resolution variants of atmospheric and oceanic models are employed in GCMs. Unresolved fluid transports, such as convection, need to be parameterized (i.e., represented in terms of the resolved large-scale variables) because these occur on scales much less than the GCM gridscale. In addition, many nonfluid diabatic

**Table 15.2** The spectrum of Earth system models.

	<b>Conceptual</b>	<b>Intermediate Complexity</b>	<b>Comprehensive</b>
Purpose	To develop understanding of emergent properties	Used to simulate past climate change	Used to predict future climate change
Spatial dimensions	0D–1D	2D–3D	3D
Typical timescales	$10^3$ – $10^9$ years	$10$ – $10^4$ years	$0.1$ – $10^3$ years
CPU usage	$\sim 10^3$ years/min on PC	$\sim 10^3$ years/day on workstation	$\sim 10^3$ years/year on supercomputer
Examples	Box models Daisyworld	CLIMBER Statistical Dynamical	GCMs

processes need to be represented in GCMs (e.g., land–atmosphere exchange, cloud and condensation processes, atmospheric radiative transfer). Uncertainty in these parameterizations leads to most of the spread seen among GCM projections of climate change (IPCC 2001). Nevertheless, GCMs have advanced significantly over the last few decades, such that they offer our best guidance on the consequences of continuing anthropogenic emissions of greenhouse gases and aerosol precursors.

Between these two extremes of complexity lie “Earth system models of intermediate complexity” (EMICs), which are designed to address longer timescales than currently feasible with a GCM. EMICs are spatially explicit (i.e., they resolve differences between different parts of the globe) but generally use economical parameterizations (e.g., of atmospheric circulation) rather than explicitly modeling all of the flows. Since they can be run for long periods, EMICs have been invaluable for the interpretation of paleoclimate data in terms of Earth system processes.

In socioeconomic modeling, the current state-of-the-art includes quite complex models used to assess the development of different components of the anthropogenic sphere. Demographic models are usually simulation frameworks that describe future population development as a function of regional or national fertility and mortality trends, as well as, to a lesser degree, a function of migration. Economic models usually maximize utility of consumption as a function of resource availabilities, labor, and capital within an equilibrium framework, either for various world regions or for individual countries. Some of the economic models include energy system submodules so as to determine the emissions. Energy models themselves are often also optimization frameworks that minimize overall energy systems costs or resulting emissions under the resource, demand,

and other constraints. Impact models range from simulation frameworks to economic models of agricultural and other sectors. Recently, such models have been coupled into “integrated assessment” (IA) frameworks to provide a more holistic perspective of future developments and trends that may characterize the Anthropocene and the interactions with Earth system. Another approach has been the development of “reduced form” IA models, which capture essential developments based only on the essential driving forces and variable interactions. These models often have very coarse resolution in time and space. They are used to develop scenarios of future developments.

### **THE EMERGENCE OF THE ANTHROPOCENE**

The main driving forces of the Anthropocene started unfolding with the onset of the Industrial Revolution some two centuries ago. However, it is only during the last decade or two that it has become evident that human activities have resulted in salient intervention and changes of planetary processes which have irreversibly changed the Earth system. Anthropogenic climate change is the most widely known example; however, humans are also impacting many other aspects of Earth system function.

In 1750, after 10,000 years of slow but steady increase, the world’s population was approximately 750 million people — the result of the spread of ever better agricultural practices throughout the world. It is estimated that during the last 1000 years, the population has been growing at a rate of 0.1% per year, or doubling on the order of 500 years. The characteristic size of the global population was less than 50 million throughout the age of agriculture (Zabel 2000).

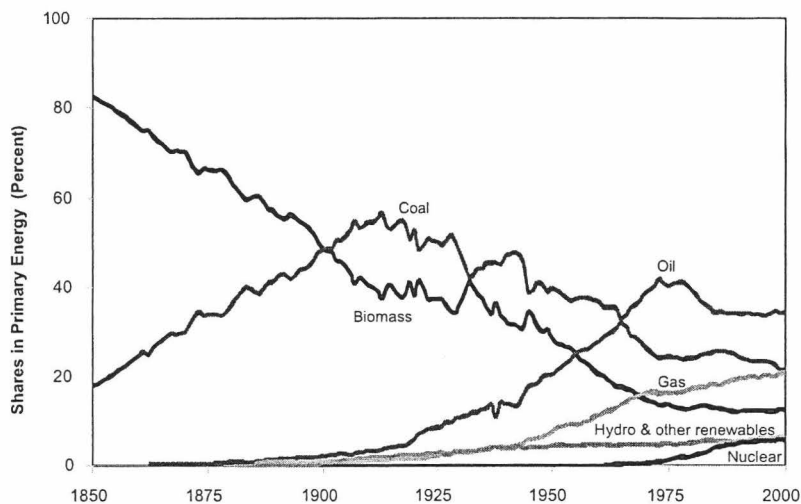
With the emergence of the Industrial Revolution, conditions changed radically. In 1800, the global human population was about 1 billion; today it is ca. 6 billion. This sixfold increase corresponds to an annual growth rate of 0.9% per year. At this rate, the global population doubles every 80 years. A drastic decrease in mortality, improved water quality, diet, sanitary conditions, and medicine have all contributed to this explosive rate of growth. Today, life expectancy in industrialized regions is twice as high as in preindustrial areas of the world (75 years vs. 35 years).

