Chapter 1

LINKING CLIMATE AND ECONOMIC DYNAMICS

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Abstract This chapter presents in a broad perspective the links that exist between climate and economic dynamics. We deal in particular with the interactions and feedbacks that may link these two dynamical systems and with possible approaches to modelling, and ultimately controlling, them in order to reach a sustainable development path. The paper provides a general introduction to the different chapters that constitute the rest of the book.

1. Introduction

In 1896 Arrhenius predicted that CO_2 released by the burning of coal, gas and oil would accumulate in the atmosphere causing a warming of the earth's surface by the greenhouse effect (Arrhenius, 1896). After a further century or so of intensive industrial, technological and scientific development, during which global population has tripled and atmospheric CO_2 has increased by around 25%, it is now recognised that warming by greenhouse gas (GHG) emissions has already significantly changed the earth's climate[1], and that further damage to climate is in store (IPCC, 2001). The purely natural dynamics of the climate system are therefore now inexorably linked with those of the global economy.

[1]In a recent "multiproxy" reconstruction of monthly and seasonal surface temperature fields in Europe the authors conclude that (Luterbacher et al., 2004):

> *500-year continental scale surface temperatures provide evidence of current European climate change...the late 20th- and early 21st-century warmth very likely exceeds that of any time during at least the past 500 years...*

Indeed, recent research has suggested that measurable human-induced climate change may have started thousands of years earlier (Ruddiman, 2003).

Previous, natural variations of the earth's climate revealed by geological and ice-core records are characterised by vacillation between extensively glaciated ice ages and relatively warm interglacials. The largest amplitude changes are related to continental configuration on 10 to 100 million year timescales, while the last million years or so have been dominated by a 100 000 year cycle of long ice ages and shorter interglacials. The periodicity is related to relatively weak changes in solar insolation resulting from variations in earth's orbit. The effects of these variations are amplified strongly by feedbacks in the natural climate system in ways which are not yet well understood. Across a range of timescales from thousands to 100's of million years, past changes in global temperature have been closely related to changes in CO_2 concentration (Joos and Prentice, 2004), again for reasons which are not yet well understood. The introduction of anthropogenic forcing has raised the levels of CO_2 higher than at any time in the last 400 000 years, creating a coupled system in which changes in climate may feed back on the socio-economic system causing both monetary losses and almost unquantifiable damage to ecosystems, while climate-induced changes in the economy may feed back on climate change itself. This double interaction between climate and economic systems is sketched in Figure 1.1.

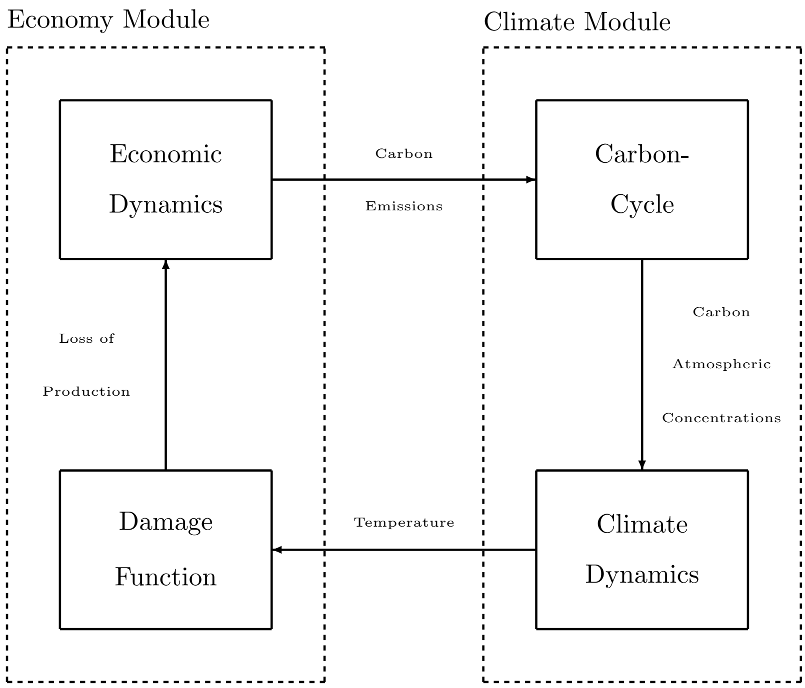

Figure 1.1. Interactions between economic and climate systems

The aim of this chapter is to place in a common perspective those features of climate and economic growth dynamics which may be accessible to joint analysis, in order to better understand the interactions and feedbacks that exist between the two systems, and to identify, in general terms, the type of control that could be exerted in order to maintain a *sustainable* or *viable* development. The chapters of this edited book address in much more detail different particular aspects that are only sketched in this introductory essay.

The chapter is organized as follows: in section 2 we provide a broad view of the fundamentals of climate dynamics with a particular focus on those features which are, or may be, accessible to integrated assessments, including the representation of the carbon cycle which controls the concentration of CO_2 in the atmosphere, the most important anthropogenic GHG. In section 3 we analyse climate change in terms of impacts and damages and we relate these issues to the concepts of *sustainability* and *viability.* In sections 4 and 5 we study the drivers of economic growth in the historical period 1750-1990; we show the relative influences of demography, technical progress, energy use, trade and development, in the economic growth process and its consequence in terms of increase of GHG emissions.

2. Climate dynamics

As mentioned in the introduction, the dynamics of the natural climate system, which have included large and rapid warming events between glacial and interglacial states, are far from well understood. These dynamics are principally driven by incoming short-wave radiative energy from the sun (some of which is reflected back to space) amplified by the greenhouse effect of atmospheric gases, in which the wavelength and energy of the compensating outgoing long-wave radiation is largely set by the very cold, upper levels of the atmosphere. The more energetic long-wave radiation emitted by the warmer surface is effectively trapped inside the "greenhouse". The sun's energy drives complex motions in the atmosphere and oceans, which interact with the land and ocean bio- and cryospheres via exchanges of heat, water, carbon and trace elements on a wide variety of timescales.

Many or all of these active processes are affected by global warming, and of relevance to human well-being and economic activity. An essential parameter in modelling climate change and its economic impact is the so-called climate sensitivity which describes the average surface temperature rise triggered by a doubling of atmospheric CO_2 from preindustrial levels. This parameter is not "well constrained" in the parlance of climate modellers[2]. The situation is the same for the radiative forcing due to aerosols which could have an important mitigating effect in the short-term, potentially leading to an underestimate of the effects of CO_2 -induced warming. Overall, this leads to large uncertainties in global warming simulations. A particularly thorny issue is the response of

[2]A range of 1.5^o-4.5^o is tentatively proposed by IPCC.

clouds, as an increase in high cloud amplifies the greenhouse effect, but low cloud can have the opposite effect, by reflecting short-wave radiation before it reaches the surface.

The rational approach to the quantitative assessment of uncertainty is to perform large ensembles of simulations (Knutti et al., 2002), but this is not possible with detailed models, as discussed later, and furthermore the statistical analysis is not trivial (Rougier, 2004). To render this hugely complex problem tractible, the simplest possible approach is to reduce the problem to the most fundamental and important quantities, namely the global average surface air temperature and the atmospheric concentration of CO_2 . Below we give a brief introduction to the carbon cycle that controls the accumulation of CO_2 in the atmosphere, then consider various models of GHG-induced climate change used for integrated assessments, starting with the simplest models which represent the global carbon cycle by a single equation. Radiative forcing of the atmosphere is then assumed to depend logarithmically on CO_2 concentration.

2.1 A brief introduction to the carbon cycle

Atmospheric CO_2 concentrations evolve according to complex dynamics describing the biogeochemical *carbon cycle*, which itself interacts very strongly with the other components of the climate system including the circulation and the *hydrological cycle*[3]. In Table 1.1[4] we can see the relative importance of the different mineral and organic carbon pools on earth. Atmospheric CO_2 is exchanged with the oceans and terrestrial ecosystems. As the total dissolved inorganic carbon in the ocean is 50 times that of the atmosphere, we can say that in the very long run (time scale of millennia) the oceans determine atmospheric CO_2 not vice versa. The situation is the same for temperature due to the very high ratio of the oceanic heat capacity compared to that of the atmosphere. Atmospheric CO_2 variations are regulated by several negative (stabilizing) feedback processes, and amplified by further, positive (destabilizing) feedback processes. Some of the negative feedbacks may be weakened or reversed in sign by global warming. The principal CO_2 feedback processes and mechanisms are (Falkowski et al., 2000):

Surface ocean uptake. This amounts to 90 Gt of carbon per year. When dissolved CO_2 forms bicarbonate that will be buffered at a rate which is much slower than the rate of anthropogenic CO_2 emissions. So in the very long run the ability of the surface ocean to absorb CO_2 will decrease. Ocean carbon uptake is driven by two processes, referred to as the solubility and biological "pumps".

