Global Environmental Change 1994 **4** (2) 97–124

Climate change implications for Europe

An application of the ESCAPE Model

Jan Rotmans, Mike Hulme and Thomas E Downing

Policy makers, charged both with identifying possible national response strategies to climate change and with negotiating international conventions and protocols, need tools which enable them to estimate the implications for climate change of a wide range of policy options and which summarize the uncertainties surrounding global climate change. One such tool, recently constructed for the Environment Directorate of the Commission of the European Communities,[1] consists of an interactive climate change impact assessment model called ESCAPE. This paper describes the model framework and illustrates the use of ESCAPE using a range of input scenarios reflecting different global policy, economic and technological futures. Three important characteristics of the global climate change problem are well illustrated: past emissions of greenhouse gases and the inertia of the global development path have committed the world to future warming irrespective of current and near-future policy interventions; the efficacy of a climate policy implemented solely within the EC on altering the course of future climate change is very small; and the impacts of climate change on the economy and environment of the European Community differ markedly between northern and southern Europe.

Jan Rotmans is with the Global Dynamics Department, National Institute for Public Health and Environmental Protection (RIVM), PO Box 1, 3720 BA Bilthoven, The Netherlands; Mike Hulme is Corresponding author, Climatic Research Unit, School
continued on page 98

Understanding future global climate change and its impacts requires an interdisciplinary perspective which encompasses the physical, social and political sciences. Policy makers, charged both with identifying possible national response strategies to climate change and with negotiating international conventions and protocols, need tools which enable them to estimate the implications for climate and climate change impacts of a wide range of policy options. These tools should also provide concise overviews of the uncertainties surrounding global climate change.[2] One such tool, recently developed for the Directorate General for Environment, Nuclear Safety and Consumer Protection (DGXI) of the Commission of the European Communities, is called ESCAPE: the Evaluation of Strategies to address Climate change by Adapting to and Preventing Emissions. The model was developed between November 1990 and May 1992 by the Climatic Research Unit at the University of East Anglia (CRU, Norwich, UK), the National Institute for Public Health and Environmental Protection (RIVM, Bilthoven, The Netherlands), the Environmental Change Unit (ECU, Oxford, UK) and Environmental Resources Limited (ERL, London, UK). The interactive, computerized framework allows the implications of different climate-related policies to be explored, both for global-mean and European climate and for indicators of the economic and environmental impact of climate change within Europe. The model provides a clear assessment of the scientific uncertainties surrounding the prediction of future climate change and its impacts. Both a *Scientific Description* and *User Manual* of the model are available.[3]

This paper describes the ESCAPE model and presents some preliminary estimates of the implications of climate change both globally and for Europe, particularly for the European Community (EC), using the model. The analysis presented here is far from complete and does not pretend to outline a comprehensive picture of the causes and effects of future climate change for Europe. Such a picture in any case cannot be drawn at present due to uncertainties in many of the atmospheric and biophysical processes involved. What we do provide, however, are

continued from page 97
of Environmental Sciences, University of East Anglia, Norwich NR4 7TJ, UK; and Thomas E. Downing is with the Environmental Change Unit, 1a Mansfield Road, Oxford OX1 3TB, UK.

ESCAPE was developed under contract to the Environment Directorate (DGXI) of the Commission of the European Communities. The four main organizations responsible for the development of ESCAPE were the Climatic Research Unit (CRU), the National Institute for Public Health and Environmental Protection (RIVM), the Environmental Change Unit (ECU) and Environmental Resources Ltd (ERL). A Scientific Advisory Panel reviewed the methodology and results during the project. The authors of this paper are indebted to the numerous individuals who contributed to the development of the model. The appropriate sections in the paper identify the specific contributors to ESCAPE. Suggestions made by two reviewers of the paper led to improvements in the clarity of the text.

[1]The European Community (EC) officially became the European Union with the adoption of the Maastricht Treaty. For consistency, the former name is used here, since the project was completed under the auspices of the EC.
[2]See, for example, H. Dowlatabadi and G.M. Morgan, 'Integrated assessment of climate change', *Science*, Vol 259, 1993, pp 1813 and 1932.
[3]These two reports were prepared for DGXI and are available from Mike Hulme at the Climatic Research Unit: *Development of a Framework for the Evaluation of Policy Options to Deal with the Greenhouse Effect: A Scientific Description of the ESCAPE Model, Version 1.1*, Climatic Research Unit, Norwich, May 1992; and *Development of a Framework for the Evaluation of Policy Options to Deal with the Greenhouse Effect: A User Manual for the ESCAPE Software: Version 1.1*, Climatic Research Unit, Norwich, May 1992.
[4]This report was prepared for DGXI and is available from Paul Wenman at Environmental Resources Limited, 106 Gloucester Place, London W1H 3BD: *Development of a Framework for the Evaluation of Policy Options to Deal with the Greenhouse Effect: Economic Evaluation of Impacts and Adaptive Measures in the European Community*, ERL, London, May 1992.
[5]C. Hope, T. Anderson and P. Wenman, 'Policy analysis of the greenhouse effect: an application of the PAGE model', *Energy Policy*, Vol 21, 1993, pp 327–337.
[6]C.K. Folland, T.R. Karl, N. Nicholls, B.S. Nyenzi, D.E. Parker and K.Ya. Vinnikov, 'Observed climate variability and change', in J.T. Houghton, B.A. Callander and S.K. Varney, eds, *Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment*, Cambridge University
continued on page 99

useful indications of the potential range and magnitude of climate change impacts in Europe and the scale of the policy interventions which are necessary to prevent the climate change which causes these impacts. This study concentrates mainly on first-order impacts in Europe. Only for some economic activities can the monetary values of these impacts be estimated. For most impact sectors only qualitative estimates of impact costs and benefits can be given. The results presented in this paper are based solely on experiments performed within the ESCAPE modelling framework. A complementary analysis of economic impacts using results from ESCAPE is reported by ERL,[4] while a parallel policy evaluation framework, PAGE (Policy Analysis of the Greenhouse Effect), enables the cost effectiveness of different climate-related policies to be compared.[5]

Problem identification

Earth's surface air temperature is significantly modified by a natural greenhouse effect. This is caused by the absorption in the atmosphere by water vapour and greenhouse gases of long-wave terrestrial radiation emitted by the surface of Earth. Without this natural process the mean surface air temperature of the planet would be some 33°C lower than it is. Since the beginning of the industrial era the concentration of most greenhouse gases (water vapour is an exception) has increased substantially, leading to a net energy input into the lower atmosphere. The direct result of this change in the energy balance is an additional warming of the lower troposphere. Various feedbacks within the climate system, however, operate to enhance or reduce this warming and, while the net effect is certainly positive, the exact magnitude of the warming is as yet unknown. Observations of global-mean surface air temperature over the last 130 years have shown a warming of the lower atmosphere of between 0.3° and 0.6°C.[6] Attributing this warming unequivocally to a rise in greenhouse gases, however, remains difficult owing to the variability of climate due to other factors such as variations in solar radiation,[7] sulphate aerosols[8] and volcanic eruptions.[9]

Carbon dioxide (CO_2) currently contributes about 55% of the theoretical enhanced greenhouse forcing and its concentration is rising at about 0.5% (1.8 ppmv) per year.[10] The main sources of CO_2 are the combustion of fossil fuels and land use changes (primarily deforestation). The present global emissions of CO_2 due to fossil fuel combustion are about six gigatonnes of carbon (GtC), to which Western and Eastern Europe contribute respectively 15% and 22%. Methane (CH_4) is increasing at a rate of about 0.9% (0.015 ppmv) per year, although the rate of increase is declining,[11] and the gas currently contributes about 15% to the calculated enhanced greenhouse forcing. Major biogenic sources of methane are natural wetlands, rice paddies, landfills, domestic ruminants and biomass burning, while fossil sources of methane include the exploitation of coal and oil and natural gas venting and distribution. In addition to methane emissions, recent decreases in the global availability of hydroxyl also lead to an enhanced level of methane in the atmosphere. Hydroxyl removes methane from the atmosphere through oxidation and therefore acts as the major sink mechanism for the gas.[12] Nitrous oxide (N_2O) is currently increasing at a rate of about 0.25% (0.8 ppbv) per year and currently contributes about 6% to the calculated greenhouse radiative forcing. The most important sources of

N_2O are assumed to be soils, oceans, fertilizer use and land use conversion from forest to grassland/arable.

Finally, the artificial compounds known as the halocarbons also act as greenhouse gases. These robust compounds leak into the lower atmosphere from industrial processes and from, for example, refrigerators and slowly diffuse up to the stratosphere. They directly perturb the radiative balance of the atmosphere, leading to a direct contribution of about 24% to the enhanced greenhouse forcing. The presence of halocarbons in the stratosphere, however, also contributes substantially to the depletion of stratospheric ozone. Halocarbons therefore also have an indirect effect on radiative forcing which tends to counter their direct impact.[13] Production of many halocarbons has been regulated in recent years through the Copenhagen and London amendments to the Montreal Protocol. For example, this Protocol now includes a phase-out of production of all the most severe ozone depleting halocarbons (the CFCs) by 1996. For replacement compounds, such as the halochlorofluorocarbons (HCFCs), the restriction on production will start in 1996 leading to a total production phase-out by 2030.

Uncertainties

Predicting future global climate change and its consequences for human society is beset with many uncertainties. These may be summarized as 'scientific uncertainties' (those which may be narrowed as a result of further scientific research) and 'socio-economic uncertainties' (those which result from the evolution of social, economic, political and demographic conditions, many of which will remain despite advancements in knowledge).

Scientific uncertainties include the magnitude of the sources and sinks of the various greenhouse gases. For CO_2 emissions, the contribution from fossil fuel combustion is relatively well known (with an estimated error of about 5%), but emissions from land use changes remain poorly known (errors in the order of 50%[14]). With respect to the oceanic and terrestrial carbon sinks, the likely errors are of the order 100%. The only well known component of the global carbon budget is the amount of carbon remaining in the atmosphere. Characteristic of the present uncertainties about the sinks in the global carbon cycle is the continuing debate about the ocean uptake of carbon.[15] The uncertainties with respect to the sources and sinks of methane are even larger. While the overall magnitude of global methane emissions is reasonably well known, estimates of methane emissions from individual sources are highly uncertain.[16] Furthermore, the reasons for the declining growth rate of atmospheric methane are unknown, indicating significant ignorance about the sources and sinks of methane and their long-term stability.

Another source of uncertainty originates from our deficient knowledge of the key physiological, chemical and biological processes that affect the climate system. Illustrative of this is the inadequate understanding of the many potential feedback responses to increasing atmospheric CO_2 and rising temperatures. Feedback processes can either amplify (positive feedback) or dampen (negative feedback) the response of the climate system to anthropogenic greenhouse gas emissions. Geophysical feedbacks (for example, the ice-albedo feedback) are caused by physical processes in the atmosphere–ocean–cryosphere

continued from page 98
Press, Cambridge, 1992, pp 135–170.
[7]P.M. Kelly and T.M.L. Wigley, 'Solar cycle length, greenhouse forcing and global climate', *Nature*, Vol 360, 1990, pp 328–330.
[8]R.J. Charlson, S.E. Schwartz, J.M. Hales, R.D. Cess, J.A. Coakley Jr, J.E. Hansen and D.J. Hofmann, 'Climate forcing by anthropogenic aerosols', *Science*, Vol 255, 1992, pp 423–430.
[9]J. Hansen, A. Lacis, R. Ruedy and M. Sato, 'Potential climate impact of the Mount Pinatubo eruption', *Geophysical Research Letters*, Vol 19, 1992, pp 215–218.
[10]This increase is variable from year to year; the 1992 increase was much lower than expected. For a discussion of this see J.L. Sarmiento, 'Atmospheric CO_2 stalled', *Nature*, Vol 365, 1993, pp 697–698.
[11]L.P. Steele, E.J. Dlugokencky, P.M. Lang, P.P. Tans, R.C. Martin and K.A. Masarie, 'Slowing down of the global accumulation of atmospheric methane during the 1980s' *Nature*, Vol 358, 1992, pp 313–315.
[12]J. Rotmans, M.G.J. Den Elzen, M.S. Krol, R.J. Swart and H.J. Van der Woerd, 'Stabilizing atmospheric concentrations: towards international methane control', *Ambio*, Vol 21, 1992, pp 404–413.
[13]V. Ramaswamy, M.D. Schwarzkopf and K.P. Shine, 'Radiative forcing of climate from halocarbon-induced global stratospheric ozone loss', *Nature*, Vol 355, 1992, pp 810–812.
[14]J. Leggett, W.J. Pepper and R.J. Swart, 'Emissions scenarios for the IPCC: an update', in J.T. Houghton, B.A. Callander and S.K. Varney, eds, *The Supplementary Report to the IPCC Scientific Assessment*, Cambridge University Press, Cambridge, 1992, pp 69–96.
[15]See P.P. Tans, I.Y. Fung and T. Takahashi, 'Observational constraints on the global atmospheric carbon dioxide budget', *Science*, Vol 247, 1990, pp 1431–1438; and E.T. Sundquist, 'The global carbon dioxide budget', *Science*, Vol 259, 1993, pp 934–941.
[16]*Op cit*, Ref 12.

system which directly affect the response of climate to radiative forcing. Biogeochemical feedbacks (for example, the CO_2-fertilization feedback) not only may affect the concentrations of the greenhouse gases themselves, and thus the radiative forcing, but may also alter the response of the climate system to any given radiative forcing. New biogeochemical feedbacks continue to be identified and quantified, as witnessed by the interactions of climate with stratospheric ozone and fossil fuel-related emissions of sulphur dioxide.[17]

Despite these major gaps in our knowledge of the sensitivity of the climate system to greenhouse gas emissions, the most precarious aspects of assessing the significance of future climate change for human society are the estimation of future greenhouse gas emissions and the ecological effects and socio-economic impacts of climate change. Likely future emissions scenarios result in a sizeable range of global-mean temperature projections (between 1.5°C and 3°C by 2100[18]). Resolving ecological uncertainties in the vegetation and water-cycle response to climate change requires extensive field data and high resolution, dynamic ecosystem models. Neither of these two requirements is fully met at present. Estimating social, economic and political impacts depends not only on all of the above processes, but also on accurate data and models of human behaviour, from the individual (eg regarding nutrition) to the world system (eg the allocation of investment). In many cases not even the direction of the impact can currently be stated.[19] It is clear that our knowledge of the phenomenon of climate change and its significance is far from complete. We do know, however, that increasing atmospheric concentrations of greenhouse gases perturb the climate system. Key questions which need answering, therefore, are:

- What will be the rate, magnitude and regional distribution of future climate change?
- What are the potential impacts on ecosystems and human society of the probable range of climate changes?
- What mix of greenhouse gas emissions control measures would reduce the rate and magnitude of climate change?