As a consequence of industrial development, productivity has increased enormously in terms of physical and monetary output per hour of work. Thus, those who were fortunate to benefit from formal employment worked roughly half as many hours as workers and farmers at the beginning of the Industrial Revolution. The annual work effort is somewhere between 1500 and 2000 hours per annum in most of the developed countries. The reduction in working time in conjunction with long life expectancy means that those engaged in formal work today have about four times as much “leisure time” over their life time, compared to 200 years ago. Free or leisure time is often expended in a consumptive mode, such as increased mobility. Mobility has increased by three orders of

magnitude during the last three centuries. For example, in 1800 an average person in France traveled some 20 m (meters) per day, mostly on horseback and to a much lesser extent by boat; today, average mobility is some 50 km per person per day and is mostly accomplished by car or bus, with about 1 km per person per day by rail and air (Grübler 1998b).

Industrialization has changed the very fabric of human society and existence. An aggregate characterization of the multitude of changes is the gross world (economic) product, which measures the value of all goods and services associated with formal economies. This has grown seventyfold over the last 200 years, corresponding to an annual increase of 2% per year and a doubling in 35 years.

An essential prerequisite for this continuous development process has been the ever-increasing quantity and quality of energy services. In 1800 the world depended on biomass (mostly fuelwood and agricultural waste) as the main energy source for cooking, heating, and manufacturing. Human physical labor and work of animals were the main sources of mechanical energy, with some much more humble contributions of wind and hydraulic power. Figure 15.1 shows how drastically the nature of energy services has been transformed through replacement of traditional (noncommercial) energy sources by coal. In 1850, coal provided some 20% of global primary energy needs and peaked in the 1920s at almost 70% (Nakicenovic et al. 1996). This can be characterized as the first energy transition. The coal age brought railways, steam power, steel, manufacturing, and the telegraph to mention some of the technologies that constituted the “coal cluster.”



**Figure 15.1** Global primary energy requirements since 1850 shown as fractional market shares of the six most important energy sources. Hydropower includes all other renewable energy sources except biomass.



Around 1900, motor vehicles were introduced along with petrochemicals, electricity, and many other technologies that constitute the “oil cluster.” It took another 70 years for oil to replace coal as the dominant source of energy in the world. Today, the global energy system is much more complex, with many competing sources of energy and many high-quality and convenient energy carriers ranging from grid-oriented forms, such as natural gas and electricity, to liquids that are mostly used in transportation to solids (coal and biomass) still used in the developing parts of the world (where a third of global population lives that still does not have access to modern energy services). Taken together, fossil energy sources provide some percentage of global energy needs, whereas fuelwood, hydropower, and nuclear energy provide the rest.

Affordable and convenient energy services were one of the primary drivers for the emergence of the Anthropocene. They helped increase human productivity in all sectors, from agriculture to industrial production and provision of services, and replaced human and animal work by abundant sources of power. Consequently, the global primary energy requirement has increased 35-fold during the last 200 years. The energy intensity of economic activities has in fact declined twofold but the 70-fold increase in economic activities required evermore energy. As the share of fossil energy sources, taken together, increased from 20–80% between 1850 and the present, so did the emissions of CO<sub>2</sub> (as an unavoidable byproduct of combustion). Consequently, energy-related emissions of CO<sub>2</sub> increased 22-fold to about 6 billion tons of carbon (6 Gt C) today.

Emissions of other radiatively active gases in the atmosphere have accompanied the increase in CO<sub>2</sub>. Carbon dioxide concentrations in the atmosphere have increased from about 280 parts per million (ppm) volume in 1750 to over 370 ppm today. Methane concentrations have doubled over the same period. Chlorofluorocarbons (CFCs) are a fundamentally new, anthropogenic constituent of the atmosphere that did not exist in nature. Another indication of the involved complexities is that emissions of sulfur aerosols and particulate matter increase along with energy consumption and emissions of greenhouse gases. Aerosol emissions are now regulated in most of industrialized countries and are declining, but they have resulted in regional cooling, which has offset some of the climate warming caused by increasing concentrations of greenhouse gases.