[3]Which includes the role of clouds and ice, including sea ice.
[4]Partly reproduced from Falkowski et al., 2000. Note that the figures quoted are estimates and may be affected by climate change.

Pools	Gt	Residence Time
Atmosphere	760	$<$ 10 yr
Oceans	38,400	
upper part	670	10-10^2 yr
deep layer	36,730	10^3-10^4 yr
Lithosphere	$>$ 60,000,000	10^6-10^8 yr
Terrestrial biosphere	2,000	
living biomass	800	1-10^2 yr
organic dead biomass	1200	1-10^3 yr
Fossil fuels	4,130	

Table 1.1. Carbon pools in the major reservoirs on earth

The solubility pump. CO_2 is more soluble in colder water, so the strength of this process depends on the formation of cold, dense water which sinks into the ocean interior, removing excess carbon. Models suggest a weakening of the circulation which drives this process. Warmer surface waters would add to this effect, reducing the efficiency of the pump, and giving a positive feedback on atmospheric CO_2 .

The biological pump. Phytoplankton organic photosynthesis[5] contributes to the absorption of CO_2 from the atmosphere. The resulting organic detritus and inorganic shell material is partially recycled by other organisms, but some (around 25%) sinks into the interior. This biological pump depends on complex biological, chemical and physical processes and interactions, including the supply of nutrients[6] from the deep and via wind-blown and riverine input. The biological pump can be decomposed further into the organic, or "soft", and carbonate, or "hard", biological pumps. Its behavior is hard to predict with confidence.

Deep ocean uptake. Carbon is exchanged between surface and deep ocean reservoirs by circulation, mixing and sedimentation. Largely due to variations in temperature and pressure, ocean carbon concentration increases rapidly with depth. On very long (10^3 to 10^4-year) timescales deep-ocean carbonate can precipitate[7], adding to seafloor sediment, to buffer CO_2 increase.

Terrestrial carbon uptake. Terrestrial ecosystems exchange CO_2 rapidly with the atmosphere. CO_2 is stored in living and dead organic matter and is returned to the atmosphere through different atmospheric pathways (respiration, fermentation, production of volatile compounds, etc). Carbon

[5] 40% of total photosynthesis.
[6] N,P,S and oligo-elements such as Fe
[7] $Ca^{2+}_{aq} + CO^{2-}_{3aq} \rightleftharpoons CaCO_{3\text{solid}}$.

storage occurs primarily in forests[8]. The turnover time of terrestrial carbon is on the order of decades[9]. A negative feedback exists at present as increased CO_2 concentrations lead to higher forest production. Increased respiration could lead to a sign reversal of the feedback beyond some "optimal" state (Ramade, 2002).

Other biogeochemical cycles. The carbon cycle interacts with other biogeochemical cycles. N, P, S, oligo-elements, and eolian iron fluxes all influence CO_2 uptake. Iron fluxes have been implicated in paleoclimate variability, and as a mechanism for macro-technological mitigation.

Other interactions and feedbacks. The strong reflectivity (albedo) of snow and ice-covered surfaces induces a strong positive feedback on temperature changes, reflecting more solar energy back to space in colder conditions. Climatic change in peat and permafrost regions can lead to methane and CO_2 release and consequently feed back on global warming. Another very important feedback is due to water vapor which is the most important GHG: due to greenhouse warming more water evaporates and so the concentration of GHGs increases. However, as noted earlier, this effect can be counteracted by increased cloud reflectivity. Ultimately the Venus syndrome illustrates an amplification of the greenhouse effect due to CO_2 where most of the water is in the atmosphere[10] and the greenhouse effect is extreme (740 K; GHG-coeff[11]= 2.2). The paleoclimate record tends to show that despite the positive feedbacks the evolution of the climate system has allowed living species to remain in a "viability envelope" through a continuous evolutive adaptation. The anthropogenic CO_2 and its speed of accumulation in the atmosphere introduce a new element in the natural regulation of the climate system[12] and this could prove to be the most destabilizing interaction between a living species and the climate system yet seen. In summary[13]:

> *[although]...on geological time scales the anthropogenic emissions of CO_2 is a transient phenomenon... there is no natural savior waiting to assimilate all the anthropogenic in the coming century... Potential remediation[14] strategies... are being seriously considered...*

[8] Approximately 2/3 of photosynthesis on emerged surfaces.

[9] It is longer for the soil organic dead biomass.

[10] Decomposed in H_2SO_4, etc.

[11] The GHG-coeff. gives the ratio between absolute temperatures with and without GHG effect.

[12] One may consider that this regulation has been effective for 3.8×10^9 years.

[13] Again quoting Falkowski et al., 2000.

[14] Potential direct remediation strategies mean purposeful manipulation of biological or chemical processes to accelerate the sequestration of atmospheric CO_2. Because of the imprecise knowledge of these mechanisms these manipulations could have unpredicted consequences and should be assessed with caution.

2.2 The carbon cycle in integrated assessment models

A variety of models have been proposed to represent carbon cycle dynamics in Integrated Assessment Models (IAMs). J.A. Viecelli proposed a single-equation model in which atmospheric emissions are buffered by a deep-ocean reservoir, which is assumed to have infinite capacity (Enting et al., 1994). The DICE-94 model (Nordhaus, 1994) used an equivalent formulation but with altered coefficients. With these specifications, a steady-state concentration level is approached asymptotically for any constant emission level. Radiative forcing of the atmosphere is then assumed to depend logarithmically on CO_2 concentration. In the DICE-99 version of the IAM developed by W. Nordhaus (Nordhaus and Boyer, 2000) a three-reservoir model is used to represent the exchanges that take place between the atmosphere, the upper layer and the deep layer of the ocean. In contrast to DICE-94, this model does not allow for capture of carbon in any of the three reservoirs. The long-term asymptotic behavior is therefore a steadily increasing atmospheric concentration for any non-zero emission rate. However, even though it predicts a constant asymptotic growth of CO_2 concentrations for any sustained emission rate, CO_2 concentrations in DICE-99 can be stabilized in the case of a steadily decreasing emissions rate.

ICLIPS (Füssel and Klein, 2004; Toth et al., 2003a; Toth et al., 2003b) is a much more complex IAM which has been well received by the scientific community. The model has a description of the carbon cycle with 4 reservoirs in the atmosphere and the ocean and two reservoirs in the biosphere. This model has been developed by the Max Plank Institute. The ICLIPS carbon cycle model predicts a slower growth of the atmospheric CO_2 concentration than DICE-99, although it also predicts an asymptotic sustained growth for any constant emissions level. It also suggests that, at a millennium time scale, reducing the emissions to a level of 2 GtC per year will tend to stabilize atmospheric carbon concentrations around 800 GtC.

The carbon cycle is only crudely represented by simple systems of a few differential equations. Generally, climate models divide the climate system into a grid of discrete spatial cells to represent spatial variation of properties. To each averaged property within each cell will typically be associated one differential equation describing the temporal variation of the property. The larger the number of cells the more accurate the representation but also the greater the complexity and the computational cost of the model. We discuss more complex models with thousands or millions of cells (and equations) below.

2.3 Models of intermediate complexity

One of the most fundamental properties of the climate system is the circulation of the atmosphere and oceans. Differential heating and cooling, complex topography and, in particular, the rotation of the earth, make these circulations intrinsically three dimensional and highly complex. The vast range of spatial scales of these circulations is associated with a vast range of timescales from minutes to millenia, while the details of the circulation strongly affect all other properties of the climate system. For this reason, physical climatological research is focused on General Circulation Models (GCMs) that resolve these 3-D flows. So far, IAMs have only used the results of high-resolution 3-D GCMs in parameterized form. The ICLIPS model, for instance, uses impulse response functions and scaled spatio-temporal patterns (EOFs) from two different GCMs. Such derived parameterizations are severely limited in their application. They may be accurate for short-term changes, but nonlinear changes involving significantly altered circulation states may lie outside their range of validity, while their representation of dynamical feedbacks is limited.