The integrated climate change assessment model, ESCAPE, was constructed to attempt to answer these questions. In view of the incomplete scientific understanding and uncertainties mentioned above, the role of ESCAPE is not to predict future changes or the optimal policy response. Rather, the value of such an interactive set of linked models is primarily to educate analysts and highlight key sensitivities in the coupled society–biosphere–climate model. ESCAPE represents one of the first attempts to synthesize current scientific understanding of the causes and impacts of global climate change due to the enhanced greenhouse effect into one regionally based integrated framework.

The modelling approach

Methodology

ESCAPE consists of a suite of linked models (modules) which enables scenarios of greenhouse gas emissions to be constructed and their impact on global and regional climate and sea level and on sectors of the European economy to be assessed. Each module consists of simple versions of more elaborate process-based compartmentalized models such as three-dimensional climate models, photochemical models and

[17] I.S.A Isaksen, V. Ramaswamy, H. Rodhe and T.M.L. Wigley, 'Radiative forcing of climate', in J.T. Houghton, B.A. Callander and S.K. Varney, eds, *Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment*, Cambridge University Press, Cambridge, 1992, pp 47–68.

[18] This range results when the six 1992 IPCC emissions scenarios (IS92a to IS92f) are run through a simple climate model holding all model parameters constant. See T.M.L. Wigley and S.C.B. Raper, 'Implications for climate and sea level rise of revised IPCC emissions scenarios', *Nature*, Vol 357, 1992, pp 293–300.

[19] W.T. Tegart, G.W. Sheldon and D.C. Griffiths, eds, *Climate Change: The IPCC Impacts Assessment, Australian Government Publishing Service*, Canberra, 1990.

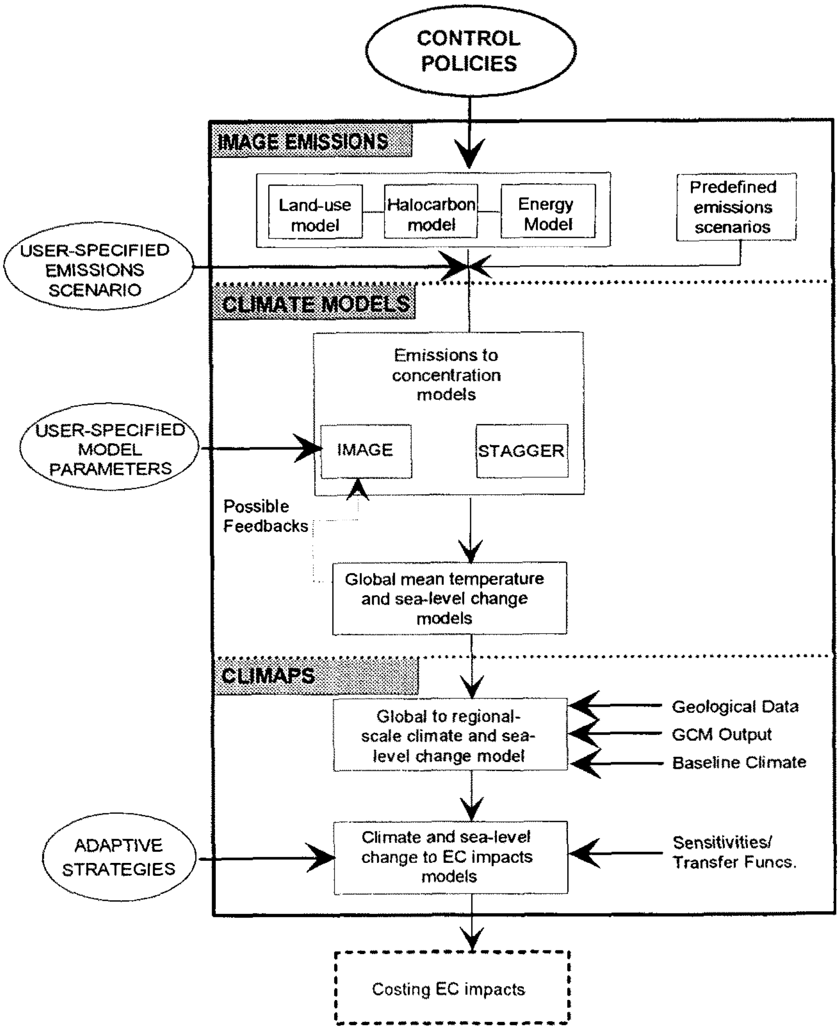

Figure 1. The conceptual framework of the ESCAPE model.

carbon cycle models. These simple models have generally been described elsewhere in the literature and enable the 'state-of-the-art' science to be captured within the ESCAPE framework.

ESCAPE comprises four basic modules which are shown schematically in Figure 1:

- an emissions module – this module, called IMAGE-Emissions, consists of three sub-models: an energy-economics model, a land-use model and a halocarbon model, all developed by RIVM;
- two integrated climate modules, called IMAGE (Integrated Model to Assess the Greenhouse Effect) developed by RIVM, and STAGGER (Sea-level and Temperature After Greenhouse Gas Emissions Reductions) developed by CRU;
- a climate change impacts module called CLIMAPS (CLimate change Impact MAPping System) developed by CRU, in conjunction with ECU and with inputs from RIVM and a number of other institutes.

The four basic modules are linked, but not fully integrated. They differ in complexity, spatial resolution, aggregation level and time step. The default time step for ESCAPE is five years and the projection period is from 1990 to 2100. The varying spatial resolution in these modules results in an 'hourglass' structure to the model. The front-end of

ESCAPE, the IMAGE-Emissions module, calculates emissions for four major world regions: the EC, the rest of the OECD, the former centrally planned countries of Europe and the former Soviet Union (CPC), and the rest of the world (ROW). The core part of ESCAPE, the IMAGE and STAGGER climate modules, uses global emissions projections to calculate global-mean changes in atmospheric concentrations, temperature and sea level. The final module, CLIMAPS, assesses the impacts in Europe of climate change at a resolution of 0.5° latitude by 1.0° longitude. Thus, the model starts with four regions, passes through a global-mean filter (the narrow part of the hourglass), before estimating geographically explicit impacts for one of the four regions: Europe. We discuss first the key assumptions and modelling strategies of the four basic modules of ESCAPE. The key limitations of the modules of ESCAPE are identified in a later subsection.

Model description

IMAGE-Emissions.[20] The main part of the IMAGE-Emissions module is an Energy-Economics model, which has been developed to allow interactive scenario construction with regard to the demand for fossil fuels and the greenhouse gas emissions which result from their combustion. It is a long-term, flexible, energy end-use model, which makes projections of energy use over time as a function of growth in (physical) activity levels and changes in the state of technology. The starting point of the model is that different energy functions, such as high and low temperature heat and the mechanical transmission of energy, are fulfilled by a collection of energy conversion techniques and processes. Each of these techniques and processes has its own energy efficiency, investment costs and emissions factors which can change with time. A dynamic and simple market-share driven substitution mechanism determines the penetration of competing techniques. In this way the demand for energy per sector (industrial, commercial, residential and transportation sectors) is calculated by the model. This demand is converted into secondary fuel types, like gasoline and electricity, and a separate component calculates the required input (production) of primary fuels such as coal and oil. The model does not allow for a coupling between demand-related trends and the response from the energy supply industry.

The Land-Use model calculates emissions from sources related to land use changes, agriculture, landfills and natural sources. Land use changes are triggered by developments in demand for agricultural and forestry products on the one hand and the production potential of the land on the other. The demand is determined by population, income per capita and the ratio between regional production and consumption. The demand can be satisfied in two ways: (i) by changes in the areas of agriculture and grassland; (ii) by changing the productivity of the land. Other causes of land use changes are commercial wood logging, shifting cultivation, firewood extraction, industrial developments, urbanization and reforestation. Eight broad land cover types are used, varying from closed tropical forests to semi-desert or tundra. As well as CO_2, methane emissions from wetland rice fields, animal waste and landfills are generated, as are emissions of nitrous oxide from fertilizer use.

The Halocarbon model generates production and emissions of two chlorofluorocarbons (CFC-11 and CFC-12) and two groups of halochlorofluorocarbons (HCFC-22 and HCFC-Y, with the latter representing

[20]The IMAGE–Emissions module was developed by (alphabetical order) Rene Benders, Lex Bouwman, Eric Kreileman, Rik Leemans, Jos Olivier, Jan Rotmans, Rob Swart, Bert de Vries, Ruud van den Wijngaart and Ge Zuidma, all at RIVM.

three HCFCs, ie HCFC-123, HCFC-124 and HCFC-141b). Each group of gases has a maximum of four applications (aerosols, foams, solvents and refrigerants).

These three models are applied to the four economic regions used by the IMAGE-Emissions module enabling global greenhouse gas emissions scenarios for each year from 1990 to 2100 to be calculated for CO_2, CH_4, N_2O, the CFCs and HCFCs. These emissions form the input for the two climate modules, IMAGE and STAGGER.[21] These climate modules are designed to calculate the effects of future greenhouse gas emissions on global-mean temperature and sea level.

IMAGE[22]

IMAGE consists of a number of independent, but interlinked and integrated, sub-models, each sub-model representing a separate component of the climate system. A thorough description of the basic IMAGE model, Version 1.0, may be found elsewhere.[23] The original IMAGE model consisted of an emissions framework (much as described above in the IMAGE-Emissions module), a core framework and a socio-economic impact model.[24] The version that is used within ESCAPE is the core part of IMAGE 1.5, which simulates the essential physical, chemical and biological processes within the climate system. Those sub-models of IMAGE which are part of the core framework used within ESCAPE are marked in Figure 2.

IMAGE takes the initial condition of the climate system as the year 1900. A central feature of IMAGE is the carbon cycle model and consists of an ocean box-diffusion model, a terrestrial biosphere model and atmospheric box model, which are all interconnected.[25] A major component of the terrestrial biosphere model is the Land-Use model, which occurs at two different places in ESCAPE: in the IMAGE-Emissions module (LU-I, see above) and in the IMAGE-carbon cycle part (LU-II). Both versions are identical, but this model duplication allows the possibility of including temperature-related feedbacks in ESCAPE. LU-I produces land-use emissions figures which are exported to the STAGGER climate model which does not consider temperature-related feedbacks. LU-II also produces land-use emissions scenarios, but since it is fully integrated with the carbon cycle model of IMAGE it is possible to calculate feedback effects within IMAGE. The modelling assumptions behind these feedbacks stem from the deforestation model described elsewhere.[26] These temperature-related feedbacks in IMAGE are not entirely realistic since there is no coupling between IMAGE and the ecosystem response to climate change modelled in CLIMAPS, ie while the emissions from a given ecosystem depend on the future temperature, the ecosystems in IMAGE which generate the emissions are not allowed to change in response to climate change.

A separate sub-model of IMAGE is the photochemical tropospheric model, which simulates key processes of the global methane/carbon monoxide/hydroxyl (CH_4-CO-OH) cycle. This model is a box model that produces globally averaged values of atmospheric concentrations of CH_4, CO and OH. This simple approach is basically an interpretation of the one-, two-and three-dimensional photochemical models simulating the CH_4-CO-OH cycle.[27] The CFC/Substitute sub-model is a two-box model which produces direct and delayed emissions and atmospheric concentrations of the major CFCs and their substitutes.[28]

The climate model of IMAGE (which in principal is similar to that

[21]For the IMAGE climate model, volatile organic compounds (VOCs), carbon monoxide (CO), oxides of nitrogen (NO_x) and sulphur dioxide (SO_2) are also exported from IMAGE–Emissions. These are not direct greenhouse gases (hence not used by STAGGER), but they do indirectly affect tropospheric chemistry which in turn alters methane concentrations.

[22]The IMAGE 1.0 model was originally developed by Jan Rotmans. The version used in ESCAPE benefitted from additional work by (alphabetical order) Rene Benders, Lex Bouwman, Michel Den Elzen, Eric Kreileman, Rik Leemans, Rob Swart and Ge Zuidma, all at RIVM.

[23]J. Rotmans, *IMAGE: an Integrated Model to Assess the Greenhouse Effect*, Kluwer Academic Publishers, Dordrecht, The Netherlands, 1990.

[24]The latter is described and applied in M.G.J. Den Elzen and J. Rotmans, 'A scenario study on the socio-economic consequences of a sea level rise for the Netherlands', *Climatic Change*, Vol 20, 1992, pp 169–195.

[25]The IMAGE carbon cycle model is based on the one published by J. Goudriaan and P. Ketner, 'A simulation study for the global carbon cycle, including man's impact on the biosphere', *Climatic Change*, Vol 6, 1984, pp 167–192.

[26]J. Rotmans and R.J. Swart, 'Modelling tropical deforestation and its consequences for global climate', *Ecological Modelling*, Vol 58, 1992, pp 217–248.

[27]*Op cit*, Ref 12.

[28]M.G.J. Den Elzen, R.J. Swart and J. Rotmans, 'Strengthening the Montreal Protocol: does it cool down the greenhouse?', *Science of the Total Environment*, Vol 113, 1992, pp 229–250.