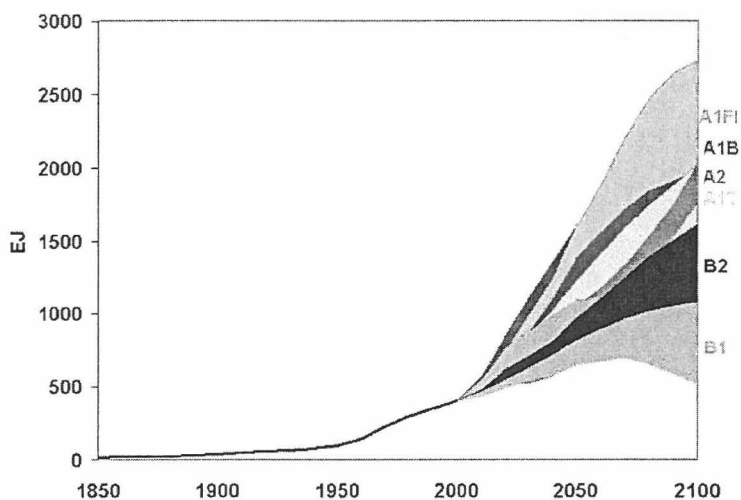
### **ENERGY USE, EMISSIONS, AND CLIMATE CHANGE SCENARIOS FOR THE TWENTY-FIRST CENTURY**

Scenarios offer a technique for assessing (alternative) evolutionary paths of the Anthropocene and possible response measures and strategies in the face of deep uncontrollable and irreducible uncertainties. Scenario planning is a systemic method for thinking creatively about possible complex and uncertain futures. The central idea of scenario development is to consider a variety of possible futures (Peterson et al. 2003) that include many of the important uncertainties in

the human systems rather than to focus on the accurate prediction of a single outcome (which is not possible). Scenarios are images of the future, or alternative futures. They are neither predictions nor forecasts. Rather, each scenario is one alternate image of how the future might unfold. A set of scenarios assists in the understanding of possible future developments of complex coupled systems. Scenarios can be viewed as a linking tool that integrates qualitative narratives or stories about the future and quantitative formulations based on formal modeling. They enhance our understanding of how systems work, behave, and evolve. Scenarios are useful tools for scientific assessments, for learning about complex systems behavior, and for policy making (Jefferson 1983; Davis 1999). In scientific assessments, scenarios are usually based on an internally consistent and reproducible set of assumptions or theories about the key relationships and driving forces of change, which are derived from our understanding of both history and the current situation. Often, scenarios are formulated with the help of numerical or analytic formal models.

The orthodox process of producing climate change projections for the twenty-first century is multistage and multidisciplinary. The drivers of climate change (anthropogenic emissions of greenhouse gases and aerosols as well as land-use change) are derived using socioeconomic and IA models, based on a range of "storylines" regarding population growth, economic development, and technological change. The emissions are then fed into atmospheric chemistry models, which produce corresponding scenarios of changes in the concentrations of greenhouse gases and aerosols for use within GCM climate models (see Steffen et al., this volume). Finally, climate change projections and socioeconomic scenarios are used to assess impacts, adaptation, and mitigation measures and strategies, which are of interest to the policy makers.

Figure 15.2 compares projected future energy requirements across the range of the IPCC SRES scenarios (Nakicenovic et al. 2000), each consistent with a given possible storyline for global economic development. These future IPCC scenarios indicate a sevenfold increase in primary energy requirements by 2100, at the high end of the scale, and almost a twofold increase at the low end. It is interesting to note that the scenarios in the lower range represent sustainable futures with a transition to very efficient energy use and high degrees of conservation. Generally, these are also the scenarios in which energy sources with low carbon intensity play an important role. These are also the scenarios where land-use patterns allow the return of some land to "nature," both because of more sustainable agricultural practices and because of changing dietary practices toward less meat. Scenarios with high shares of renewable energy sources, biomass in particular, would however need substantial shares of nonagricultural land for energy farming and plantations. This is again linked to additional interference in the Earth system. Currently, such complex feedbacks cannot be included in the energy and land-use models, or in IA models, except at the level of explicit assumptions.

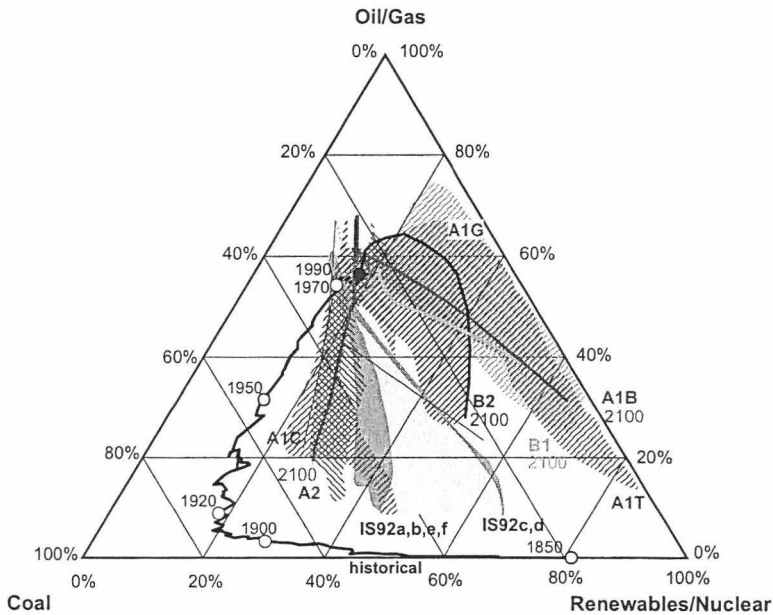


**Figure 15.2** Global primary energy requirements since 1850 and in the IPCC SRES scenarios to 2100 (EJ per year). Based on IPCC SRES (Nakicenovic et al. 2000).