Here we explicitly make the distinction between high-resolution atmosphere-ocean (AO) GCMs such as HadCM3 (Gordon et al., 2000) and Earth System Models of Intermediate Complexity, or EMICs. Models in the latter category may also technically include 3-D models of the general circulation of the ocean (C-GOLDSTEIN (Edwards and Marsh, 2004) and UVic (Weaver et al., 2001)) or atmosphere or both (ECBILT-CLIO (Goosse et al., 2001)), although the term GCM is often assumed to refer exclusively to high-resolution models. EMICs typically have lower spatial resolution, and are often dynamically simplified as well, neglecting, for example dynamical atmospheric processes (Edwards and Marsh, 2004). The number of spatial cells in C-GOLDSTEIN is around 10^4 whereas high-resolution GCMs have millions of cells. The principal advantage of EMICs is computational efficiency: the integration speed of extant EMICs ranges from minutes (Bern 2.5-D model Knutti et al., 2002) to days (UVic model) or weeks (ECBILT-CLIO), for a 1000-year simulation, but high-resolution AOGCM integrations of this length would typically take months.

Clearly, the continued development of more efficient and faithful EMICs offers great potential to improve the representation of climate in IAMs. A thorough review of the issues and challenges of integrated assessments, and of the state of the art in extant models, as represented by ICLIPS, is given by Ferenc Toth in the next Chapter of this volume. This is a rapidly developing field, however, and in Chapter 3 of this book, an indication of possible future developments in IAMs is given by the demonstration that an EMIC with fully 3-D ocean circulation (in this case C-GOLDSTEIN) can be incorporated effectively into an IAM with two-way coupling between climate and economic models (in this case a version of DICE). Although this is a prototypical example, the potential implications are clear. With a 3-D ocean, the earth's surface, where climate-economic interaction is localised, becomes fully two dimensional, creating the possibility for a fully regional representation of interactions.

Against the obvious limitations of detail inherent to EMICs, the label Earth System Model, or ESM, carries the implication that such models often include representations of processes which are not always included in high-resolution GCMs such as ocean biogeochemistry and sedimentation, ice-sheet dynamics and dynamical land-surface processes. These may be highly relevant to IAMs. For instance melting of the Greenland ice sheet in the long term may be irreversible (Toniazzo et al., 2004) while HadCM3 simulations including a dynamical land-surface scheme have indicated the possibility of Amazonian deforestation (Cowling et al., 2004). The 2003 summer drought, which had severe socio-economic consequences, was strongly amplified by short-term soil moisture effects[15], while the long-term fate of excess carbon in the climate system is effectively controlled by ocean biogeochemistry.

Efficient climate models, or EMICs, thus offer the possibility of inclusion of important processes, regional impacts, and circulation effects, at a computational cost which is within the range of useful IAMs. The evolution of certain types of extreme events such as a collapse of the North Atlantic ocean circulation, can be directly calculated when the circulation is represented. The analysis of such catastrophic events can lead to much more cautious policy recommendations (Wright and Erickson, 2003). Another very important potential application of efficient models is the calculation of uncertainties via large ensembles of runs (Hargreaves et al., 2004). In contrast, the computational cost of high-resolution GCMs makes it extremely difficult to asses the uncertainties associated with their forecasts.

2.4 Climate-economy feedbacks

The justification for building integrated models of climate and economic dynamics, beyond the convenience of joint analysis and presentation, is the possibility of representing feedbacks between the two systems. Economic development is a principal driver of climate change, thus the effects of climate change on the economy, such as enhanced damages from droughts and floods, represent a feedback on the economy. If the effects of climate on the economy lead directly, or indirectly via policy, to changes in climatic forcing factors such as GHG emissions, then this represents a feedback of the economy on the climate. Land-use changes represent another area of potentially important feedback on climate via changes in surface reflectivity (albedo) and soil moisture content. Such feedbacks typically involve delays across a wide range of timescales, one of the major challenges of integrated modelling (Toth, 2004). Global warming related to GHG emissions will take hundreds or thousands of years to fully take effect due to the inertia of the ocean circulation and ocean carbon cycle, whereas inertia in the socio-economic system is also important on short timescales. On the other hand the economic system will respond to scientific projections of future climate change, inducing what is technically a negative delay. This effect may be difficult to incorporate in a pure simulation IAM (ie a pure initial-value problem), but be overestimated in an optimization model such as DICE which assumes perfect foreknowledge.

In a general system, strong delays and feedbacks may cause oscillations, or in the case of over-reaction, (oscillatory) instability. It is therefore of interest to ask what the strengths of the feedbacks between climate and economy may be.

[15] As noted by Schär et al., 2004.

This is not necessarily an easy question to formulate. Feedbacks in the climate system are often represented in a simplified control-theoretic form as a parallel series of gains (Peixoto and Oort, 1992) but such an analysis may involve an unphysical separation of processes and an inherent assumption of linearity. Moreover, the strength of a feedback is always a function of the timescale of the perturbation considered. As an example, we consider a modification of the prototype IAM described in this book (Drouet et al., 2004) in which the economy and climate are linked in cost-benefit mode (Drouet et al., 2005) and attempt to calculate the strength of the feedback of economy on climate. One measure of this strength is a comparison of the behaviour of the climate model forced by an uncoupled DICE emissions scenario, with the behaviour of the climate model in the fully coupled optimal solution. However, this difference is not necessarily equivalent to the strength of the feedback in the coupled system.

To arrive at the latter we consider the effect of an exogenous addition of radiative forcing, in this case by an enhancement of the solar constant (the average solar forcing) by 4 Wm^{-2}. The feedback strength will be the degree of reduction of this exogenous forcing by the coupled system, compared with the effect of such an additional forcing on the uncoupled climate (given the emissions relating to the unperturbed coupled solution). The feedback strength is a function of timescale, but we can at least calculate it for a given perturbation, initially an impulsive change in solar forcing. The result is shown in Figure 1.2. The increase in solar forcing leads to a significant, additional warming of around 0.4 C, which is reduced by the response of the economy. This reduction is delayed, and at 200 years amounts to about 0.04 C, or a 10% reduction of the net additional warming.

2.5 Asymptotic goals for climate change control

Investigating policy options consistent with acceptable sustainability is the main motivation for integrated assessment modelling. Figure 1.3, reproduced from Edwards and Marsh, 2004, shows the response of an ensemble of runs of the EMIC C-GOLDSTEIN to a single, illustrative scenario in which CO_2 equivalent GHG concentrations in the atmosphere increase at a constant rate of 1% per year for 100 years then remain constant. The figure shows the mean surface air temperature for the forced warming period and for the following 1000 years. The spread is due to uncertainty in model parameters. Of interest is the increase of SAT after model year 2100 when GHG concentration is held constant. The implication of this increase is that realistic analyses of sustainability will have to reckon with continued increases in global temperature, and associated increasing global change, resulting from inertia in the physical system. In this particular model ensemble experiment, the increase in SAT in the 200 years immediately following the cessation of emissions is around 1/2 degree C per hundred years. Changes of a similar order are believed to have occurred during the last 500 years (Luterbacher et al., 2004) but future changes will take place in the context of a previously unknown, anthropogenically warmed world.

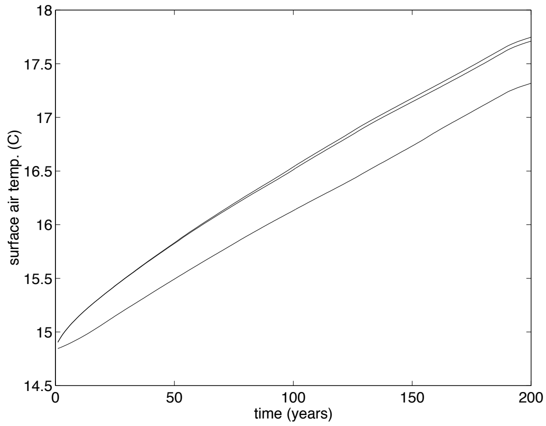

Figure 1.2. The effect of the feedback of economy on climate in the IAM of **?**. *The lower line is the unperturbed solution of the cost-benefit optimisation, the middle line is the solution under perturbed forcing (increased solar constant), the uppermost line is the response to perturbed forcing of climate with no feedback from economy to climate. The feedback reduces the warming by 10% at 200 years.*

Similar behaviour is observed in simulations of global warming using high-resolution GCCMs, as summarised by the IPCC (IPCC, 2001). These models consistently predict a sensible long-term climate impact of anthropogenic CO_2 emissions. We notice that the stabilization scenario (with a target temperature increase of 1.5 degree C) asks for a drastic reduction of CO_2 emissions by the end of the century. This is consistent with the report in Enting et al. where a variety of carbon cycle models have been used to define the evolution of emissions that would lead to a stabilizing of the atmospheric CO_2 concentration; they consistently lead to an asymptotic 2GtC/yr emission rate to be reached by year 2100 (Enting et al., 1994). Results from the full range of available models therefore predict severe climate change in the long run if the CO_2 emissions are not curbed. However the climate system has considerable inertia and, therefore, the current generations will not witness all the impacts of their economic decision to (or not to) curb CO_2 emissions. On the other hand, if GHG emissions continue unabated, the temperature and sea-level changes predicted for the next millennium greatly exceed those of the next hundred years (Hasselman et al., 2003). Over a time horizon of a century, our societies should be able to reduce considerably the yearly emissions of carbon in the atmosphere, probably to a level around 2GtC/y, which is very low in comparison with the current level (around 8 GtC in 2004). In the next section we consider the question of sustainability in more detail from a socio-economic perspective.