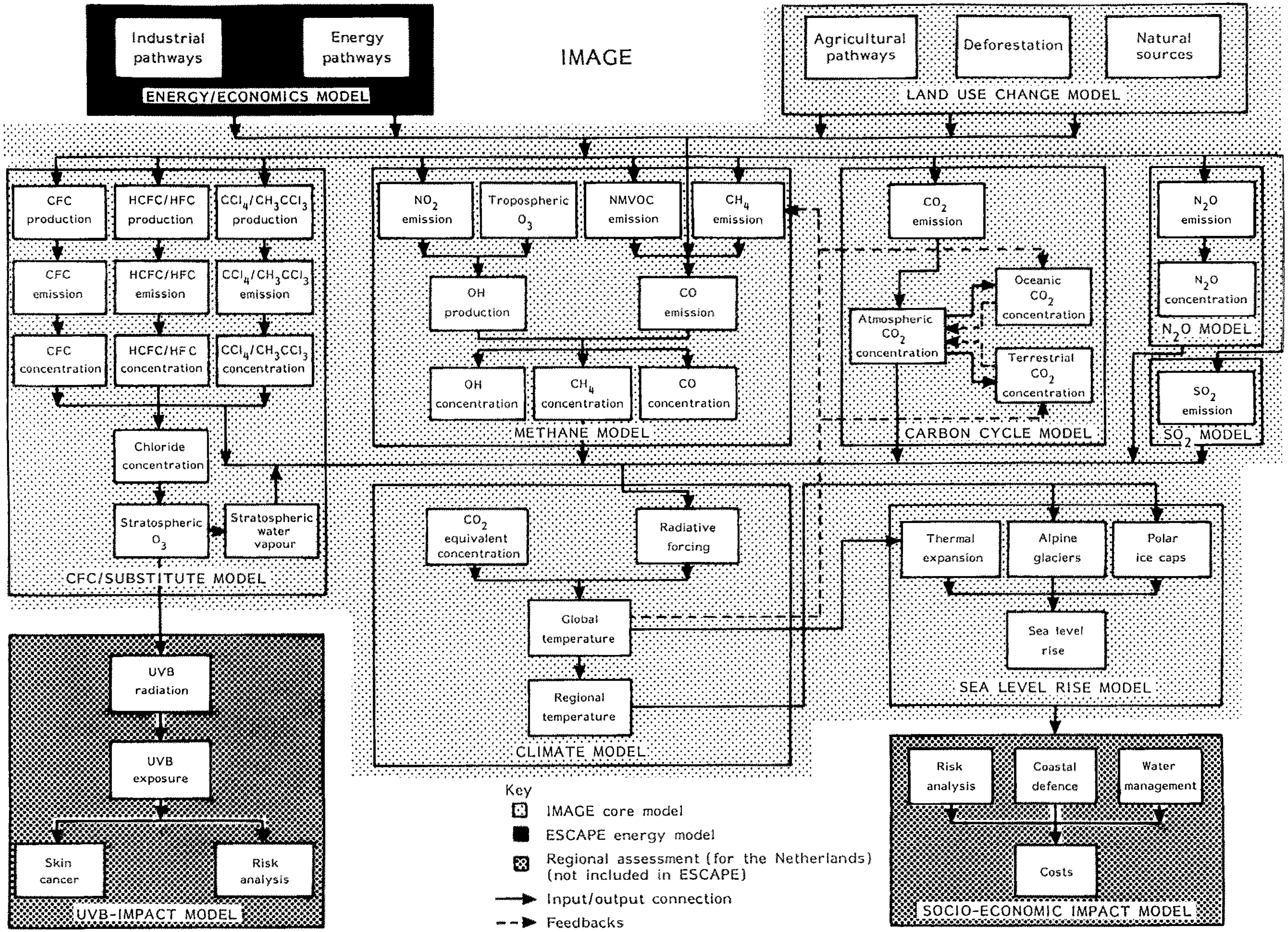

Figure 2. The conceptual framework of IMAGE 1.5.

The IMAGE core model components have been incorporated into ESCAPE. The UVB and socio-economic impact models have not been used by ESCAPE.

used in STAGGER) calculates the total change in radiative forcing at the tropopause which is the sum of the individual contributions of the different gases. The total radiative forcing is then input into the energy balance upwelling box-diffusion model. This model includes a land box, an ocean box and atmosphere boxes over land and ocean, and fully parameterizes the exchange of heat between the different boxes. IMAGE contains a sea level sub-model, in which the complex processes of ocean expansion, glacier melting and ice cap dynamics are represented by simple dynamic relationships.[29]

A number of terrestrial feedback processes are included in IMAGE. Two terrestrial temperature-related feedbacks are modelled: the temperature effect on the net primary production (net photosynthesis minus respiration of non-photosynthetic plant components) and the temperature effect on the respiration of soils and litter. In addition, the so-called 'CO_2-fertilization' feedback is also included. This refers to the stimulating effect that elevated CO_2 concentrations can have on plant photosynthesis and, consequently, on the accumulation of carbon in vegetation. Two oceanic feedback mechanisms are also incorporated in IMAGE which enable the ocean–atmosphere carbon flux to vary: the temperature-diffusivity feedback (which represents the temperature effect on the CO_2 uptake by the oceans) and the temperature-CO_2-solubility feedback (whereby the warming of the ocean surface reduces the CO_2 solubility of the ocean resulting in a smaller net uptake of atmospheric CO_2 by the ocean).

Three climate-related methane feedbacks are also considered in IMAGE. First, increasing microbial activity due to global warming leads to the additional release of methane by both wetlands and rice paddies – a positive feedback. Second, global warming also leads to the destabilization of methane hydrates in ocean sediments, releasing additional methane. Third, both a positive and negative feedback may occur through the increased production of tropospheric ozone due to elevated methane concentrations: positive because of the role of tropospheric ozone as a greenhouse gas, but negative because tropospheric ozone triggers hydroxyl production which is the major sink of atmospheric methane. Although not pretending to give a comprehensive picture of the total role of the biogeochemical feedbacks within the climate system, simulation experiments with these feedbacks give indications about their potential role and order of magnitude.

STAGGER[30]

The forerunner of STAGGER was STUGE (Sea level and Temperature Under the Greenhouse Effect) which was originally developed as a contribution to Working Group 1 of the Intergovernmental Panel on Climate Change (IPCC). STAGGER, where appropriate, uses revised model parameters in accord with the 1992 IPCC Supplementary Report.[31] The primary enhancement in STAGGER compared to STUGE is the inclusion of a CO_2-fertilization feedback effect which ensures a balanced carbon cycle at the start of the model projections in 1990.

Emissions are converted to concentrations using gas cycle models that give results which agree well with the Annex of the 1990 IPCC report.[32] A full comparison is given in the STUGE manual.[33] Concentration changes are converted to radiative forcing changes using the expressions

[29] *Op cit*, Ref 23.
[30] STAGGER was developed by (alphabetical order) Sarah Raper, Mike Salmon and Tom Wigley, all at the Climatic Research Unit.
[31] J.T. Houghton, B.A. Callander, and S.K. Varney, eds, *Climate Change 1992: the Supplementary Report to the IPCC Scientific Assessment*, Cambridge University Press, Cambridge, 1992.
[32] J.T. Houghton, G.J. Jenkins and J.T. Ephraums, eds, *Climate Change: the IPCC Scientific Assessment*, Cambridge University Press, Cambridge, 1990.
[33] T.M.L. Wigley, T. Holt and S.C.B. Raper, *STUGE: An Interactive Greenhouse Model: Users Manual*, Climatic Research Unit, Norwich, 1991.

recommended by the IPCC.[34] These forcings are then applied to the upwelling-diffusion climate model of Wigley and Raper[35] to make transient global-mean temperature projections.

The climate model generates two outputs: global-mean temperature changes and the thermal expansion component of global-mean sea level change. The temperature changes are used as input to ice-melt models for small glaciers and for the Greenland and Antarctic ice sheets. The ice-melt and thermal expansion terms are combined to give a total global-mean sea level rise projection. The ice melt models are minor modifications of the ones used by the 1990 IPCC report.[36]

The model structure of STAGGER is therefore broadly comparable with that of IMAGE. The main difference is that, although both models are relatively simple representations of complex physical and chemical processes, IMAGE is somewhat more process-oriented than STAGGER and includes a number of biogeochemical feedbacks. STAGGER, however, can calculate the climatic effects of a number of emissions scenarios very quickly. By varying the values of a selected number of parameters, STAGGER produces a range of projections, expressed as a 'best guess' value with an uncertainty band around it. This uncertainty band calculated by STAGGER does not encompass the temperature-related feedbacks handled by IMAGE, but these are of secondary importance compared to the geophysical feedback effects which *are* included in the STAGGER range. IMAGE and STAGGER therefore complement each other. IMAGE gives more detailed information about climate-related feedbacks and about basic processes within the various sub-models, while STAGGER has a faster run-time and produces an uncertainty range for each global-mean projection.

CLIMAPS[37]

The final module of ESCAPE, CLIMAPS, uses the global-mean temperature projections of IMAGE and/or STAGGER to construct regional climate scenarios of mean monthly and seasonal temperature and precipitation for Europe for any given year between 1990 and 2100. This future climatology then 'drives' a series of impact models which calculate indicators of climate change impact on different sectors of the European environment and economy: agriculture, water, natural vegetation, energy, tourism and transport. The sectoral models are based on previous work, but adapted specifically for ESCAPE. CLIMAPS also uses the global-mean sea level change calculated by IMAGE and/or STAGGER to determine the net mean sea level change for the European coastline.

CLIMAPS uses a baseline climatology, comprising monthly mean temperature and precipitation, constructed from observed station data for the period 1951–80 and interpolated to a resolution of 0.5° latitude by 1.0° longitude (eg about 50 km).[38] Available soil water holding capacity is based on a similar gridded dataset.[39] Changes in other required variables, such as potential evapotranspiration, minimum temperature, relative humidity and sunshine hours, are related to the two primary variables in the baseline climatology. The approach used in CLIMAPS estimates changes in certain resource potentials rather than using high-resolution, process-oriented models to predict detailed changes in physical parameters.

Regional climate change patterns due to greenhouse gas forcing are

[34]Table 2.2 in K.P. Shine, R.G. Derwent, D.J. Wuebbles and J.J. Morcrette, 'Radiative forcing of climate', in J.T. Houghton, G.J. Jenkins and J.T. Ephraums, eds, *Climate Change: The IPCC Scientific Assessment*, Cambridge University Press, Cambridge, 1990, pp 41–68.
[35]*Op cit*, Ref 18; T.M.L. Wigley and S.C.B. Raper, 'Thermal expansion of sea water associated with global warming', *Nature*, Vol 330, 1987, pp 127–131; T.M.L. Wigley and S.C.B. Raper, 'Natural variability of the climate system and detection of the greenhouse effect', *Nature*, Vol 344, 1990, pp 324–327.
[36]R.A. Warrick and H. Oerlemans, 'Sea level rise', in J.T. Houghton, G.J. Jenkins and J.T. Ephraums, eds, *Climate Change: The IPCC Scientific Assessment*, Cambridge University Press, Cambridge, 1990, 257–282.
[37]CLIMAPS was developed by scientists from numerous institutions. These names are given in alphabetical order with the affiliation at the time of development – Atmospheric Impacts Research Group, University of Birmingham: Tim Carter, Julia Porter, Jianmin Shao, John Thornes, John Wright; Climatic Research Unit: Mike Hulme, Tao Jiang, Bob Marsh, Richard Warrick, Tom Wigley; Department of Geography, University of Durham: Ian Shennan; Environmental Change Unit, Oxford: Paul Brignall, Tom Downing, Paula Harrison, Gavin Kenny, Martin Parry; Whimbrel Consultants Ltd, Huddersfield Polytechnic: David Briggs, K. Kerrell, H.Wu; Oceanide/EUROCOAST, Toulouse: Emmanual Quelennec; RIVM, Bilthoven: Rik Leemans.
[38]This climatology is largely based on that described in T.R. Carter, M.L. Parry and J.H. Porter, 'Climatic change and future agroclimatic potential in Europe', *International Journal of Climatology*, Vol 11, 1991, pp 251–269.
[39]H. Groendijk, *Estimation of Waterholding Capacity of Soils of Europe: The Compilation of a Soils Dataset*, Simulation Report CABO-TT No 19, CABO, Agricultural University of Wageningen and ISRIC, Wageningen, 1989.

estimated using results from seven General Circulation Model (GCM) experiments.[40] These model experiments all generate equilibrium changes, with the exception of the coupled ocean–atmosphere GCM transient experiment of the Max Planck Institute.[41] In summary, the method scales the standardized patterns of change in temperature and precipitation generated by the GCMs according to the global-mean temperature projections of STAGGER and/or IMAGE. Inter-model differences in these patterns are quantified and used to estimate a range of change patterns, as well as the GCM 'best guess'.[42]

The climate change impact sub-models are only briefly summarized here. The agricultural impact model consists of crop suitability models for grain maize and spring barley[43] and grapes.[44] These models calculate the potential suitability for the crops according to climatic constraints, but do not attempt to estimate the actual areas of production. For grain maize, spring barley and grass, relative yields and potential irrigation demand are estimated using the BIOPOT monthly water balance model.[45] The water balance model also enables change in runoff to be calculated and this index is used by CLIMAPS as an indicator of climate change impact on water resources. The vegetation sub-model estimates changes in the equilibrium distribution of natural vegetation types due to climate change, using the empirical climate–vegetation classification of Holdridge.[46] Fourteen biomes are separately identified for Europe. Changes in natural vegetation are also used to calculate the percentage of nature reserves in Europe which would be subject to stress under a changing climate. The database of the World Conservation Monitoring Centre (Cambridge, UK) was used to identify large (>1000 ha) nature reserves.

The energy impact sub-model estimates future changes in energy demand for domestic and commercial cooling and heating as a result of climate change. Two indices are used relating to degree days below 15.5°C (heating) and degree days above 18°C (cooling). These thresholds are based on work performed by the UK Energy Efficiency Office.[47] The effect of climate change on tourism is based on Hatch's comfort index.[48] The original index includes monthly minimum temperature, precipitation and sunshine data and is closely related to patterns of European beach holidays (the dominant tourist destination, primarily in summer). Changes in the original Hatch index were correlated with changes in the CLIMAPS baseline climatology to estimate the impact of climate change on seasonal tourism.[49] The need for de-icing agents in winter to maintain safety on roads has been related to climatic conditions and the thermal balance of the road surface.[50] A simplified model was incorporated in CLIMAPS to provide one indicator of the impact of climate change on the transport sector.[51]

Finally, CLIMAPS contains a European coastal impact sub-model. The global-mean sea level rise projections generated by STAGGER and IMAGE, together with a database of natural vertical land movements around Europe,[52] are used to make net sea level rise projections for the EC coastline. Spatial variations in sea level rise due to changes in ocean circulation are not considered. This sub-model also displays the vulnerability of the EC coastline to sea level rise using data on coastline attributes from the CORINE database.[53] This vulnerability index considers whether or not the coastline is currently protected, whether the shoreline is rocky, sandy or estuarine, and whether the coastline is currently accreting, eroding or stable.

[40]The seven GCM experiments include six equilibrium experiments performed by the Geophysical Fluid Dynamics Laboratory (1986); the Goddard Institute for Space Studies (1984); Oregon State University (1989); Lawrence Livermore National Laboratory (1990); and the UK Met Office (1987 and 1990). The transient experiment performed by the Max Planck Institute for Meteorology (1990, IPCC Scenario A, ie the BaU used here) was also used.

[41]U. Cubasch, K. Hasselmann, H. Höck, E. Maier-Reimer, U. Mikolajewicz, B.D. Santer and R. Sausen, 'Time-dependent greenhouse warming computations with a coupled ocean–atmosphere model', *Climate Dynamics*, Vol 8, 1992, pp 55–69.

[42]The method follows that originally suggested by B.D. Santer, T.M.L. Wigley, M.E. Schlesinger, and J.F.B. Mitchell, *Developing Climate Scenarios from Equilibrium GCM Results*, Max Planck Institute für Meteorologie, Report No 47, Hamburg, 1990; and further refined in M. Hulme, Z-C Zhao and T. Jiang, 'Recent and future climate change in East Asia' *International Journal of Climatology*, 1994 (in press).