Figure 15.3 illustrates how world primary energy structure evolves for each scenario. It shows the contributions of individual primary energy sources — the percentage supplied by coal, oil, and gas, as well as by all nonfossil sources taken together. Each corner of the triangle corresponds to a hypothetical situation in which all primary energy is supplied by a single source — oil and gas at the top, coal to the left, and nonfossil sources (renewables and nuclear) to the right. Historically, the primary energy structure has evolved clockwise according to the two “grand transitions,” which are shown by the two segments of the “thick black” curve (see also Figure 15.1). From 1850 to 1920 the first transition can be characterized as the substitution of traditional (nonfossil) energy sources by coal. The share of coal increased from 20% to about 70%, during which time the share of nonfossils declined from 80% to about 20%. The second transition, from 1920 to 1990, can be characterized as the replacement of coal by oil and gas (while the share of nonfossils remained essentially constant). The share of oil and gas increased to about 50% and the share of coal declined to about 30%.

Looking into the future, different possibilities unfold across the scenarios. Figure 15.3 shows the divergent evolution of global primary energy structures across scenarios between 1990 and 2100, regrouped into their respective scenario families and four A1 scenarios groups that explore different technological developments in the energy systems. In a clockwise direction, A1 and B1 scenario groups map the structural transitions toward higher shares of nonfossil energy in the future, which almost closes the historical “loop” that started in 1850. The B2 scenarios indicate a more “moderate” direction of change with about half of the energy coming from nonfossil sources and the other half shared by coal on one side and oil and gas on the other. Finally, the A2 scenario group

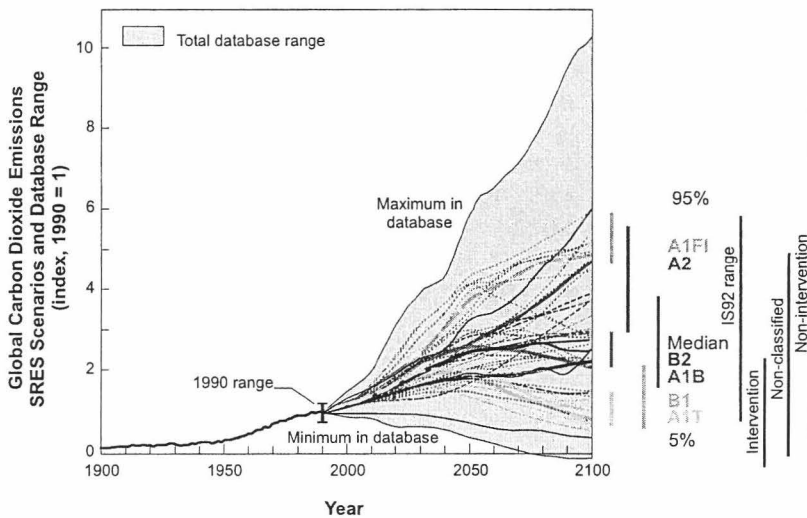
marks a return back to coal. This is especially important for those regions of the world that have ample coal resources (e.g., India and China). Shares of oil and gas decline while nonfossils increase moderately. What is perhaps more significant than the diverging developments in the four marker scenarios is that the whole set of 40 scenarios covers virtually all possible directions of change, from high shares of oil and gas to high shares of coal and nonfossils. In particular, the A1 scenario family covers basically the same range of structural change as all other scenarios together. In contrast, the IPCC IS92 scenarios cluster into two groups: (a) IS92c and IS92d and (b) the four others. In all of these, the share of



**Figure 15.3** Global primary energy structure, shares (%) of oil and gas, coal, and nonfossil (zero carbon) energy sources: Historical development from 1850 to 1990 and in SRES scenarios. Each corner of the triangle corresponds to a hypothetical situation in which all primary energy is supplied by a single source: oil and gas on the top; coal to the left; nonfossil sources (renewables and nuclear) to the right. Constant market shares of these energies are denoted by their respective isoshare lines. Historical data from 1850 to 1990 are based on Nakicenovic et al. (1998). For 1990 to 2100, alternative trajectories show the changes in the energy systems structures across SRES scenarios. They are grouped by shaded areas for the scenario families A1, A2, B1, and B2 with respective markers shown as lines. In addition, the four scenario groups within the A1 family (A1, A1C, A1G, and A1T) explore different technological developments in the energy systems and are shaded individually. For comparison, the IPCC IS92 (Leggett et al. 1992) scenario series are also shown, clustering along two trajectories (IS92c, d, and IS92a, b, e, f). For model results that do not include noncommercial energies, the corresponding estimates from the emulations of the various marker scenarios by the MESSAGE model were added to the original model outputs. Source: Nakicenovic et al. (2000).

oil and gas declines, and the main structural change occurs between coal and nonfossils. This divergent nature in the structural change of the energy system and in the underlying technological base of the SRES results in a wide span of future greenhouse gas and sulfur emissions.