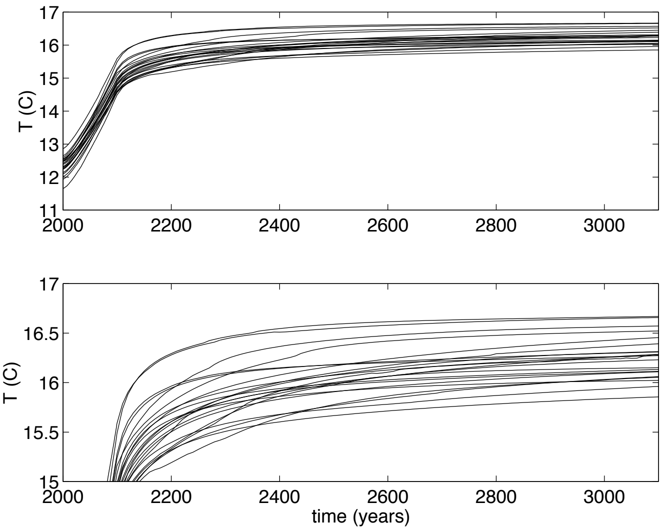

Figure 1.3. *Global average surface air temperatures for an ensemble of simulations of the EMIC C-GOLDSTEIN. CO_2 is forced to increase at 1% per year for 100 years then kept constant. The lower panel is an enlargement. The spread is due to uncertainty in model parameters.*

3. Sustainability

Anthropogenic climate change is an archetypal issue for sustainable development. In this section we explore the most important linkages that exist between climate and societies. We first revisit the concepts of sustainability and viability which propose an analytic framework to study such interactions. We then focus on the impacts that can be expected from climate change and we discuss the relative importance of mitigation and adaptation in the societal response to a climate change threat.

3.1 Sustainability and viability

Sustainable development is generally defined as

> *... paths of social, economic and political progress that meet the needs of the present without compromising or endangering the ability of future generations to meet their own needs.*

This heuristic definition, self-adjusted to human activities, corresponds to an ethical management of the earth resources (responsibility, equity, solidarity between generations or social groups and territories, respect of ecological equilibria, prevention, precaution). This programme is clearly not realized currently in any part of the world. Since palaeolithic times "global" sustainability has been achieved at the expense of the transformation or disappearance of local cultures and civilizations. Consequently, the biosphere, ecosystems and environment[16] have been modified and this has changed the burden of human activity on the local resources. The proposal to implement a global and local sustainability is therefore an ambitious challenge that has never been realized before in human history.

A scientific approach to sustainable development calls for a deep understanding of the structure and dynamics of the *biosphere-society-environment* system. The study of the coupling between climate and economic dynamics is part of this endeavor. The scientific approach should be accompanied by an axiology that will have some effects on cultural values. This would trigger socio-economic actions compatible with a high quality human life in a heterogenous cultural perception by different societies[17]. Deep knowledge of the structure and dynamics of the systems composing the triad *biosphere-society-environment* is necessary for the design of a global management toward real and progressive sustainability during this century. Many indicators or variables have been proposed to describe and analyse the complex socio-economic, environmental and ecological networks that sustain human life and societal organization. Since these variables don't all share the same significance a hierarchy could be made to first identify the most limiting factors for a sustained, secured and robust life viability of human species (and of the rest of biosphere.) This would define *viability envelopes*[18] which would dictate the long-term mitigation or adaptation absolutely necessary for a sustainability policy at the socio-economic, biosphere and environmental levels. The earlier the detection of such a *hard limit* the lower will be the cost to mitigate or to adapt (Schellnhuber and Wenzel, 1998).

3.2 Climate change impacts

How will the economic system be impacted by climate change? Among the different economic sectors, agriculture is certainly one of the most directly linked with climatic conditions. Other sectors may also suffer from output losses when temperature and precipitations change, and some may gain. We briefly review these impact evaluations.

3.2.1 Agriculture. Since the Neolithic times (10'000 years ago), agricultural activities have been the main factor of economic and social progress in terms of security and organization. Recently, as a result of scientific and industrial progress, this activity has evolved rapidly and has considerably transformed the natural ecosystems and landscape of the world. More than a third

[16] Biomass, biodiversity, food and other resources, climate, etc.

[17] From equi-finality to sustainability.

[18] At the limit one could consider viability in a more restricted sense: "alive or dead" for human population and ecosystems. This would correspond to the minimal platform for viability. Some sentinel variables like mean life expectancy, biodiversity , biomass evolution, temperature, water variation, surface concentrations in O_2, CO_2 , CH_4, etc, could be used to delineate these envelopes (Greppin et al., 2002).

of land is utilized for agriculture (47% if we exclude deserts and high altitudes). To sustain the photosynthetic activity agriculture needs large surfaces to access light, a considerable flux of water[19], CO_2 , nitrogen, phosphate, sulfate, potassium, etc., as well as a soil of high quality. The influence of climate is therefore significant, and this whatever the state of economic development of the region concerned. Between 1650 and 2000, the world population has increased by 1100%, to reach 6.4×10^9 inhabitants, the agricultural surface has increased by 500% (crop cultures 1.5×10^7 km^2, pastures 3.3×10^7 km^2) and a limit is imposed by the necessity to maintain sufficient forest areas. The decrease in *per capita arable land* has been compensated by a considerable increase of the yield (300 to 600 %). Despite its overall capacity to offer sufficient per capita feeding (4.6 GJ/y/h), a fraction of the population (0.8×10^9 people) remains chronically undernourished and a quarter of the world population is affected by food insecurity even in the absence of climate change.

A great diversity characterizes the importance of the agriculture sector in different countries: from 2 to 40% of GDP, 3 to 70% of working population, consumption of 0.5 to 80% of the natural flux of water. Over the last 40 years irrigation has progressed by 110%, 40% of the crop production comes from the 16% of land which is irrigated, although 64% of crop surfaces are in developing countries where 2/3 of the world population lives with only 1/4 of the annual rainfall. The use of fertilizers and pesticides has considerably increased, accompanied by pollution effects. About 40% of the arable land is degraded to some degree. The mechanization, fertilizer and energy use contribute to GHG forcing. The great sensitivity of the agro-ecosystem to climatic change is amplified by yield management practices and by its insulation from neighbouring ecosystems (Alexandratos, 1995; P.A. Matson, 1997; Reilly and Schimmelpfenning, 1999). Agricultural vulnerability in respect of predicted climate change could be very variable according to the area of the globe that is concerned. Crop cultivation capacity may increase in North America (Alaska, Canada, Eastern USA) and Europe (in particular Russia), as well as in South-East Asia (China, Indonesia), African and South American equatorial regions, and some Eastern regions of South America. The loss could be severe in other regions, especially in developing countries. Agriculture will gain in strategic importance for economic growth, access to territorial space, and the global security of nations (Fisher et al., 2002).

3.2.2 More general impacts. Other economic sectors than agriculture may be directly affected by climate change: tourism and also energy production are very much climate dependent (heat waves may impact both on electricity demand and power supply[20]. More generally the GHG climate forcing will modify the earth's landscape at all scales (spatial and temporal) as it

[19] Around 700 t of water are necessary to produce 1 t of organic food.

[20] The Summer 2003 heat wave in France triggered a decline in nuclear power supply because of cooling failures. It also triggered a rush to air conditioning and an increase in demand.

will change the distribution of dynamic climatic conditions. This will trigger a redistribution of environmental risks such as strong winds, hurricanes, fires, floods, drought, desertification, landslides, lightning, ecosystem biotic perturbations by pests and pathogens, etc. All these perturbations have economic consequences.