[43]T.R. Carter, J.H. Porter and M.L. Parry, 'Climatic warming and crop potential in Europe: prospects and uncertainties', *Global Environmental Change*, Vol 1, 1991, pp 291–312. This paper discusses the grain maize calculations; the same approach was used in CLIMAPS for spring barley.

[44]G.J. Kenny and J. Shao, 'An assessment of a latitude-temperature index for predicting climate suitability for grapes in Europe', *Journal of Horticultural Science*, Vol 67, 1992, pp 239–246.

[45]This model is based on the monthly water balance approach documented by the Food and Agricultural Organization (eg see *Manual and Guidelines for Cropwat*, FAO, Rome, 1991); and more fully documented in D.J. Briggs, *Biomass Potential of the European Community: A Report of a Case Study to Develop a Bio-Climatic Method of Assessing the Potential for Biomass Production*, University of Sheffield, Sheffield, 1983. A further application is described in D.J. Briggs and A.S. Wickramasinghe, 'Modelling forest growth–environment relationships: theory and applications', *Applied Geography*, Vol 10, 1990, pp 187–204. This model calculates potential evapotranspiration using the Thornthwaite method which used temperature and latitude.

[46]The original Holdridge scheme is described in L.R. Holdridge, *Life Zone Ecology*, Tropical Science Center, San José. A comparison of different global vegetation schemes can be found in R.A. Monserud and R. Leemans, 'Comparing global vegetation maps with the Kappa statistic', *Ecological Modelling*, Vol 62, 1992, pp 275–293.

[47]UK Energy Efficiency Office, *Degree Days*, Fuel Efficiency Report No 7, UK

continued on page 108

Deficiencies and limitations of ESCAPE

Since ESCAPE is a set of linked models, validation of the individual models is critical. All the sub-models described here have been extensively tested during the development of ESCAPE. Most are based on well known approaches published in the scientific literature. Individual models can be, and are being, improved, refined and updated. The results presented in this paper should therefore be considered as illustrative and treated with proper caution. Some of the major limitations of the four modules are listed below.

End-use Energy model. (a) The estimation of the income and price elasticities of energy demand is hampered by the lack of disaggregated global data. The end-use model requires an enormous amount of reliable data which cannot easily be checked for consistency.

(b) The model contains an extremely simple supply model which neglects any coupling between demand-related trends and response from the energy supply industry.

(c) The end-use model is not connected to the energy demand impact model in CLIMAPS.

Land-Use model. (a) The present model is a 'book-keeping system' rather than a dynamic model, in the sense that most non-linear causalities are excluded. The problem, however, is that the basic mechanisms which form the driving forces behind land use change differ from region to region.

(b) GNP-demand functions attempt to specify the relationships between per capita national income and consumption levels. These relationships have been used in ESCAPE by aggregating agricultural products in food and feed,[54] which is a large oversimplification of reality. While this aggregation appears to be adequate at the global level, it is not necessarily satisfactory for regions or countries.

(c) Developments in trade patterns are not included. A desired development can be evaluated for individual regions by using self-sufficiency ratios, but this is a rather static approach.

(d) The interrelations between the land use and end-use energy models which need to be improved are the demand and production of firewood, the demand for ethanol, and the production of crops used for biofuel production.

IMAGE and STAGGER. (a) The photochemical tropospheric modules of IMAGE and STAGGER are an oversimplification of complex reality. These modules should be further improved and validated against one-, two-, and three-dimensional photochemical models.

(b) IMAGE and STAGGER do not include all known feedback processes, such as the negative forcing effect of sulphate (SO_2-derived) aerosols and negative feedback due to stratospheric ozone depletion.

CLIMAPS. (a) The methodology used to produce regional climate changes assumes that the spatial pattern of the enhanced greenhouse signal remains constant with time. This is somewhat uncertain: more results from transient coupled ocean–atmosphere GCM experiments would be useful to include in this respect.

(b) The composite GCM scenario approach used by CLIMAPS potentially distorts the internal consistency of results from individual GCM experiments.

continued from page 107
Department of Energy, London, 1989. Further analysis of the climate sensitivity of heating and cooling requirements in buildings can be found in M. Hulme, P. Haves and B. Boardman, 'Impacts of climate change', in *Proceedings of the Workshop on Innovative Cooling*, sponsored by the International Energy Agency – Future Buildings Forum, Birmingham, 12–14 May 1992.

48 D. Hatch, *Weather Around the World: Standardized Climatic Data for 500 Places, Tabulated, Ranked and Mapped*, Amsterdam, 1984.

49 See Climate Research Unit, *op cit*, Ref 3, for further details.

50 J.E. Thornes and J. Shao, 'Objective methods for improving the operational performance of a road-ice prediction model using interpolated meso-scale output as a template for correcting systematic error', *Meteorological Magazine*, Vol 142, 1992, pp 197–204.

51 *Op cit*, Ref 49.

52 J. Shennan, 'Holocene crustal movements and sea level changes in Great Britain', *Journal of Quaternary Research*, Vol 4, 1989, pp 77–90.

53 D.J. Briggs and D. Martin, 'CORINE: an environmental information system for the European Community', *European Environment*, Vol 2, 1988, pp 29–34.

54 *Food Balance Sheets (1962–1988)*, FAO Data Bank, Rome, 1991.

(c) The impact models are simplified. More complex models exist that incorporate daily weather effects, micro-environments, pest interactions and elevated CO_2 concentrations. Some of these factors – not considered by ESCAPE – could substantially alter the impacts discussed below.

(d) The climate change impacts for the various economic and environment sectors are not translated into damage costs. This translation has, however, been attempted outside the ESCAPE modelling framework.[55]

(e) Social, economic and policy changes are not included in CLIMAPS, but would greatly affect the evolution of actual land use, the impact of climate change and the incremental responses to climate change.

ESCAPE integrates scenario results from the linked models. As an integrated framework, it is also subject to limitations.[56] (a) The framework does not include the world economy and trade. Thus, there are no interactions between regions to estimate changes in prices, investment, comparative advantage, trade and demand. This has major implications for modelled emissions, land use and impacts.

(b) Feedbacks are not constructed between models. For example, the impact of climate change on space heating demand does not alter the end-user emissions scenarios.

(c) Uncertainty in each module is not standardized or passed to each subsequent module. The final results may therefore give an artificial estimate of confidence, although the analyst may undertake repeated experiments to estimate a wide range of results. The framework does not readily encourage the evaluation of risk or optimum responses.

(d) The choice of individual models reflects what is readily available (and to a large extent published in the scientific literature) and does not necessarily cover all the sensitive sectors, the critical linkages between sectors (eg water resource conflicts), or new understanding of the science.

(e) The variability of spatial coverage and temporal scale limit the articulation of inter- and intra-regional effects.

Many of these limitations are being addressed in subsequent research and in the next generation of integrated models being developed for the assessment of climate change.[57]

Definitions of scenarios and sustainability

Emissions scenarios

In this paper we use two reference scenarios which have been developed for, and used by, the 1990 Intergovernmental Panel on Climate Change report:[58] the Business-as-Usual scenario in which current energy-use trends continue and a considerable growth in the use of fossil fuels is forecast, and the Accelerated Policies scenario which involves application of the best available technologies, and assumes strong environmental policies, stricter international protocols and environmental standards. These scenarios are denoted as BaU-90 and AP-90. The suffix '90' is necessary since in 1992 the IPCC updated their 1990 scenarios. These revised 1992 scenarios reflect continuing research and the latest policy initiatives to reduce the emissions of the greenhouse gases. Since the development of ESCAPE proceeded between 1990 and 1992 and

[55] *Op cit*, Ref 4.

[56] For additional insight on integrated modelling see B.I. Spector, ed, 'Systems support for international negotiation: implications and application', *Theory and Decision*, Vol 34, May 1993, Special Issue.

[57] A major revision of the IMAGE model has led to a new version, IMAGE 2.0, described in J. Alcamo, M. Kreileman, G. Krol and G. Zuidema, 'Modelling the global society–biosphere–climate system: Part I: model description and testing', *Water, Air and Soil Pollution*, 1994 (in press). A forthcoming workshop proceedings provides a state-of-the-art summary of integrated climate models as of October 1993: N. Nakicenovic and F. Töth, ed, *Integrative Assessment of Mitigation, Impacts and Adaptation to Climate Change*, IIASA Collaborative Paper Series, Laxenburg, 1994 (in press).

[58] *Op cit*, Ref 32.

was largely tied to the science reported by the IPCC in 1990, we continue to use the original 1990 IPCC emissions scenarios. The detailed background of the 1990 IPCC scenarios are discussed elsewhere.[59] Here, we describe only some of the basic assumptions upon which the scenarios are based.

Each scenario is based on a set of assumptions for key factors influencing the future changes in emissions of greenhouse gases. These factors include population growth, economic growth, the costs of technology used to convert energy from one form to another, end-use efficiency, deforestation rates, halocarbon emissions and agricultural emissions. In the scenarios, the reduction of energy intensity is the most important method of reducing CO_2 emissions. The BaU-90 scenario assumes that no steps are taken to limit greenhouse gas emissions. Energy use and the clearing of tropical forests continue to increase and fossil fuels, in particular coal, remain the world's primary energy source. The Montreal Protocol is not strengthened (now known to be unrealistic) and participation of the developing countries is assumed to be only 85%. In the AP-90 scenario the development and penetration of renewable energy sources and nuclear energy are encouraged. This results in a decrease of fossil CO_2-emissions after 2000, while the fossil-related emissions at the end of the next century are about 50% of those in 1985. In this scenario, deforestation is stopped around the turn of the next century and there is a net increase in forests through large-scale reforestation programmes. To implement a change from the premises of the BaU-90 scenario to the AP-90 scenario, an average reduction in energy intensity of 1% to 2% annually would be required in the developing countries and 2% to 3.5% in the industrialized countries. Furthermore, a reduction of the carbon intensity of the fuel supply by more than 1.5% to 2% per year would be needed.

In order to illustrate the effect of any European climate policy on the global emissions of greenhouse gases, we consider three additional scenarios in which the energy-related emissions have been varied:

- CTAX:for this scenario a global ecotax (consisting of a carbon tax as proposed by the EC) is implemented, increasing from 0 in 1990 to 65 ECU/ton C by 2000 (equivalent to about $10 per barrel of oil). In the BaU-90 scenario the oil price (per barrel) is expected to rise to $21 by 2000. By 2000 the carbon tax of $10 therefore amounts to approximately 50% of the expected price of oil.
- EC-AP:the second scenario which is considered assumes an implementation of the AP-90 scenario within the EC, while the rest of the world follows the BaU-90 scenario.
- NON-EC-AP: to demonstrate the relative contribution of Europe to climate change, the third scenario assumes that the EC will adhere to the BaU-90 scenario, while the rest of the world will follow the AP-90 scenario.

Sustainable targets of climate change

Attempts have been made to define thresholds concerning both the rate and eventual magnitude of climate change which, if not exceeded, will ensure a reasonable chance that the impacts of future climate change can be sustainably adapted to. The scientific basis for these thresholds remains exceedingly weak and the concept of global climate change targets to ensure sustainability needs much further development. This must be guided by the relationships between global and regional climate

[59]Intergovernmental Panel on Climate Change, *Climate Change: The IPCC Response Strategies*, WMO/UNEP, Geneva, 1991.

changes and by the evaluation of differential vulnerability. Even when future global-mean temperature and sea level changes remain below the above thresholds, smaller or larger changes in future regional climate and sea level are likely. It is these regional rates and magnitudes of change which will actually determine whether sustainable adaptation to climate change can be achieved. For want of more scientifically based thresholds, however, we use the rates and absolute values of global-mean changes defined below as reference standards by which the policy scenarios defined earlier in this paper can be evaluated.

To allow ecosystems to adapt to changes in temperature and precipitation, a maximum tolerable rate of global-mean temperature change of 0.1°C per decade has been advocated by the UNEP/WMO Advisory Group on Greenhouse Gases (AGGG).[60] This limiting value of 0.1°C per decade is a global-mean value. On a regional scale, however, faster or slower changes in climate associated with this global rate of change are likely to occur. In a similar way, provisional limits to the rate of sea level rise which would prevent significant damage to coastal areas, wetlands and coral reefs can be set. A 2 cm to 5 cm rise in global-mean sea level per decade has been recommended by the AGGG.

Limits to the maximum tolerable absolute global-mean temperature and sea level rise have also been formulated. Based on analyses from temperature changes and ecosystem reconstructions in the past, a global-mean temperature increase of greater than 2.0°C relative to the pre-industrial climate is considered to present major difficulties for sustainable adaptation. A global-mean temperature change of more than 2°C can be viewed as an upper limit beyond which the risk of considerable damage to ecosystems and sensitive coastal areas, and of unexpected sudden changes in the climate system, is expected to increase rapidly. For global-mean sea level rise, the maximum tolerable absolute rise is estimated by the AGGG at between 20 cm to 50 cm above the 1990 sea level.

Results[61]

The BaU-90 scenario

Under the BaU-90 scenario anthropogenic emissions of CO_2 rise from 7.9 GtC in 1990 to 21.1 GtC by 2100. A doubling of the atmospheric CO_2-concentration relative to the pre-industrial value (280 ppmv) occurs by 2075, although the CO_2-equivalent doubling occurs substantially earlier, by about 2030. The global-mean surface temperature change associated with this reference scenario is shown in Figure 3. The range around this projection results from applying the low (1.5°C) and high (4.5°C) climate sensitivities defined by the IPCC.[62] The 'best guess' projection assumes a climate sensitivity of 2.5°C and results in a global-mean warming by 2050 of 1.51°C (0.25°C per decade) relative to 1990.

The impacts of such a climate change are dependent on the rate of regional climate change, on the change in the regional climate pattern, and on the magnitude of sea level rise. The mean winter (December, January, February; DJF) and summer (June, July, August; JJA) temperature changes over Europe resulting from the BaU-90 scenario are shown in Figures 4 and 5 for the year 2050. These changes represent the 'best guess' pattern of regional climate change generated by

[60]J. Rijsberman and R. Swart, eds, *Targets and Indicators of Climatic Change*, Report of Working Group II of the Advisory Group on Greenhouse Gases, Stockholm Environment Institute, Stockholm, 1990. These estimates rely on earlier work by F. Krause, W. Bach and J. Koomey, *Energy Policy in the Greenhouse; Volume 1: From Warming Fate to Warming Limit: Benchmarks for a Global Climate Convention*, International Project for Sustainable Energy Paths, El Cerrito, 1989; and J. Jäger, *Developing Policies for Responding to Climatic Change*, Summary of the Discussions and Recommendations of the Workshops held in Villach (28 September – 2 October 1987) and Bellagio (9–13 November 1987), WMO/UNEP, WMO/TD-No 25, Geneva, 1988.