Here we summarize the related scenarios of CO<sub>2</sub> and SO<sub>2</sub> emissions, although it should be noted that similar projections have been made for other radiatively active species. Figure 15.4 illustrates the range of CO<sub>2</sub> emissions from energy for each of the SRES scenarios, normalized to unity at the current day (Morita et al. 2000). The range of future emissions is very large so that the highest scenarios envisage more than a sevenfold increase of global emissions by 2100, whereas the lowest have emissions that are less than today. Together, the SRES scenarios span jointly from the 95<sup>th</sup> percentile to just above the 5<sup>th</sup> percentile of the distribution of energy emissions scenarios from the literature. There is a substantial overlap in the emissions ranges across the 40 SRES



**Figure 15.4** Global CO<sub>2</sub> emissions from energy and industry: Historical development from 1900 to 1990 and in 40 SRES scenarios from 1990 to 2100, shown as an index (1990 = 1). The range is large in the base year 1990, as indicated by an “error” bar. The dashed time paths depict individual SRES scenarios and the shaded area the range of scenarios from the literature (see also Figure 15.1). The 5<sup>th</sup>, 50<sup>th</sup> (median), and 95<sup>th</sup> percentiles of the frequency distribution are shown. Jointly, the scenarios span most of the range of the scenarios in the literature. The emissions profiles are dynamic, ranging from continuous increases to those that curve through a maximum and then decline. Colored vertical bars indicate the range of the four SRES scenario families in 2100. Also shown as vertical bars on the right are the ranges of emissions in 2100 of IPCC IS92 scenarios and of scenarios from the literature that include additional climate initiatives (designated as “intervention” scenarios emissions range), those that do not (“non-intervention”), and those that cannot be assigned to either of these two categories (“non-classified”). Source: Nakicenovic et al. (2000).

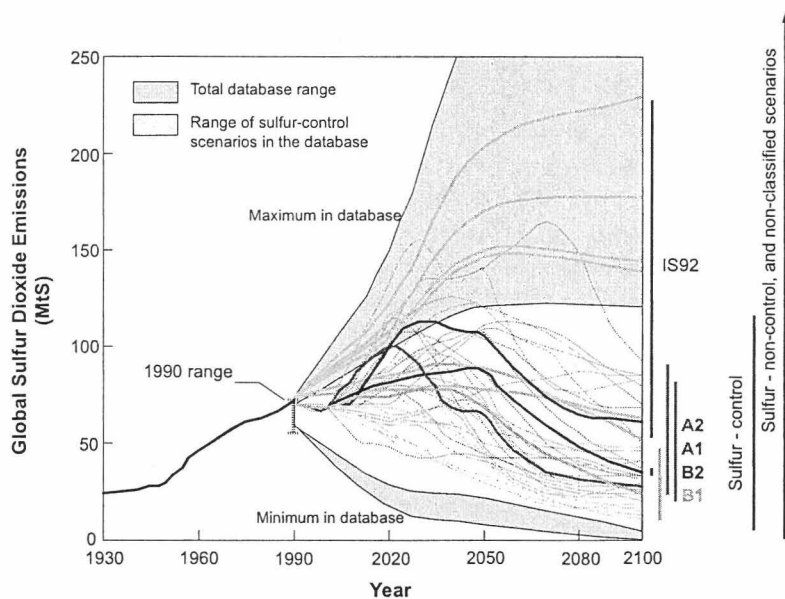
scenarios. Many share common driving forces, such as population and economic growth, yet lead to a wide range of future emissions. This result is of fundamental importance for the assessments of climate change impacts and possible mitigation and adaptation strategies. It is also important in the broader context of human interference with the Earth system, especially during the future unfolding of the Anthropocene.

Of the greenhouse gases, CO<sub>2</sub> is the main contributor to anthropogenic radiative forcing because of changes in concentrations from preindustrial times. According to Houghton et al. (1996), well-mixed greenhouse gases (CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O, and the halocarbons) induced additional radiative forcing of around 2.5 W m<sup>-2</sup> on a global and annually averaged basis. Carbon dioxide accounted for 60% of the total, which indicates that the other greenhouse gases are significant as well. Whereas CO<sub>2</sub> emissions are attributable primarily to two major sources, energy consumption and land-use change, other emissions arise from many different sources and a large number of sectors and applications.

The SRES emissions scenarios also have different emissions for other greenhouse gases and chemically active species, such as carbon monoxide, nitrogen oxides, and non-methane volatile organic compounds. The uncertainties that surround the emissions sources of the other greenhouse gases, and the more complex set of driving forces behind them, are considerable and unresolved. Therefore, the models and approaches employed for the SRES analyses cannot produce unambiguous and generally approved estimates for different sources and world regions over a century. Emissions of other gases are not shown here; however, they follow dynamic patterns much like those shown in Figure 15.4 for CO<sub>2</sub> emissions (Nakicenovic et al. 2000).