According to the different scenarios proposed by IPCC (SRES scenarios), and simulated by HadCM3, CSIRO and NCAR, the following changes are possible: in the northern hemisphere the global warming could provoke a northward shift in thermal regime and, as a consequence, a significant reduction (around 60 %) of boreal and arctic ecosystems. A large expansion of temperate climate area in Siberia, Canada and Alaska may occur, accompanied by an extension of the forest fire season in the boreal part (risks of severe forest fires). Soil respiration could be stimulated (GHG source). In the southern hemisphere, however, the temperate zone of Argentina and Chile may disappear almost completely. The subtropical zone would keep its extent. A major expansion may occur in the tropical zone that will cover most of Africa. The diminution of the thermal difference between the poles and the equator would affect the oceanic and continental water balance (evaporation and precipitation zones). A large drying of the extended Mediterranean basin, South Africa and Western Australia, and part of Eastern Brazil and central America may be envisaged. This diminution of precipitation in the intertropical zone would be compensated by more humidity in higher latitudes (Scandinavia for example) and in the Pacific ocean. In general this would result in an increase of arid areas, mostly in developing countries. At a more local scale, the impact of global warming is more uncertain and difficult to predict. The changes in rainfall patterns in addition to shifts in thermal regimes would influence the local, seasonal and annual water balance. Probably in many regions one could observe a change in the frequency of occurrence of extreme events (intensive rainfall, gales, floods, snow-stones-mud avalanches, etc...).

3.3 To mitigate or to adapt?

Given the level of past emissions and the inertia of the climate and economic systems, some degree of climate change cannot be prevented. Adaptation to climate change is therefore an issue (Füssel et al., 2003). There are still divergent views on whether climate change will seriously affect society. Some authors identify a set of fundamental characteristics of natural systems to be taken into consideration to analyse adaptation strategies (Reilly and Schimmelpfenning, 2000). They are: Short-term autonomous flexibility; short-term non-autonomous flexibility; knowledge and capacity to undertake short-term actions; long-term autonomous flexibility; long-term non-autonomous flexibility; and knowledge and capacity to plan for and undertake adaptations that require changes in long-lived assets. Adaptation is certainly a significant societal issue that should be an important part of the climate research agenda in the coming years. We can relate the choice between mitigation and adaptation to the different time scales involved in the dynamics of the climate and economic systems. Climate change is a long lived phenomenon; reducing emissions today will not prevent some warming; therefore the mitigation activities are to be inscribed in a long-term environmental policy. The dynamics of climate change assures that some warming and precipitation changes are already under way and that strong impacts will be effective at the end of the century. So, during this century the economy will have to adapt to the new climatic conditions. Some adaptation decisions will have to be taken on a much shorter time scale, as different societies will sense the changes in climate variables and assess their vulnerability to these changes.

3.4 Sustainability, viability and Intergenerational Equity

The very long time horizon and the slow time scale associated with climate change dynamics offer a new challenge to economists when they try to implement a cost-benefit analysis in the *management of the global commons*. The fundamental question addressed in these analyses is (Chao and Peck, 2000):

> *"How much and who pays"*?

The archetypal cost-benefit analysis model is DICE-94 (Nordhaus, 1994) or its close descendant DICE-99 (Nordhaus and Boyer, 2000). In these models, the driver of the economic systems is the maximization of a discounted sum of the utility derived from consumption; more precisely

$$\max \int_0^\infty e^{-\rho t} L(t) U(c(t))\, dt \tag{1.1}$$

where ρ is the *pure time preference rate*, $L(t)$ is the population level, and $U(c(t))$ is the utility derived from per-capita consumption level $c(t)$. In the economic growth paradigm the economic output can be used for consumption or capital accumulation. However emissions abatement and climate change both induce a loss of output. The representative economic agents have thus to trade-off consumption today versus investment for consumption tomorrow but also loss of output due to climate change versus loss of output due to abatement. Because these decisions imply a comparison between consuming today and consuming at a future date, the discounting factor $e^{-\rho t}$ is introduced in the criterion. The choice of the parameter ρ has a considerable influence on the asymptotic behavior of the economic growth model. The asymptotic steady states of the DICE-94 model have been compared for values of ρ ranging from 0[21] to 10 % (Haurie, 2002). The asymptotic level of capital would be 3 times higher in the $\rho = 0$ case than in the 10 % case. The GHG concentrations would be 50 % higher in the 10 % case than in the $\rho = 0$ case. Sustainable consumption will be 10 % higher when $\rho = 0$ than when $\rho = 10$ %. So, in brief, discounting

[21] One can easily overcome the difficulty of dealing with a nonconvergent integral in (1.1) when $\rho = 0$.

induces a long-term economy which is less equipped, more polluted and which consumes less. This is an illustration of the thorny issue of discounting and intergenerational equity discussed by a group of eminent economists (Portney and Weyant, 1999). Even though a low discount rate seems more attractive in the long run, no rational economic agent will accept the proposal to base its investment decision on 0-discount rate.

Chichilnisky has introduced an axiomatic for the decision rules that would avoid both *dictatorship of the present* and *dictatorship of the future*[22]. According to this prescription the driver of the economic growth system should take the form

$$\max \left[\beta \int_0^\infty e^{-\rho t} L(t) U(c(t))\, dt + (1-\beta)\Phi(c(\infty))\right] \tag{1.2}$$

where $0 \leq \beta \leq 1$ and $\Phi(c(\infty))$ is a utility associated with the very long-term (asymptotic) per-capita consumption rate. However, the use of this criterion would lead to a decision path which is not *time-consistent* (Lecocq, 2000). This criterion will commit forthcoming generations to use a decision criterion which does not correspond to their rate of time preference. A solution to this difficulty has been hinted at by Arrow (Arrow, 1999) who formulated a noncooperative game among successive generations of economic agents[23]. This idea has been exploited in different articles where intergenerational equity is obtained through the computation of an intergenerational equilibrium, which, by definition does not commit the decisions of forthcoming generations but assumes that they will share the same level of altruism as the current generation (Lecocq, 2000; Haurie, 2003; Haurie, 2004). Also one assumes that the current generation takes into account, in its utility function, the well-being of forthcoming generations[24].

4. Demographics, economic development and GHG emissions

As explained in section 2, the net global GHG emissions to the atmosphere must eventually decline substantially to maintain any stable steady-state atmospheric carbon concentration. To estimate the GHG emissions reduction effort and to assess the associated economic costs, one has first to evaluate the global future GHG emission levels if nothing is done. However this future is highly uncertain (IPCC, 2000). Almost all driving forces are controversial: long-term population growth, economic growth, technological change; fossil-fuel reserves; non-climate environmental policies, etc. The controversy concerns not only the dynamics of each variable, but also their mutual interactions (between economic growth and population; technological change and economic growth;

[22] See Chichilnisky, 1996 and Chichilnisky et al., 2000.

[23] Arrow referred to a formalism proposed long ago (Phelps and Polak, 1968) to represent selfishness in a multigeneration investment process.

[24] For a more detailed analysis of the technical aspects of these new classes of criteria that have to be introduced when economics has to deal with the very long lived effects of current decisions concerning climate change, see Ambrosi et al., 2003.

technological change and fossil-fuel reserves, etc.) In this section, we revisit the IPCC projections for carbon emissions from fossil fuels[25]. We focus on the key assumptions in GHG emissions for these scenarios and address the uncertainty concerning the main driving forces in the dynamics of carbon emissions. We then compare the IPCC scenarios with historical trends for the 1750-1990 historical period. To decompose the effect of demographic, economic, and technological dynamics and transitions on the evolution of global CO_2 emissions from fossil fuels, we use the Kaya identity[26]. In other words, total world CO_2 emissions at time t depend on per capita emissions and population. In its turn, the per capita CO_2 emission rate can be decomposed into (i) per capita GDP and (ii) CO_2 emissions per unit of GDP (GHG emission/GDP intensity factor). Finally, one can decompose the intensity factor defined as the ratio GHG emission/GDP into two subcomponents (i) the energy/GDP intensity and (ii) the emissions per energy unit that reflects the GHG emission intensity of energy consumption.

4.1 Global CO_2 emissions from fossil fuels

In 1992 the Intergovernmental Panel on Climate Change (IPCC) released six emissions scenarios providing alternative GHG emissions trajectories over the 1990-2100 period (Leggett et al., 1992)[27]. It has been argued that, for the purposes of driving atmospheric climate models, the CO_2 emissions trajectories of the IS92 scenarios provide a reasonable reflection of variations found in the open literature(Alcamo et al., 1995). Other analysts have noted that

[25]In 1992 and 2000 the Intergovernmental Panel on Climate Change (IPCC) released alternative GHG emissions scenarios over the 1990-2100 period (Leggett et al., 1992; IPCC, 2000). These scenarios embodied a wide array of assumptions affecting how future GHG emissions might evolve in the absence of new climate change policies. The different emissions projections reflect contrasted assumptions in terms of economic, social and environmental conditions.