[61]The maps which illustrate this section were produced as direct screen dumps from the ESCAPE model running on a desktop 486-PC and using a Hewlett-Packard PaintJet printer.

[62]W.L. Gates, J.F.B. Mitchell, G.J. Boer, U. Cubasch and V.P. Meleshko, 'Climate modelling, climate prediction and model validation', in J.T. Houghton, B.A. Callander and S.K. Varney, eds, *Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment*, Cambridge University Press, Cambridge, 1992, pp 97–134.

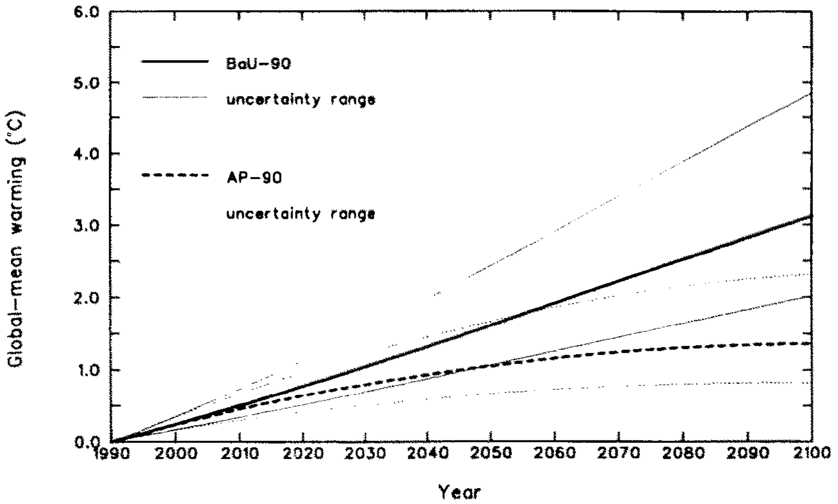

Figure 3. Global-mean temperature projections from 1990 to 2100 for the reference scenario BaU-90 and for the accelerated policies scenario AP-90.

The uncertainty ranges around the 'best guess' projections result from using the high and low climate sensitivities in STAGGER.

ESCAPE and indicate that the winter temperature increase will be greater than the annual global-mean change (1.85°C for the EC compared to 1.51°C for the annual global-mean). The mean summer temperature change over the EC will be much closer to the global-mean change. The extent of uncertainty in these regional temperature change patterns (which reflects the uncertainty with which GCMs predict regional climate change) can be illustrated by comparing the 'high' and 'low' estimates[63] generated by ESCAPE. This range is presented in Figures 6 and 7, where the EC-mean winter temperature change associated with a global-mean warming of 1.51°C is estimated to lie between 1.31° and 2.39°C.

Regional precipitation changes over Europe are generated by

[63]CLIMAPS generates three sets of climate change patterns for any given magnitude of global warming. These patterns are referred to as the 'low', 'best guess' and 'high' and derive from the range of results from the seven GCM experiments used in ESCAPE. The 'low' and the 'high' patterns roughly correspond to the 90% confidence interval around the 'best guess'. See Hulme *et al*, *op cit*, Ref 42, for further details.

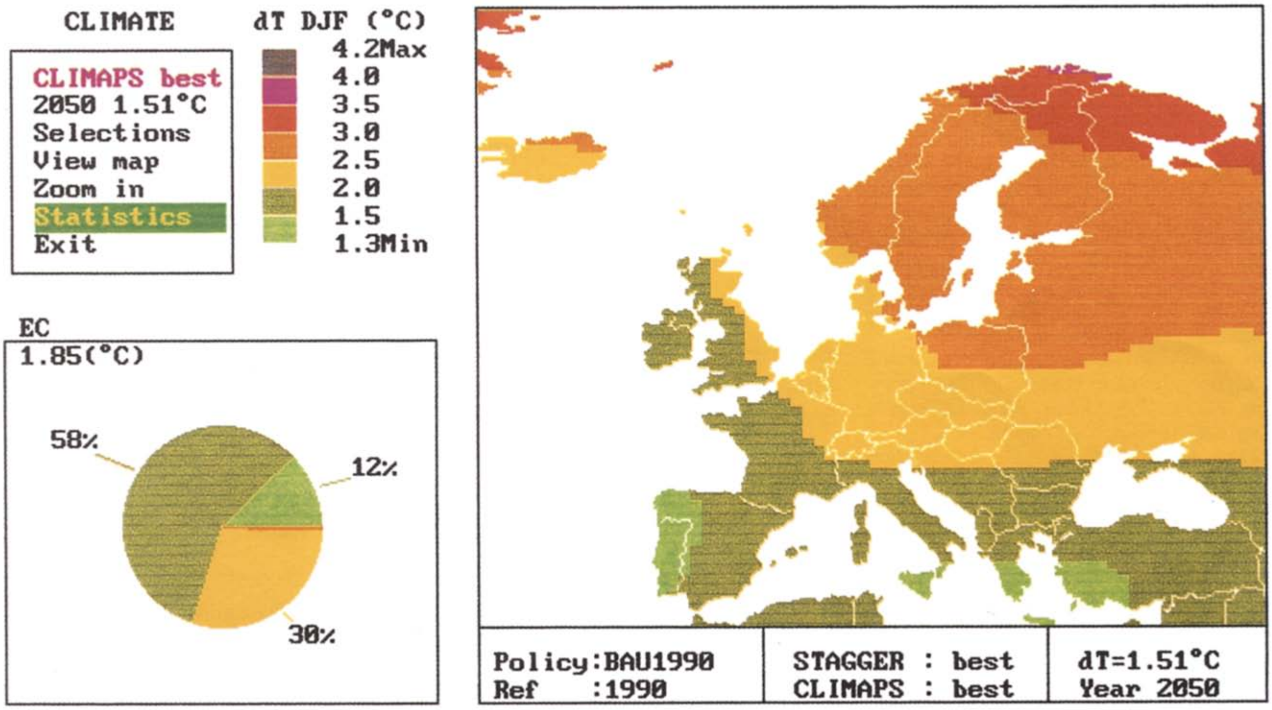

Figure 4. Regional change in mean seasonal temperature by 2050 relative to 1990 under the BaU-90 scenario for the winter (DJF) season.

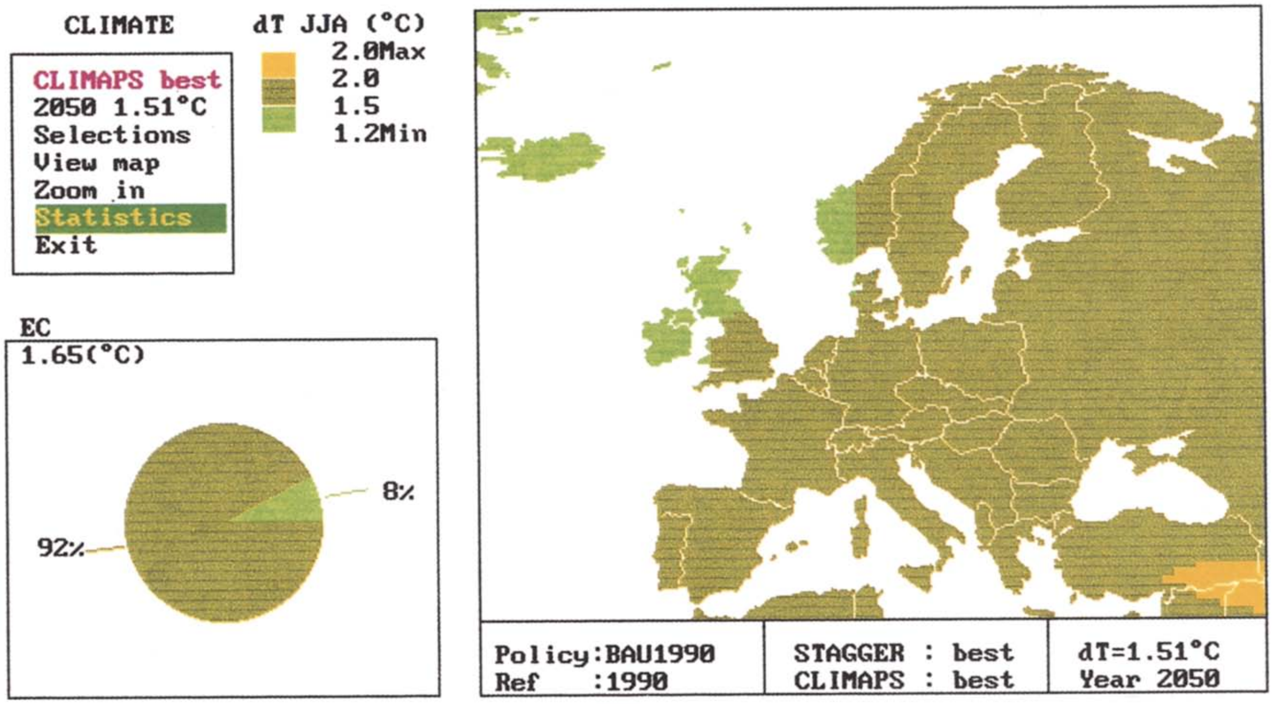

Figure 5. Regional change in mean seasonal temperature by 2050 relative to 1990 under the BaU-90 scenario for the summer (JJA) season.

ESCAPE in a similar way, although presented as percentage changes relative to 1990. The 'best guess' mean winter and summer changes in precipitation by 2050 under the BaU-90 scenario are shown in Figures 8 and 9 respectively. The uncertainty in these patterns is considerably

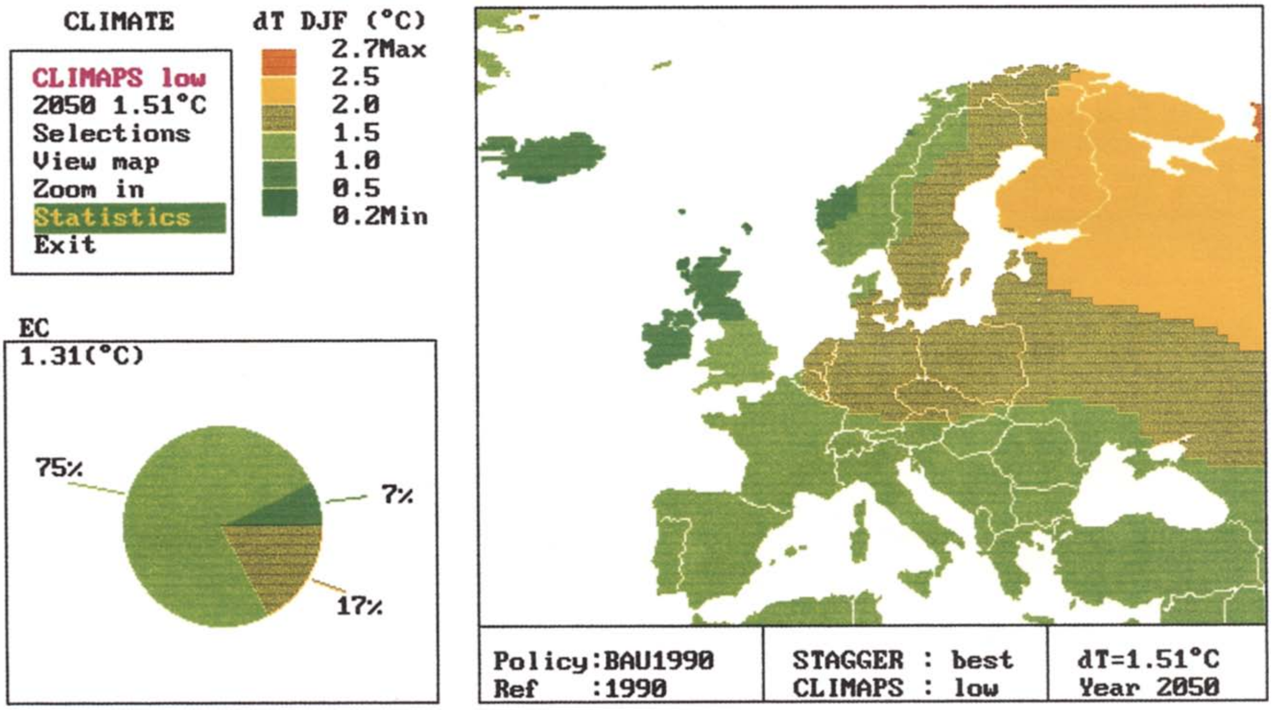

Figure 6. Regional change in mean winter (DJF) temperature by 2050 relative to 1990 under the BaU-90 scenario assuming the 'low' end of the regional climate change range.

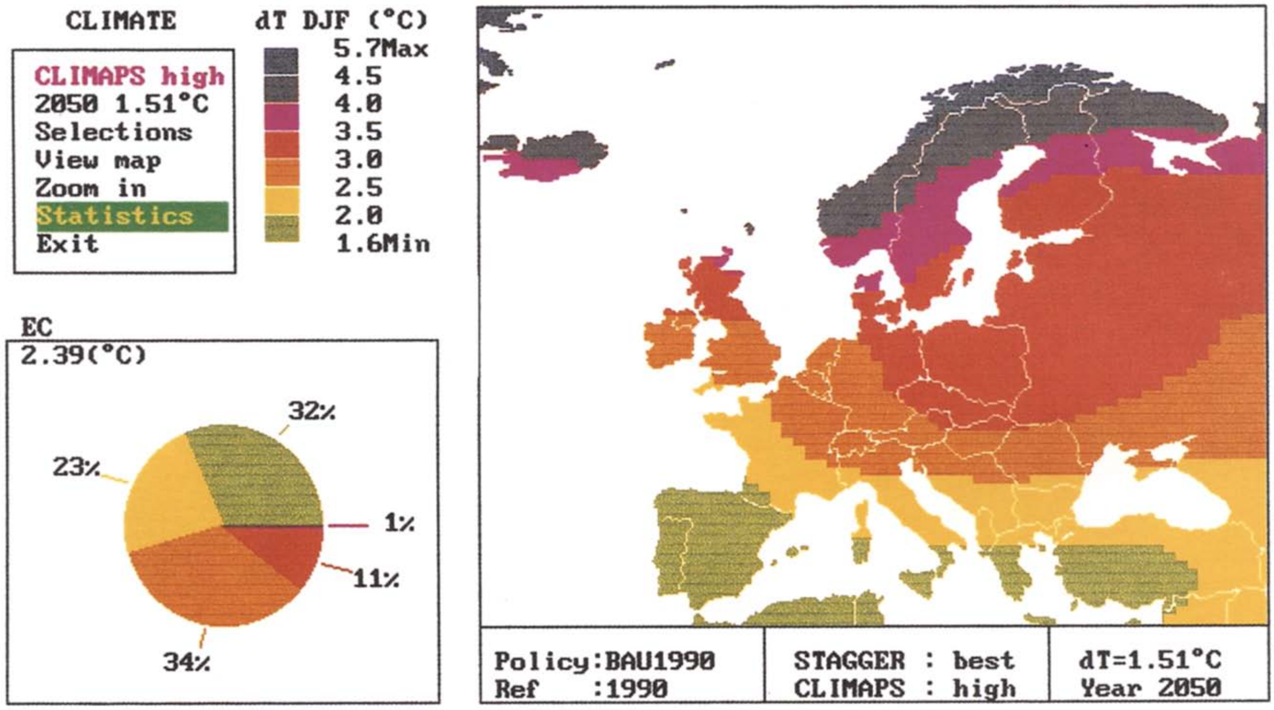

Figure 7. Regional change in mean winter (DJF) temperature by 2050 relative to 1990 under the BaU-90 scenario assuming the 'high' end of the regional climate change range.

greater than in the case of temperature. The EC-mean summer precipitation change by 2050 may lie between a decrease of 13% (Figure 10) and an increase of 5% (Figure 11), although in either case there remains a general contrast between southern (relatively drier) and northern (relatively wetter) Europe.