Emissions of sulfur portray even more dynamic patterns in time and space than the CO<sub>2</sub> emissions shown in Figure 15.4. Factors other than climate change (namely regional and local air quality, and transformations in the structure of the energy system and use) intervene to limit future emissions. Figure 15.5 shows the range of global sulfur emissions for all SRES scenarios compared to the emissions range of the IS92 scenarios, 81 scenarios from the literature, and the historical development.

A detailed review of long-term global and regional sulfur emission scenarios is given in Grüber (1998a) and summarized in Nakicenovic et al. (2000). The most important new finding from the scenario literature is recognition of the significant adverse impacts of sulfur emissions on human health, food production, and ecosystems. As a result, scenarios published since 1995 generally assume various degrees of sulfur controls to be implemented in the future and thus have projections substantially lower than previous ones, including the IPCC IS92 scenario series. A related reason for lower sulfur emission projections is the recent tightening of sulfur control policies in the Organization for Economic Cooperation and Development (OECD) countries, such as the Amendments of the Clean Air Act in the U.S.A. and the implementation of the Second European



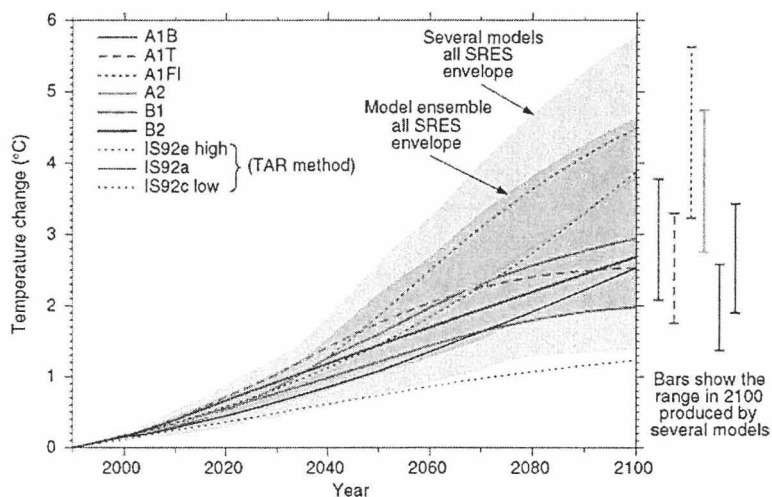
**Figure 15.5** Global anthropogenic  $\text{SO}_2$  emissions (Mt S): Historical development from 1930 to 1990 and in the SRES scenarios. The dashed colored time paths depict individual SRES scenarios, the solid colored lines the four marker scenarios and two dashed curves the illustrative scenarios, the solid thin curves the six IS92 scenarios, the shaded areas the range of 81 scenarios from the literature, the gray-shaded area the sulfur control and the blue shaded area the range of sulfur noncontrol scenarios or “non-classified” scenarios from the literature that exceeds the range of sulfur control scenarios. The colored vertical bars indicate the range of the SRES scenario families in 2100. Source: Grüber (1998a) and Nakicenovic et al. (2000).

Sulfur Protocol. Such legislative changes were not reflected in previous long-term emission scenarios, as noted in Alcamo et al. (1995) and Houghton et al. (1995). Similar sulfur control initiatives due to local air quality concerns are beginning to impact sulfur emissions also in a number of developing countries in Asia and Latin America (see IEA 1999; La Rovere and Americano 1998; Streets and Waldhoff 2000; Streets et al. 2000). The scenarios with the lowest range project stringent sulfur control levels that lead to a substantial decline in long-term emissions and a return to emission levels that prevailed at the beginning of the twentieth century. The SRES scenario set brackets global anthropogenic sulfur emissions between 27 to 169 Mt S by 2050 and between 11 and 93 Mt S by 2100.

Reflecting recent developments and the literature, it is assumed that sulfur emissions in the SRES scenarios will also be controlled increasingly outside the OECD. As a result, both long-term trends and regional patterns of sulfur emissions evolve differently from carbon emissions in the SRES scenarios. Global sulfur emissions rise initially to decline even in absolute terms during the second

half of the twenty-first century, as indicated by the median of all scenarios in Figure 15.5. The spatial distribution of emissions changes markedly. Emissions in the OECD countries continue their recent declining trend (reflecting the tightening of control measures). Emissions outside the OECD rise initially, most notably in Asia, which compensates for the declining OECD emissions. Over the long term, sulfur emissions decline throughout the world; however, the timing and magnitude vary across the scenarios. An important implication of this varying pattern of sulfur emissions is that the historically important, but uncertain negative radiative forcing of sulfate aerosols may decline in the long term. This view is also confirmed by the model calculations reported in Subak et al. (1997), Nakicenovic et al. (1998), and Smith et al. (2000) based on recent long-term greenhouse gas and sulfur emission scenarios.