[26]Recall that this identity is based on the following elementary relation:

$$C = \frac{C}{E}\frac{E}{Y}\frac{Y}{P}P \tag{1.3}$$

where C, E, Y, P stand for world CO_2 emissions from fossil fuels in metric tons of carbon, final energy consumption in tons of oil equivalent, GDP in 1990 U.S. dollars, and population, respectively. Data on C are based on United Nations estimates of national energy consumptions (Marland et al., 1999). Data on P and E are from the International Energy Agency (IEA/OECD) and other studies (Kremer, 1993; Darmstadter, 1971; Etemad et al., 1991). Data on Y are real GDP for the world at purchasing power parity estimates in 1990 international dollars (Maddison, 1995).

[27]The IPCC scenario "IS92a" represented an average situation with medium population and economic growth, and access to a mix of conventional and renewable energy sources. The highest carbon emissions IPCC scenario "IS92e" used, among other assumptions, moderate population growth, high economic growth, high fossil fuel availability and possible phasing-out of nuclear power. At the other extreme, "IS92c" has a CO_2 emissions path that eventually falls below its 1990 starting level. It assumes that the population is growing initially and then declines by the middle of the century, it also assumes a low economic growth and severe constraints on fossil fuel supply (see figure 1.4).

the IPCC growth assumptions were generally conservative (Eckaus, 1994) and that emissions forecasts based on recent historical patterns give much higher worldwide CO_2 emissions than predicted in the IPCC IS92 emission scenarios (Schmalensee et al., 1998).

In its 2000 report on emissions scenarios (IPCC, 2000), the IPCC proposes four alternative scenario "families", or "storylines", describing different GHG emissions futures based on contrasted dynamic changes and transitions. The IPCC does not put any particular order among the storylines. The main characteristics of the four IPCC-SRES scenario families are presented in Table 1.4[28]. As shown in Figure 1.4, the new IPCC-SRES emissions projections are in a lower range compared with the IS92 scenarios. The IPCC projects the highest carbon emissions from fossil fuels (27.5 GtC in 2100) in scenario "A2" by assuming high population and energy growth combined with medium GDP growth. For the low population and energy-growth scenarios "B1", worldwide carbon emissions are projected to come back more or less to the 1990 level by 2100. In the average scenarios "A1B" and "B2", the emissions trajectories vary greatly but converge to a level around 15 GtC/y in 2100.

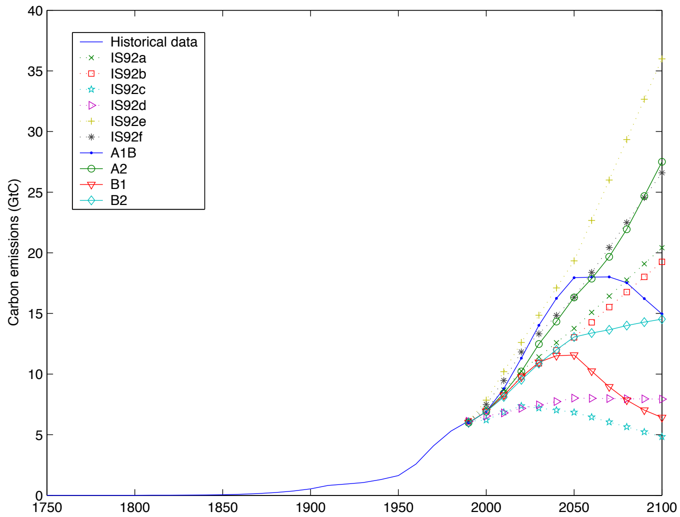

Figure 1.4. Comparison of global CO_2 emissions forecasts for the IPCC IS92 scenarios

[28]The IPCC report is based on simulation results coming from six different economic models. We use the average of the six models' projections for comparison purposes.

Table 1.2. Characteristics of the IPCC-SRES storylines

Scenario Group	**A1B**	**A2**	**B1**	**B2**
Population growth	low	high	low	medium
GDP growth	very high	medium	high	medium
Energy use	very high	high	low	medium
Land-use changes	low	medium/high	high	medium
Fossil-fuels availability	medium	low	low	medium
Technological change	rapid	slow	medium	medium
Change favoring	balanced	regional	efficiency & dematerialization	"dynamics usual"

4.2 Demographics and CO_2 emissions

The growth in worldwide carbon emissions results from population growth and the evolution of per capita emissions. As shown in Figure 1.5, the world population cannot be simply extrapolated from historical population patterns. The world population multiplied by two in 150 years between 1700 and 1850 (+0.45% per annum) and multiplied by 5 in 150 years between 1850 and 2000 (+1.1% per annum). The theory of the demographic transition states that population might stabilize at a high living standard as a result of fertility decline and a high life expectancy at birth. But the speed and extent of this demographic transition is difficult to predict. If we consider the fertility rate of 2.1 children per woman as corresponding to the replacement level, in conditions of low mortality (life expectancy around 70 years), in 2003, about 50% of the world population is in that situation or below this rate (15% under 1.5)[29]. A great diversity in fertility exists in the developing world where the demographic transition is not reached for the moment: 32% of the world population ranges between the rate of 3 to 6 children per woman (i.e. northern India, Pakistan, Afghanistan, Arabian Peninsula, sub-saharan Africa). Most future growth will be produced in these areas (Baldwin, 1998). Because of this uncertainty, the IPCC retains three contrasted population trajectories that reflect future demographic uncertainty (see Figure 1.5).

Historical per capita emission patterns are plotted in Figure 1.6. Not surprisingly, per capita emissions increased very rapidly with the early stage of industrial development. At the world level, per capita emissions have tended to grow over the entire period[30]. However, industrialized countries have had a two-phase pattern for per capita emissions (Lanne and Liski, 2003). The first phase was characterized by fast growth of per capita emissions as early industrialization and development was heavily based on coal (1750-1910). The second phase showed a lower growth of per capita emissions due to the change

[29]See Wilson, 2004.

[30]The reduction of per capita emissions at the world level in the end period is mainly due to the sharp decline in per capita emissions associated with the economic recession in the former Soviet Union and Eastern European countries.

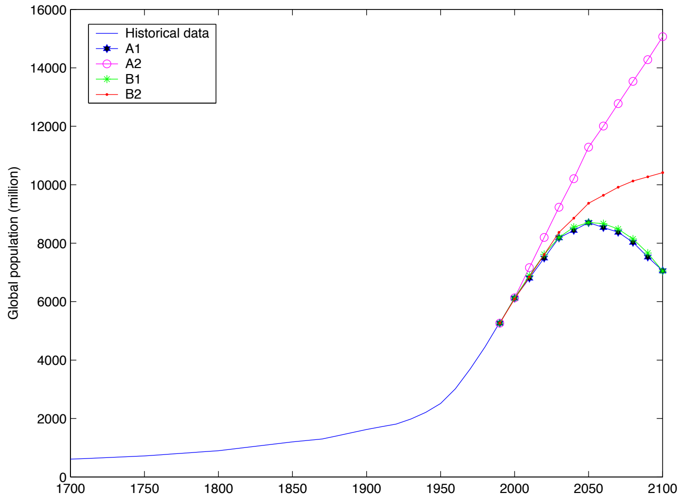

Figure 1.5. Global population

in the fuel mix (i.e. the shift from coal to oil and gas), and to technological progress. By contrast, there is little historical evidence for a third phase characterized by declining per capita emissions. However, one finds evidence for early downturns in per capita trends in developed countries in the first decade of the 20th century (Lanne and Liski, 2003). Figures 1.5-1.6 show that the medium emission scenarios "A1B" and "B2" are based on different assumptions about population and per capita emission growth. The "A1B" scenario combines low population growth with high per capita emission coefficient whereas the "B2" scenario is built on medium population and per capita growth. The low emissions scenario "B1" is explained by a sharp decline of population and per capita emissions from 2050. The high-growth scenario "A2" assumes medium per capita emission growth but high population growth. As defined by the IPCC, scenario "A2" might be considered as a rather pessimistic scenario. However, one might imagine a similar scenario in terms of emission forecast based on the U.N. medium population scenario used for the "A2" scenario and a per capita emissions forecast that would fit with historical patterns used in scenario A1B. This "conservative" scenario would give emissions from fossil fuels totalling 22 GtC/y by 2100.