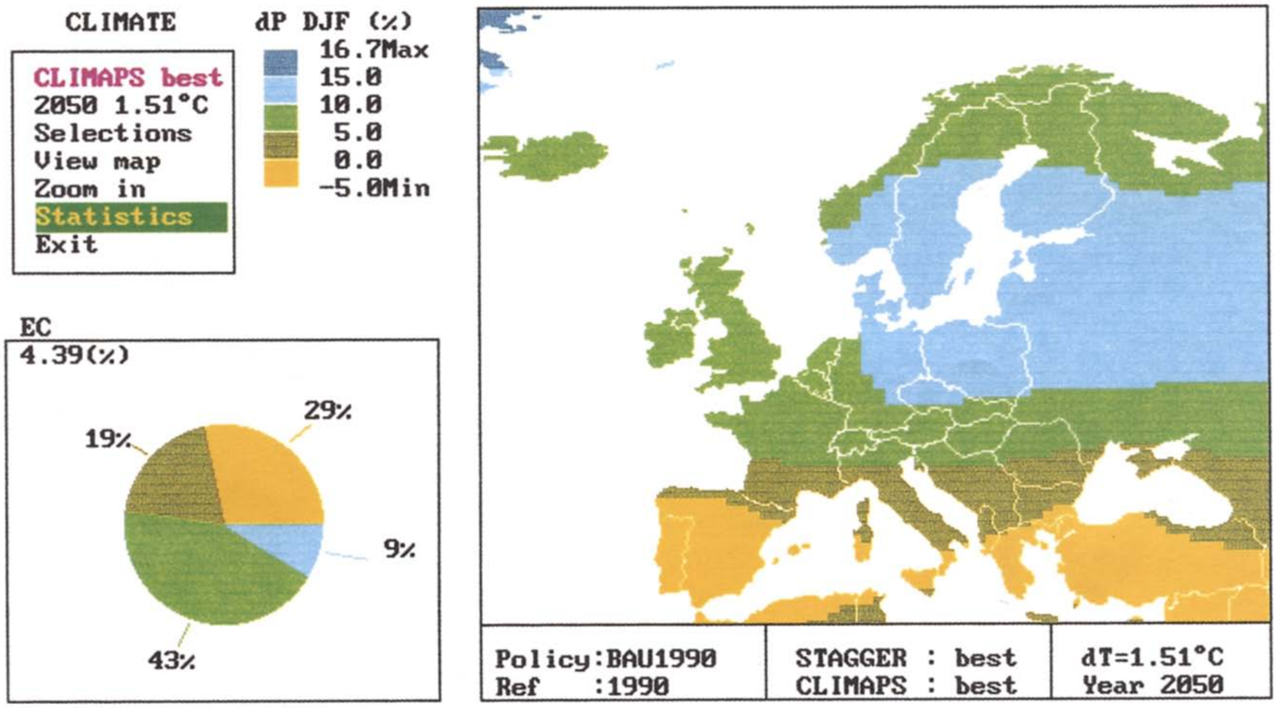

Figure 8. Regional change in mean seasonal precipitation by 2050 relative to 1990 under the BaU-90 scenario for the winter (DJF) season.

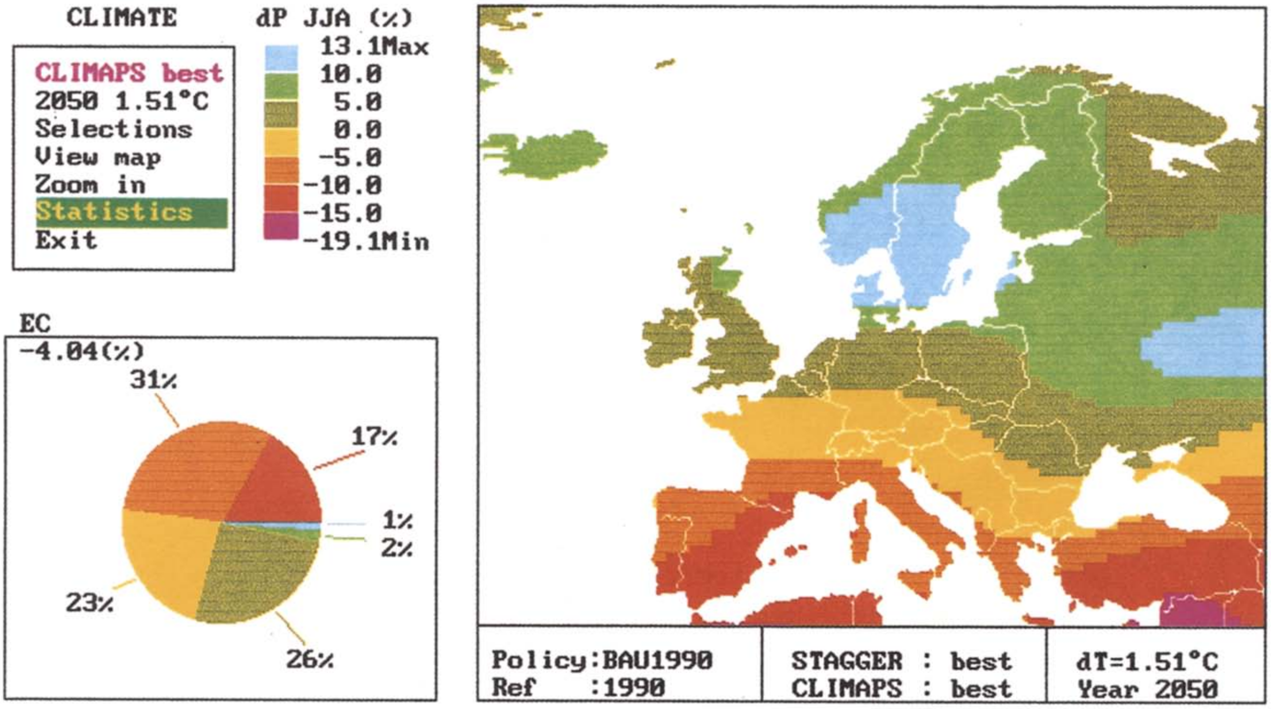

Figure 9. Regional change in mean seasonal precipitation by 2050 relative to 1990 under the BaU-90 scenario for the summer (JJA) season.

Agriculture in Europe will be affected by climate change through changes in crop yields, changes in the areas suitable for different types of crop, and (to a lesser extent) through the reduction in potential agricultural areas as a result of sea level rise. One agricultural impact

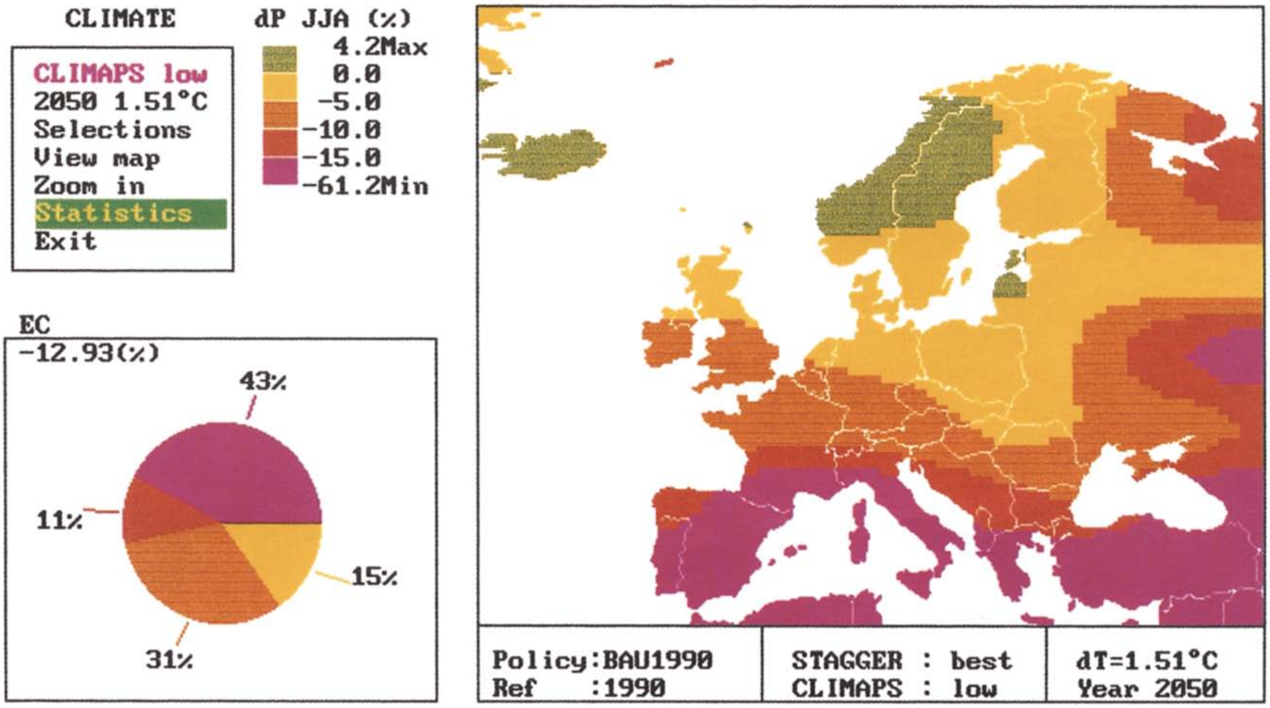

Figure 10. Regional change in mean summer (JJA) precipitation by 2050 relative to 1990 under the BaU-90 scenario assuming the 'low' end of the regional climate change range.

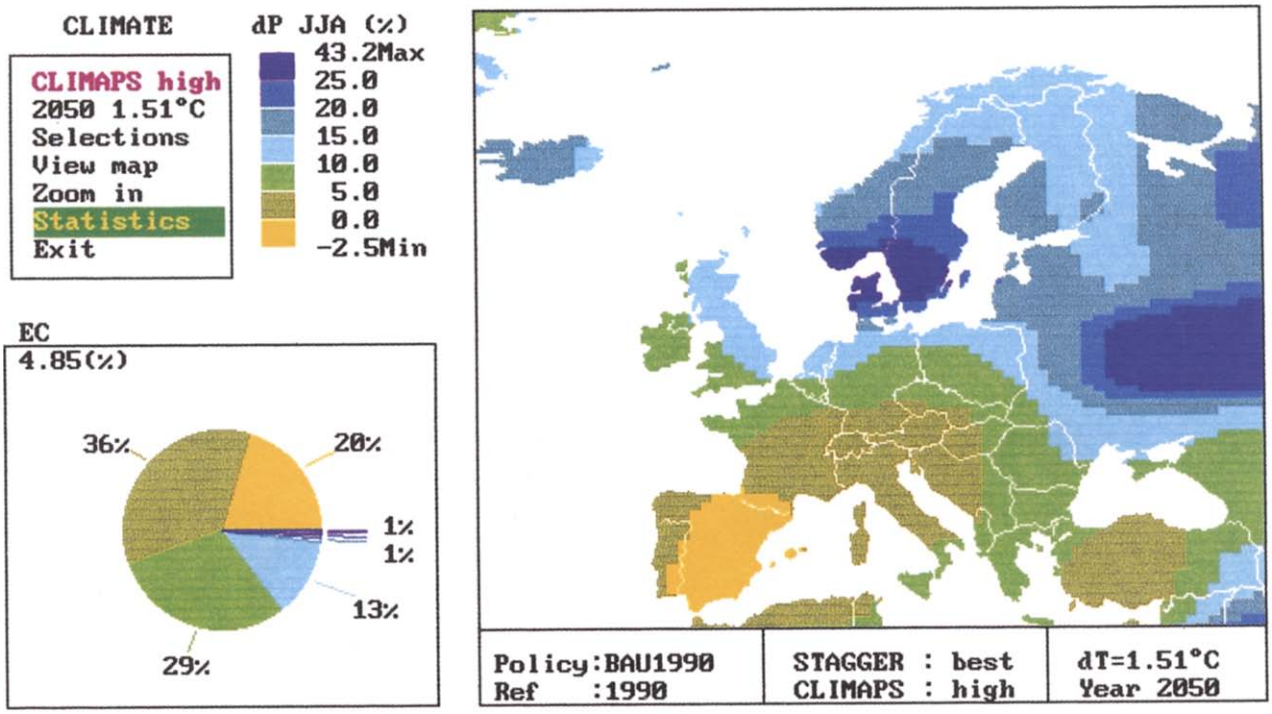

Figure 11. Regional change in mean summer (JJA) precipitation by 2050 relative to 1990 under the BaU-90 scenario assuming the 'high' end of the regional climate change range.

indicator calculated by ESCAPE, the relative change in potential yield for grain maize, is shown in Figure 12. There are clear regional variations in the impact of climate change on grain maize, with 7% of the EC experiencing decreased yields (mostly Spain, Portugal and Italy)