The alternative developments of the energy systems structure and land-use patterns in the future imply the need to develop a whole host of new energy technologies, and have different implications for climate change. Figure 15.6 is from the IPCC Third Assessment Report (IPCC 2001). It shows projections of changes in the mean global surface temperature for the twenty-first century, based on the various SRES storylines and a range of GCM climate sensitivities. The full range of projections (as indicated by the light grey shading) is approximately half due to divergences among the SRES scenarios, and half due to uncertainties in GCM responses. Neglected feedbacks, such as those between climate and the carbon cycle (Cox et al. 2000; Jones et al. 2003), are likely to extend the range of uncertainty still further.



**Figure 15.6** Impact of uncertainties in GCMs and emissions scenarios on projected twenty-first century temperature rise (IPCC Third Assessment Report). About half of the uncertainty in the range of future temperature change is due to the range of emissions scenarios while the other is due to climate models.



## NEW TOOLS REQUIRED TO GUIDE POLICY IN THE ANTHROPOCENE

The methodology outlined above has been remarkably successful in coordinating different research disciplines to produce projections of anthropogenic climate change. This approach, however, is not capable of answering some of the most critical questions posed by scientists and policy makers.

Policy makers require information on national and regional levels, which will continue to drive comprehensive GCMs to higher and higher spatial resolution. This branch of model development is typified by the Japanese Earth Simulator Centre, which contains the largest supercomputer in the world, built largely to run century-scale climate simulations at a spatial resolution of 10 km (equivalent to the resolution of a mesoscale weather forecast model, and to be compared with the 250 km resolution of typical GCMs).

The scientific community is also being asked questions that cannot be addressed purely through increases in resolution or integration across approaches:

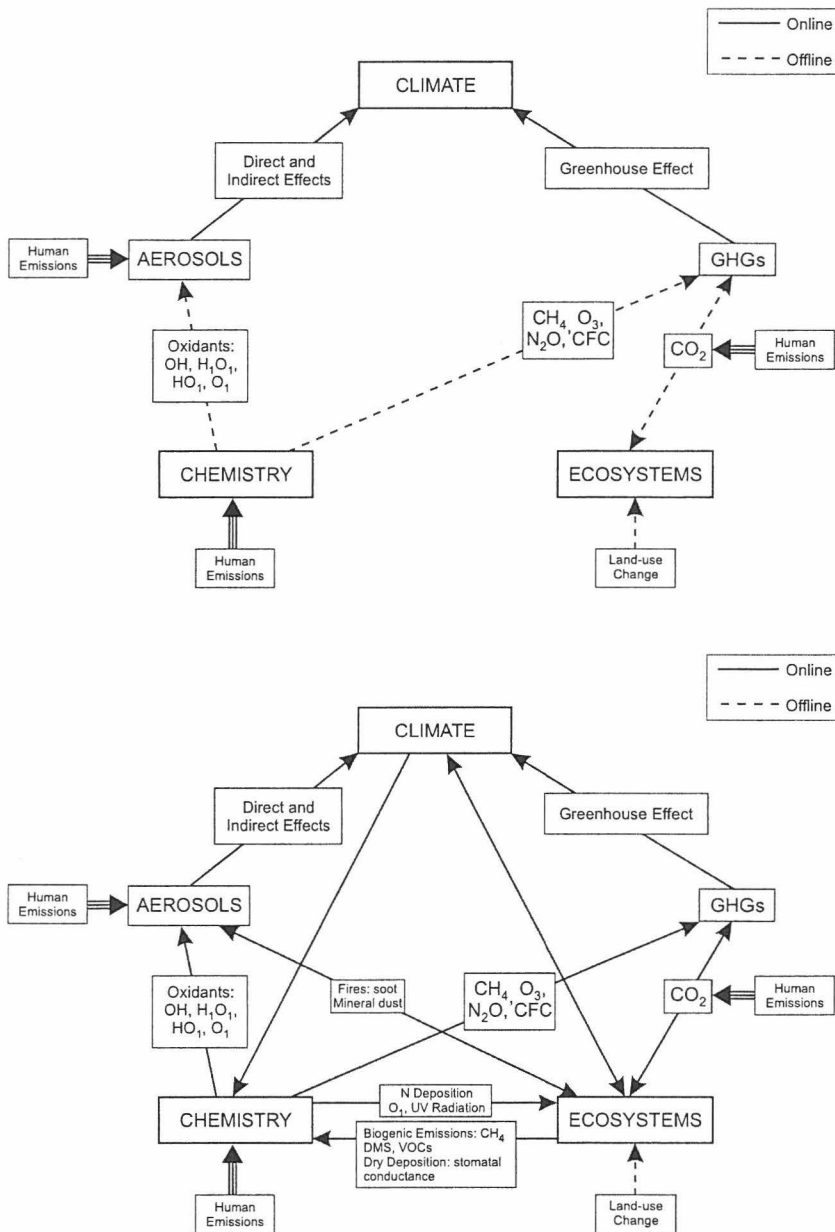
- *What are the uncertainties in the projections of climate change?* This question has typically been addressed qualitatively simply by comparing the scatter of results from a range of GCMs; however, this does not supply the necessary information for risk analysis, etc. Attempts are now underway to produce a “probability distribution function (PDF)” of future climate using a given GCM with a whole range of plausible internal parameters. The future projections of each model variant are then weighted according to their ability to reproduce key features of the current climate. Such “physics ensembles” require in excess of 50 members, so this approach requires that further advances in CPU are at least partly devoted to assessing uncertainty in models of the existing resolution, rather than committed to further increases in resolution with a “single shot” model. As future climate change is co-determined by human actions (e.g., as described by the ranges of emissions scenarios), treatment of climate uncertainties needs to include future developments in complex coupled systems of socioeconomic and Earth system that are unpredictable (among other reasons due to as yet unknown nature of human response strategies) in addition to being compounded by deep and irreducible scientific uncertainties.
- *Where are the critical points that define “dangerous climate” change?* This requires the ability to explore model phase spaces much more completely than before (since thresholds by definition occupy small parts of phase space, we have a “needle in a haystack” problem). To utilize the paleodata constraints, the Earth system model also needs to be able to run over long periods of the past. What is “dangerous” will also depend on human response capacities to changes in the Earth system and is thus also