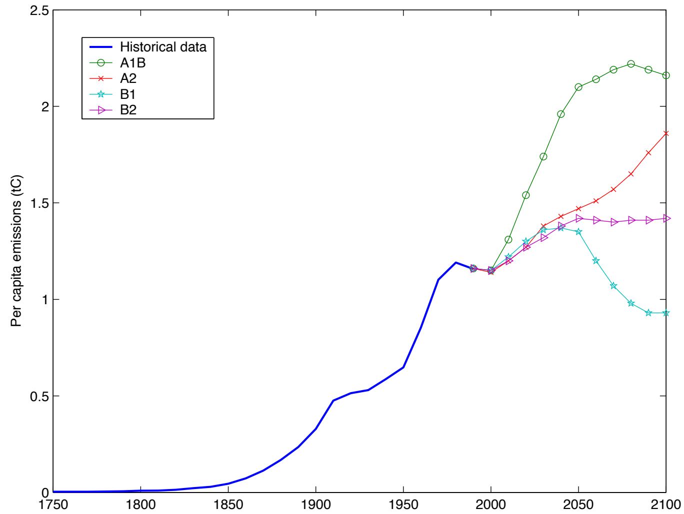

Figure 1.6. CO_2 emissions per capita (scenario A1B)

4.3 CO_2 emissions and economic growth

Most research concerning the relationship between the environment and economic growth uses the paradigm of the *Environmental Kuznets Curve* (EKC)[31]. A number of studies have cautioned the EKC hypothesis on theoretical grounds (Arrow et al., 1995; Stern et al., 1996). Others have criticized the EKC model on econometric grounds (Stern and Common, 2001; Stern et al., 1996). It has been shown that environmental improvements are possible in developing countries and that pollution peaks might be lower than in early developed countries[32]. This indicates that EKC curves may shift down for developing countries, and that emissions may decline simultaneously in low and high income countries over time[33]. The existing literature shows little evidence for a common inverted U-shaped curve that countries follow as their income rises (Stern, 2003). In the CO_2 case one observes that per capita emissions have tended to rise with per capita gross domestic product (GDP) but to stabilize

[31]The EKC is an empirical proposition according to which an indicator of environmental degradation is an inverted U-shaped function of income per capita (Grossman and Krueger, 1991; IBRD, 1992). It basically says that in the early stage of economic growth environmental degradation and pollution increase, but beyond some level of income per capita the trend reverses and the environment indicator improves with structural changes in the economy, the development of better technology, changes in the fuel mix, and the enforcement of stricter environmental regulations.
[32]See Dasgupta et al., 2002.
[33]The income elasticity of emissions is likely to be less than one but hardly negative in wealthy countries as proposed by the EKC literature.

or even reverse in highly developed countries from 1950 to 1990 (Schmalensee et al., 1998). As shown in Figure 1.7, there is a regular increase of per capita emissions with per capita GDP at the world level over the 1750-1990 period. Two IPCC scenarios are consistent with the EKC hypothesis: on average, the six models used for evaluation of scenario "A1" and scenario "B1" find a turning point in 2080 and 2040-50, respectively. In scenario "A2" and "B2", per capita CO_2 emissions are projected to increase monotonically with per capita income. The income elasticity of emissions is supposed to be close to one in "A2" and approximately 0.4 in B2 by 2100.

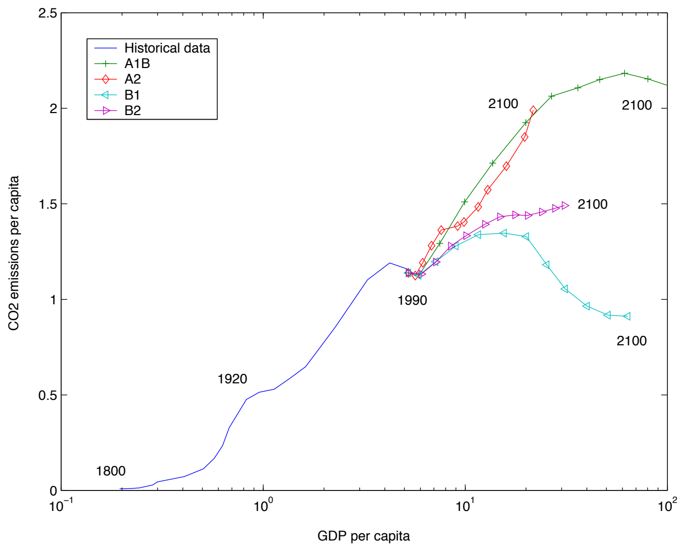

Figure 1.7. CO_2 emissions and GDP Growth (1800-2100)

The decomposition of per capita carbon emissions into carbon intensity of GDP and per capita income is presented in Figure 1.8. At the world level, per capita emissions have increased as a result of the two components from 1800 to 1910. The carbon intensity of GDP reached a peak in 1910, and then reduced from 1910 to 1990 by 1.2 % per year. The reduction of carbon intensity has been too low to compensate the effect of income growth on per capita emissions. The EKC model assumes implicitly that the growth in per capita income can be more than compensated by a decline in carbon intensity of GDP. This hypothesis is easier to support if one supposes that income growth were to decline over time, and that the economy should be in steady state in the long run[34]. The IPCC emission scenarios are built on assumptions of declin-

[34]This kind of reasoning, assuming an exogenous rate of technological progress, has been introduced by Ramsey and Solow , and popularized by the neo-classical optimal growth theory

ing GDP growth rates. This has been criticized by some experts who believe that IPCC's growth assumptions are generally conservative in light of recent experience, and that there is no historical basis for the common assumption that per capita income growth slows down over time in developed countries[35]. Indeed, the exchange rates approach overstates the income gap between rich and poor countries in the base year. As a result, the IPCC may assume too high economic growth in poor countries as per capita income may be expected to converge in the long run. However, the choice of the market exchange rates approach does not necessarily lead to an overestimation of developing countries' emission growth if one expects a closure of the emission intensity gap between rich and poor countries with the convergence of per capita income among countries. This latter driving force may well compensate the bias in GDP growth (Manne and Richels, 2003).

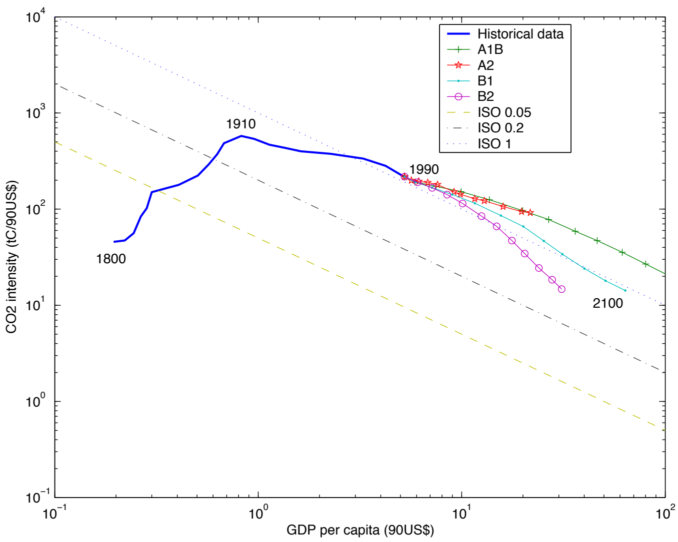

Figure 1.8. Decomposition of CO_2 per capita (1800-2100). The straight lines are contours of constant per capita emission rate.

(Ramsey, 1928; Solow, 1956). By contrast, endogenous growth models are characterized by increasing return to scale and generate sustained growth over long periods of time (Lucas, 1988; Romer, 1990).

[35]For example, see Eckaus, 1994; Nordhaus, 1994; Schmalensee et al., 1998. Other experts have also criticized the IPCC emission scenarios for using GDP weights based on exchange rates rather than purchasing power parities (Castles and Henderson, 003a; Castles and Henderson, 003b).

5. Energy and economic development

Several authors have also used a decomposition approach to analyse changes in carbon emissions in industrialized countries into structural (e.g. output mix), technological and fuel mix effects (Selden et al., 1999; Viguier, 1999; Schipper et al., 2001). These studies show that the reduction of energy intensity has played a major role in the decline of carbon intensity as compared to the fuel composition effects and structural changes in the economy[36]. The comparison of modelling results shows that none of the projections expect a decline in carbon intensity of fuels, similar to the historical rate, to continue beyond 2020 (Viguier et al., 2003). At the world level, GHG emission intensity has been caused by a continuing reduction of energy intensity since 1910 (see Figure 1.8). The carbon intensity of energy consumption has been very stable in the whole period 1800-1990. However, one can see on the graph that all IPCC's scenarios except the "A1B" scenario assume a sharp decline in emissions due to rapid energy substitutions from carbon intensive energy (e.g. coal) to less-carbon intensive energy or carbon-free energy. Can we expect such a change in the composition of fuel consumption in a baseline emission scenario? Will energy intensity continue to decrease over time without new environmental policies?