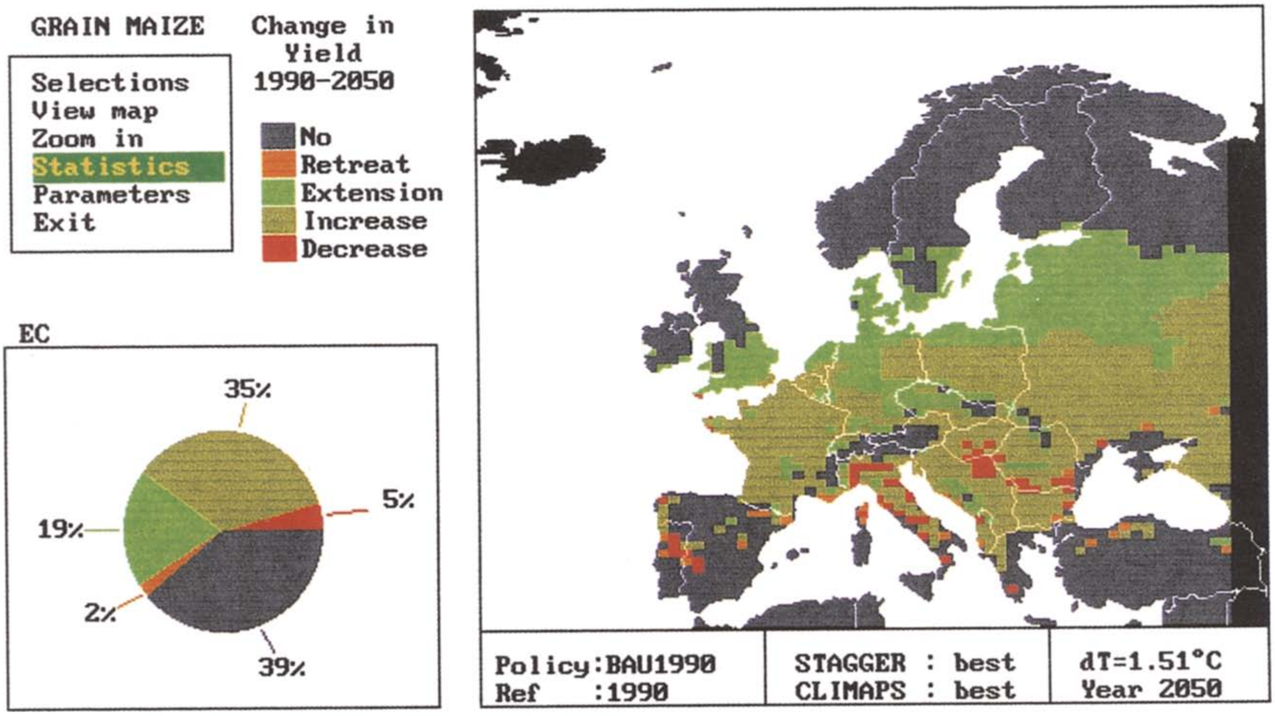

Figure 12. Relative change in potential grain maize yield by 2050 under the BaU-90 scenario using default parameters for the grain maize model.

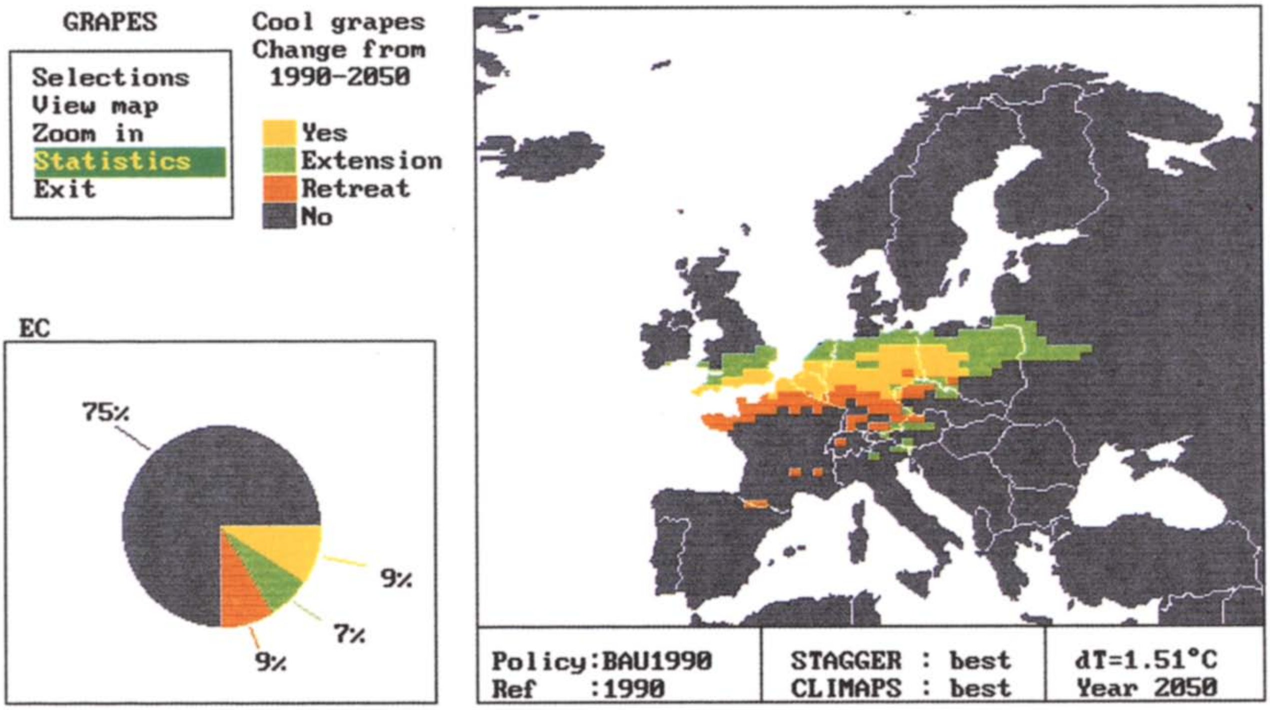

Figure 13. Relative change in potential suitability for cold-climate grape cultivation by 2050 under the BaU-90 scenario relative to 1990.

and 54% of the EC increased yields (mostly France, Germany and Belgium).[64] Figure 13 provides an illustration of the impact of climate change on the areas potentially suitable for cultivation of cold-climate grapes. The areas potentially suitable for cultivation are strongly dependent on latitude, with a 1.5°C global-mean warming by 2050 leading to a 100–200 km northward shift in potential cultivation zones.

Changes in water availability arising from climate change will have major implications for agriculture, industry and public utilities. A useful indicator of changing water availability is surface runoff. The runoff indicator in ESCAPE estimates the amount of surplus water at the surface of the soil after the evapotranspiration demand and soil moisture deficit have been met. Figure 14 displays the change in mean annual runoff by 2050 under the BaU-90 scenario, expressed as a percentage change from the baseline value in 1990. While it is quite clear that there are large local differences in the sensitivity of surface water runoff to climate change, there is also a more general spatial variation between northern (eg the UK and Ireland; general increase in availability) and southern (eg Portugal, Italy, Greece; general decrease) EC countries. Overall, 73% of the EC experiences a decrease in surface water runoff by 2050 under the BaU-90 scenario.

Climate change will affect the tourism industry in different regions of the EC in a variety of ways. ESCAPE calculates a comfort index, varying between 0 and 100, as an indicator of areas suitable for sun-related tourism. The indicator shows the areas falling above or below a given comfort threshold in each month and can be used to estimate the changing attractiveness of regions for sun-related tourism. Figure 15 displays the change by 2050 in the duration of the tourist season, where the tourist season is defined as the number of months above a specified comfort index value, in this case 70. In 18% of the EC

[64]39% of the EC remains climatically unsuitable for grain maize production in 2050.

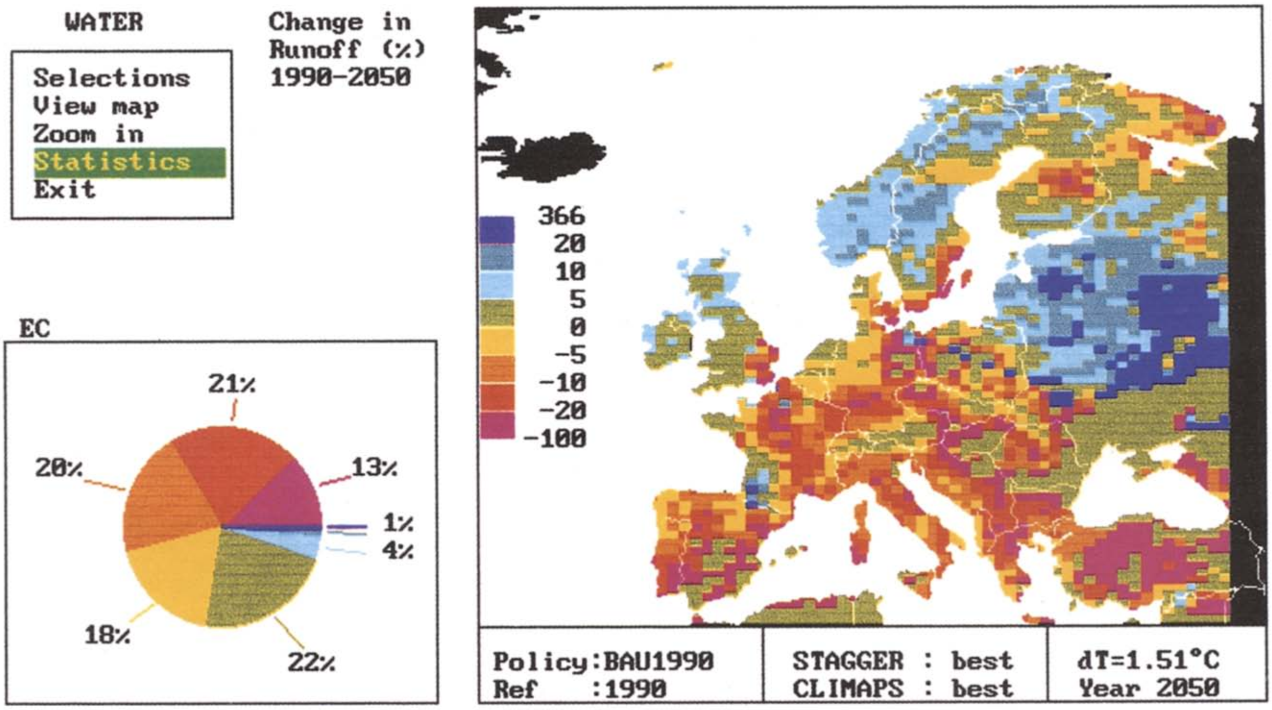

Figure 14. Percentage change in mean annual surface runoff by 2050 relative to 1990 under the BaU scenario.

the tourist season lengthens (74% of the EC remains unchanged), with central France and northern Spain particularly benefiting. Some areas of the southern EC countries, particularly parts of Italy and Greece, experience decreases in the length of the tourist season. For any given

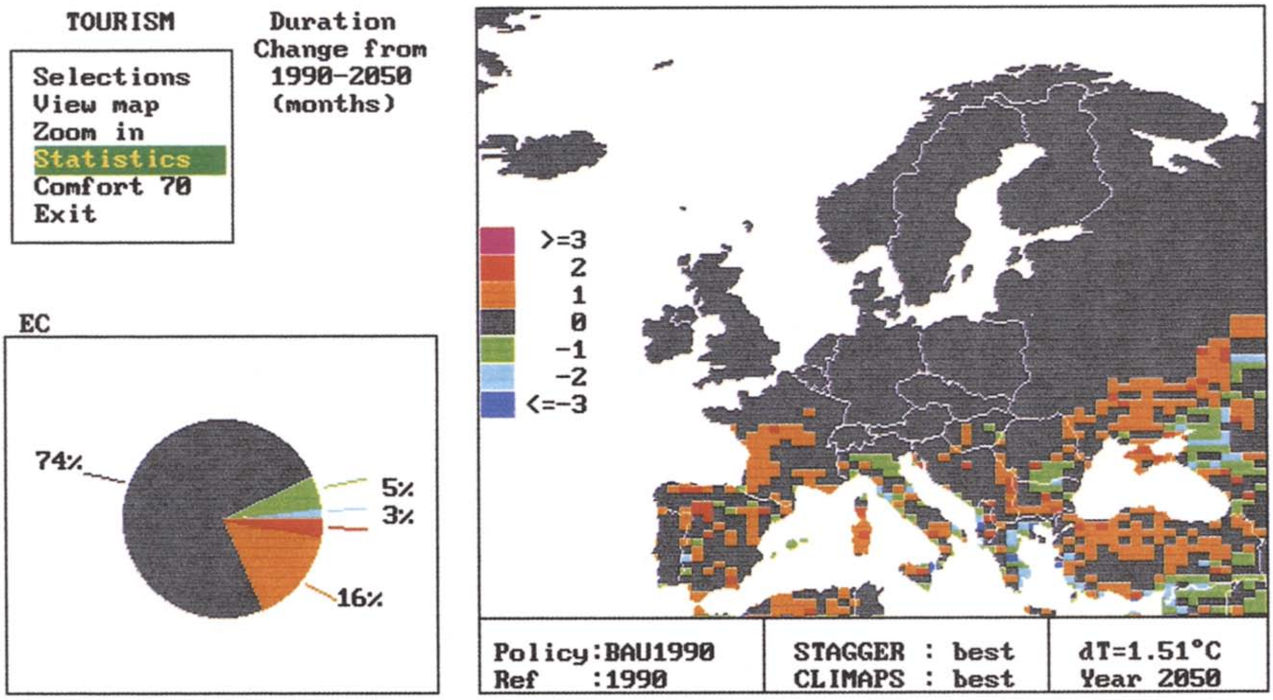

Figure 15. Percentage change in duration of the 'tourist season' in months by 2050 relative to 1990 under the BaU scenario

The tourist season is defined using a comfort index threshold of 70.

Table 1. Change over time in the percentage of nature reserves in each EC country which are subject to 'ecosystem stress' under the BaU-90 scenario.

Year	1990	2000	2025	2050	2075	2100
Global temperature (°C)	0.00	0.22	0.83	1.51	2.25	2.98
Belgium	0	0	0	0	1	1
Denmark	0	0	0	0	0	8
France	0	1	8	24	57	66
Germany	0	0	0	1	6	15
Greece	0	4	11	26	49	71
Ireland	0	0	0	0	17	33
Italy	0	5	15	29	55	77
Luxembourg	0	0	0	0	0	0
Netherlands	0	0	0	0	0	0
Portugal	0	0	75	83	84	84
Spain	0	2	11	27	41	46
UK	0	0	3	9	18	70
EC	0	2	10	21	40	55

location, the optimum season for tourism may shift through the year or split toward the current 'shoulders' of the main tourist season. This decline in suitability of southern Europe for tourism arises because summer temperatures become too uncomfortable for 'beach tourism'.