dependent on socioeconomic conditions and progress in science and technology.

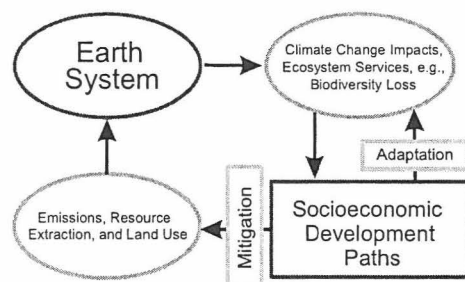
- *How will feedbacks between the biophysical and human dimensions of the Earth system influence global change?* Recently, a wide range of “integrated assessment” models have been developed that either link state-of-the-art submodels described in the previous paragraph or take a new more simplified approach of capturing only the most essential relationships. Considerable advances have been made; however, there is still a significant gap between the capacity to assess response strategies directed at reducing emissions and to assess possible impacts and adaptation to changes in Earth system and climate change in particular.

To address these new questions new tools are required:

- *A traceable spectrum of Earth system models:* Impact assessments demand higher-resolution models, whereas estimates of uncertainty and exploration of critical thresholds require faster models (to explore model parameter spaces more completely). The continuing development of the entire spectrum of Earth system models — from conceptual models (which can be used to develop qualitative understanding and to guide the development of more complex models), to intermediate complexity models (for approaching past climate data constraints), to comprehensive GCMs (for detailed projections) — is therefore critical (see Figure 15.7). Although models of all these types already exist, there is now an urgent need to relate them to one another in a more rigorous manner. Only then can we have a traceable spectrum in which findings in a model at one complexity can be used to inform other parts of the modeling spectrum (e.g., where a lower-resolution model can be used to estimate error bars on a high-resolution projection).
- *Earth system models with interactive socioeconomics:* It is clear that socioeconomics is driving change in the Anthropocene, but it is unclear to what extent the human dimension needs to be treated as a fully interactive component of Earth system models. Environmental change can certainly feed back on regional socioeconomic factors (e.g., local population, migration) through impacts on humans (e.g., changes in water availability), but to what extent can such regional feedbacks affect the global socioeconomic scenarios (e.g., GHG emissions) and thereby feedback on the global Earth system? To address this will require the development of Earth system models with fully interactive socioeconomics (see Figure 15.8). This, in turn, necessitates IA models with much higher scales of spatial and temporal resolution in driving forces and, even more critically, in human response measures and strategies. The challenges include the treatment of deep uncertainties that are likely to increase with higher model resolution and emergent properties of coupled complex systems. For example, such IA models would need to treat endogenously learning processes and



**Figure 15.7** Modeled interactions between the physical, chemical, and biological components of the Earth system as modeled in GCMs previously (top) and in the near future (bottom). DMS: dimethyl sulfide; VOCs: volatile organic compounds; GHGs: greenhouse gases; CFC: chlorofluorocarbon.



**Figure 15.8** Schematic illustration of an integrated modeling framework that includes the future evolution of the Anthropocene characterized by alternative socioeconomic development paths coupled to the changes in the Earth system through mitigation and adaptation measures and strategies in response to impacts such as climate change and biodiversity loss. Adapted from IPCC (2001).

human capacity building in addition to evolution of physical dimensions of the Anthropocene such as the embodied capital and infrastructures.

- *Earth system monitoring*: Data-model fusion, utilizing both ground-based and remotely sensed data, has the potential to produce a more complete diagnosis of the Earth system than has thus far been achieved. More comprehensive data gathering and monitoring of human dimensions of the Anthropocene at higher levels of resolution would help improve IA and socioeconomic models. Routine monitoring of the vital signs of the Earth system will help to constrain projections of the future (because the current Earth system state is better known and because its “observed” evolution can be used to test and develop models) in a way that model development alone is unlikely to achieve.

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