Most economic models include exogenous technical change represented as a single scaling factor – the autonomous energy efficiency improvement (AEEI) – that makes aggregate energy use per unit of output decline over time, independently of any changes in energy prices. Although the definition of the AEEI varies from model to model, in all models it implicitly represents the effect of technological progress. In some models it also represents one or both of two additional trends: (1) changes in the structure of the economy, resulting in a shift in the relative contribution of energy-intensive industry output to total economic output; and (2) an improvement in energy efficiency over time, reflecting the gradual removal of market barriers that prevent some energy consumers from choosing more efficient energy technologies. In reality, higher prices do spur greater innovation and more rapid diffusion of energy-saving technologies (Huntington and Weyant, 2002). AEEI is critical because even small rates (e.g. 1% per year) can generate large reductions in energy use and carbon emissions when applied over a long time horizon. However, it is not clear what an appropriate rate for AEEI should be.

The extent to which technical change is energy-saving is a source of considerable controversy (Jorgenson and Wilcoxen, 1993). Hogan and Jorgenson present econometric evidence that aggregate technical change may be slightly energy-using (Hogan and Jorgenson, 1991). Modelling technical change with a

[36]For example, it is shown that the reduction of the carbon intensity of US GDP has been mostly due to the reduction of energy intensity (Viguier et al., 2003). In Europe, both the decline of energy intensity and the evolution of the fuel mix are responsible for a falling emissions intensity of GDP for the 1960-1995 period. Historically a decline in the carbon intensity of fuels has been a significant contributor to the decline in carbon intensity of GDP for the EU.

deterministic trend may also overestimate future AEEI. A deterministic trend implies that AEEI will continue *ad infinitum.* However, one should model technical change as a stochastic process and account for the limits on the structural changes responsible for AEEI (e.g. the ability of households to substitute non-energy goods and services for energy purchases; resource and technical limits on the ability to reduce energy intensity) (Kaufmann, 2004). One should better represent technological change by incorporating some degree of price sensitivity (Huntington and Weyant, 2002). Recent econometric studies that take into account the presence of price-induced technical change and the stochastic nature of technical change conclude that current estimates for AEEI may overstate future reductions in energy use and thus underestimate the welfare effect of climate change policies (Kaufmann, 2004).

In the IPCC scenarios "A1B", "B1", and "B2", the reduction of carbon intensity of energy consumption is generally obtained through a shift from fossil fuel to biomass and carbon-free energy. But the fuel-by-fuel composition of energy consumption may greatly differ from one economic model to another. In general, the projected fuel mix is characterized by less coal and oil, and a high share for natural gas and renewable energy in the three scenarios[37] by 2100. By contrast, Manne and Richels have included new assumptions about oil and gas resources in the MERGE model[38]. In the reference case where a production-reserve ratio of 5% and a resource depletion factor of 2% are assumed, world oil and gas production are supposed to decline to 87.6 and 101.3 exajoules (EJ) per year in 2100, respectively. As shown in Figure 1.9, almost fifty percent of total primary energy supply would come from coal, and oil and gas would represent around 6% each. This picture is relatively different from all the IPCC's scenarios. Under this fuel mix, the decline of carbon intensity of energy consumption might be more limited than expected in IPCC scenarios depending on the penetration of new clean-coal technologies.

As a final remark we may notice that baseline emissions scenarios produced by the economic models generally assume (i) a rapid shift from fossil fuels to carbon-free energy in the baseline scenario, and (i) constant AEEI rates which are typically in the range 0.5% to 2.5% per year. If one challenges these underlying assumptions, GHG emission intensity might be higher than projected by the IPCC. *Ceteris paribus*, worldwide carbon emissions might then be higher than one might expect from the IPCC – or closer to the "A2" scenario than the others. 'Consequently, both the environmental burden *and*

[37]If one takes the IPCC projections from the Asian-Pacific Integrated (AIM) model as an example, the share of oil in total primary energy supply is supposed to reduce to 6% in "A1B" and to 12% in "B1" in 2100; the share of coal ranges from 10% to 13%; natural gas ranges from 10% to 25% and renewable energy goes from 21% in "B2" to 44% in "A1B".

[38]They estimate oil and gas supply curves by 2100 based on estimates of the quantities of conventional oil, gas, and natural gas liquids outside the United States that have the potential to be added to reserves in the next 30 years (1995 to 2025) from the U.S. Geological Survey "World Petroleum Assessment 2000".

the economic *and* the economic costs of mitigation policies (i.e. Kyoto targets) tend to be underestimated.

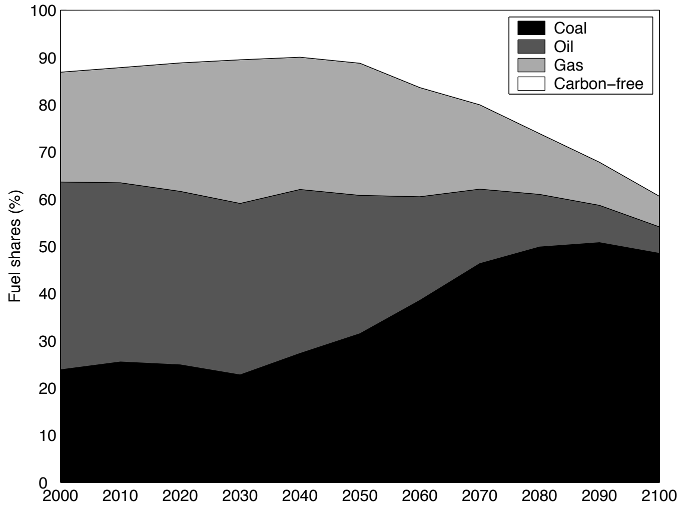

Figure 1.9. Fuel Shares in Total Primary Energy Supply (MERGE 5 - Reference case)

6. Conclusion

To summarize this rapid survey of the interplay between climate and economic dynamics we may draw the following conclusions:

- Knowledge of the dynamics of the carbon cycle and the forcing by greenhouse gases permits us to predict global climate change due to anthropogenic influences on a time scale of a century (albeit with uncertainty).
- Stabilizing the global mean temperature change to a level around 2^oC calls for a drastic worldwide reduction of the GHG emissions level (to around a quarter of the 1990 level) over the next 50 years.
- Climate inertia implies that those who will benefit (suffer) most from our mitigation actions (lack of mitigation) are not yet born.
- The climate change impacts may be large and unequally distributed over the planet, with a heavier toll for some DCs.
- The rapid rise of GHG emissions has accompanied economic development since the beginning of the industrial era; new ways of bypassing the *Kuznets curve* phenomenon have to be found for permitting DCs to enter into a necessary global emissions reduction scheme.

- The energy system sustaining the world economy has to be profoundly modified; there are possible technological solutions but their implementations necessitate a drastic reorganization of the infrastructures with considerable economic and geopolitical consequences.

- The policies to implement at international level must take explicitly into account the intergenerational and interregional equity issues.

- The magnitude of the changes that will be necessary impose the implementation of market-based instruments to limit the welfare losses of the different parties (groups of consumers) involved.

The global anthropogenic climate change problem is now relatively well identified. The decision process which has to be implemented in order to solve it must be adapted to the particular spatial and dynamic structure of the interplay between climate and economic dynamics. As exemplified by the difficulties of the Kyoto protocol[39], viable policy options will have to be designed as *equilibrium solutions to dynamic games played by different groups of nations.* The paradigm of dynamic games is particularly well suited to represent the conflict of a set of economic agents (here the nations) involved jointly in the control of a complex dynamical system (the climate), over a very long time horizon, with distributed and highly unequal costs and benefits. Already many papers have proposed such an approach (Carraro and Filar, 1995). The time has come to construct models based on a more precise description of climate dynamics; the economic response to the need for drastic mitigation actions; the costs incurred by the different regions, and the possibility of integrating mitigation policies within an incentive for clean development. Some dynamic games involving detailed economic descriptions of the consequences of climate change policies have recently been proposed ((Haurie and Viguier, 2003; Bernard et al., 2002; Viguier et al., 2004)). In another vein a game-theoretic approach to the long-term dynamic management of the world energy system has been sketched out (Labriet and Loulou, 2003).

In this book the papers by Carraro and Kemfert address specifically, in a dynamic game setting, the issue of linkage between development or R&D and mitigation policies. The other papers gathered in this book are a contribution to the identification of the parameters that could define the models that will be required.

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[39]For an interesting economic analysis of this protocol, see Guesnerie, 2003.

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