The current distribution of natural ecosystems is broadly correlated to various climate parameters. ESCAPE models the effects of climate change on the large-scale equilibrium distribution of 14 life-zones (or biomes) in Europe. It has been estimated that ecosystems can adapt to changing climate by shifting location at the rate of about 50 km (or about one grid cell in ESCAPE) per century. For a grid cell to change its natural biome type is therefore a reasonable indication of ecosystem stress and ESCAPE uses this method to calculate the impact of climate change on nature reserves. Table 1 shows for each of the EC countries the percentage of currently designated nature reserves which over time experience a change in natural biome as a result of the BaU-90 scenario. Again, there are large differences from country to country with more than 65% of nature reserves in France, Greece, Italy, Portugal and the UK experiencing a biome change by 2100.

A major impact of climate change on the environment and economy of Europe is likely to be through sea level rise. Sea level rise will cause damage to coastal areas through increased erosion, increased flooding risk and, in some areas, through permanent inundation. Figure 16 shows the global-mean sea level rise projected by ESCAPE for the BaU-90 scenario. The information shown here is comparable to that shown for global-mean temperature in Figure 3. The rate of global-mean sea level rise for BaU-90 is estimated to be about 6 cm per decade (with a range of 3 cm to 10 cm), and the total sea level rise is expected to reach 30 cm by 2050, increasing to 60 cm by 2100. The uncertainty around these sea level projections is relatively larger than for global-mean temperature, since not only is there uncertainty over the magnitude of the warming which causes ocean water to expand, there is additional uncertainty in how land glaciers and polar ice sheets will respond to warming.

In ESCAPE, the net mean sea level change for the EC coastline is determined as the sum of the global-mean change plus the natural vertical land movement which would occur in the future given an extension of current trends. In order to estimate potential damage of future net sea level rise on the EC coastline, details of the character of

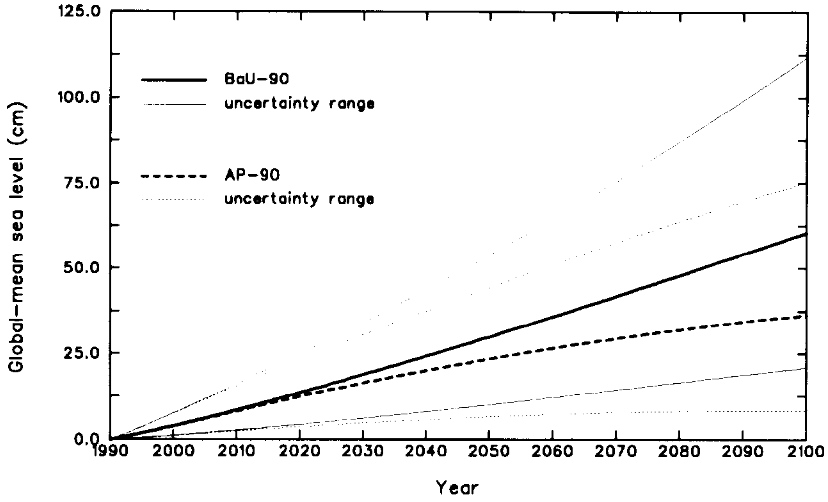

Figure 16. Global-mean sea level projections from 1990 to 2100 for the reference scenario BaU-90 and for the accelerated policies scenario AP-90.

The uncertainty ranges around the 'best guess' projections result from using the high and low model parameters in STAGGER.

the coastline are also needed. For each of the 431 0.5° latitude by 1.0° longitude coastal cells of the EC, ESCAPE calculates an index of coastal vulnerability varying from very low (1) to very high (5). This index combines information on the nature of the shoreline (rocky, sandy, etc), whether it is currently eroding or accreting, and whether it is currently protected or 'natural'. Figure 17 displays this index for the EC coastline and Figure 18 a table presenting a detailed assessment of the UK coastline. The countries considered by ESCAPE to be most vulnerable to sea level rise are Denmark, France and Italy. Although individual cells around the UK are highly vulnerable (eg Suffolk and parts of the south coast), the overall vulnerability of the UK is 'low'. Of the 15 700 km of the UK coastline, over 40% falls in the 'very low' vulnerability category and only 4% in the 'very high' category.

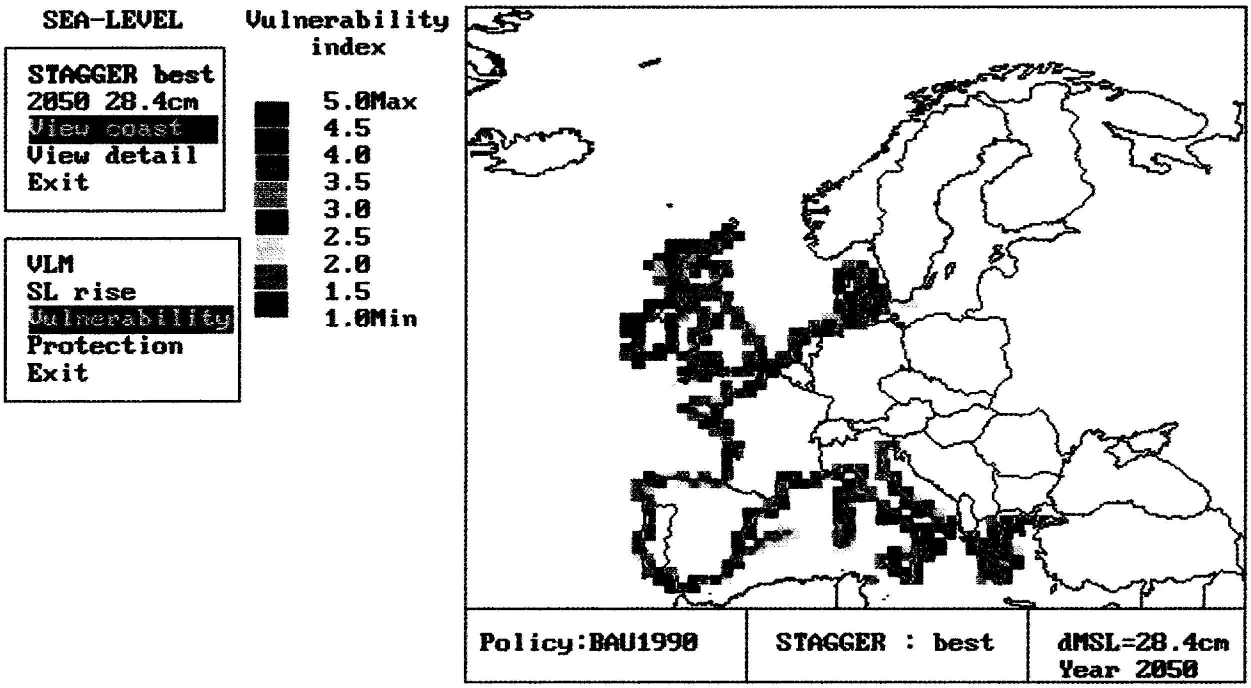

Figure 17. An index of vulnerability to sea level rise for the EC coastline.

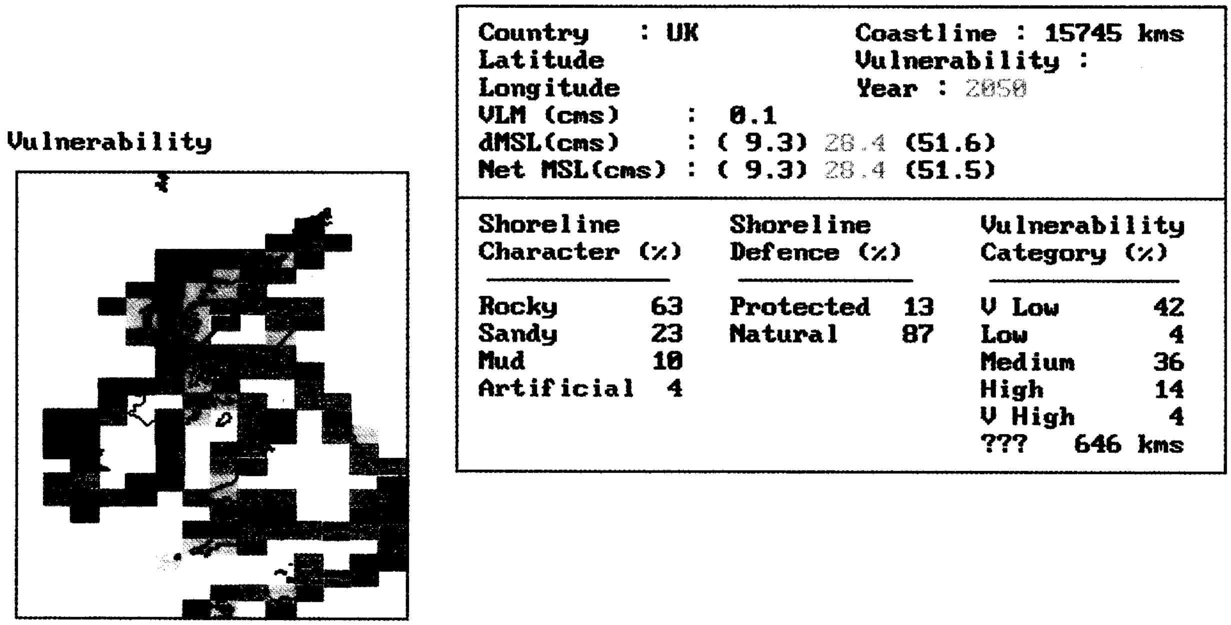

Figure 18. A summary of coastline characteristics for the UK.

For the UK as a whole, vertical land movements average to nearly zero, although there are large differences between northern Britain (rising) and southern Britain(sinking). The changes in mean sea level shown in parentheses indicate the low and high estimates made by STAGGER around the best guess by 2050 of 28.4cm under BaU-90.

Alternative scenarios

So far we have only considered the consequences of the BaU-90 scenario. What are the implications for global climate and regional climate change impacts in Europe of our four alternative scenarios? Table 2 shows the CO_2 emissions from industrial sources for the five scenarios for the world and for Europe by 2050 and 2100. These CO_2 emissions are converted into atmospheric CO_2 concentration projections and, together with the radiative forcing from the other greenhouse gases, converted into global-mean temperature projections (Figure 19).

Were the EC alone to follow the Accelerated Policies pathway, while the Rest of the World continued with the BaU-90 pathway (scenario EC-AP), the resulting CO_2 concentrations by 2100 would be only about 6% lower than the reference case (BaU-90; Figure 19). The introduction of a carbon tax at the level stated earlier leads to global CO_2-emissions by 2100 6% lower than BaU-90. This corresponds to a reduction of only about 4% in CO_2 concentrations relative to BaU-90,

Table 2. CO_2 emissions (GtC) from industrial sources for the European Community and for the whole world under the five scenarios.

Scenario	Region	1990	2050	2100
BaU-90	Global	6.0	14.6	20.8
	EC	0.80	0.87	0.82
EC-AP	Global	6.0	14.2	20.2
	EC	0.80	0.45	0.19
CTAX	Global	6.0	13.9	19.5
	EC	0.80	0.78	0.71
NON-EC-AP	Global	6.0	6.7	3.7
	EC	0.80	0.87	0.82
AP-90	Global	6.0	6.3	3.1
	EC	0.80	0.45	0.19

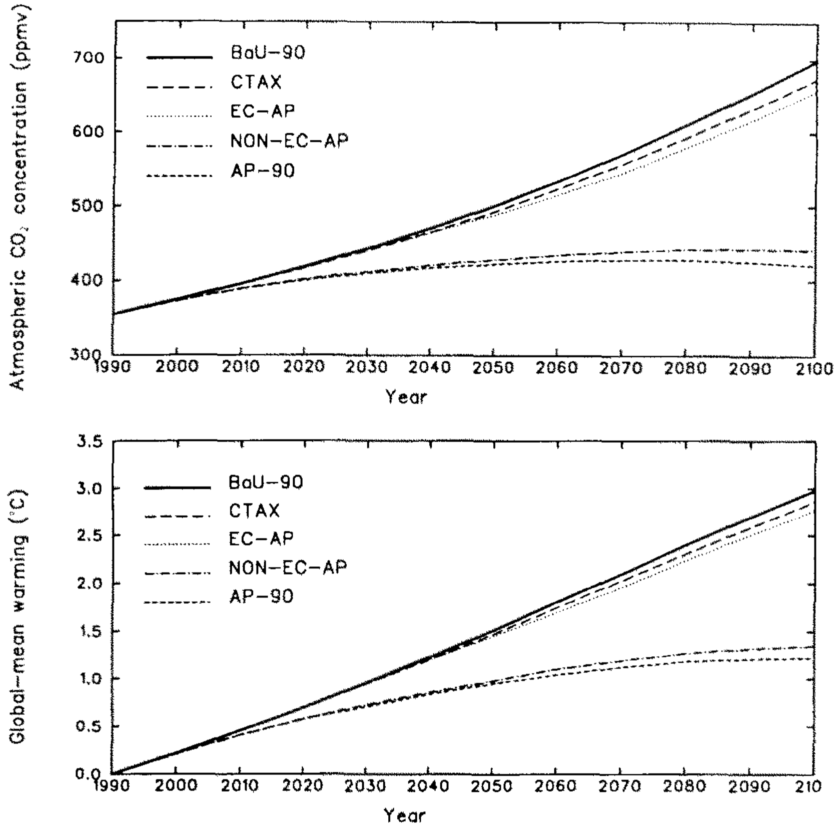

Figure 19. Projections made by ESCAPE of (top) the atmospheric CO_2 concentrations for the five scenarios and (bottom) global-mean temperature.

not as effective as the EC-AP scenario. It should be noted, however, that in ESCAPE the effect of a carbon tax is calculated in terms of a shift in the fossil fuel mix (from coal to gas) by a market-driven substitution process and in terms of a power plant shift (exogenously imposed). No shifts of activities between sectors and/or regions are assumed, so elasticities only affect the energy demand. In our calculations the elasticities were put to zero; taking elasticities of −0.15 and −0.40, for all sectors, respectively, yields an extra reduction of global CO_2 emissions by 2100 of between 1% and 4%. In the hypothetical scenario NON-EC-AP, the resulting atmospheric CO_2 concentrations are approximately 37% lower by 2100 compared with BaU-90. Of the five scenarios considered, only the AP-90 and NON-EC-AP achieve stabilization of atmospheric CO_2; this occurs by the years 2075 (at a level of 429 ppmv) and 2090 (442 ppmv) respectively.

Figure 19 also shows the rate of global-mean temperature increase for these alternative scenarios. Whichever scenario is realized a further substantial change in global climate cannot be avoided. Even under the AP-90 scenario the world by 2100 has warmed by 1.2°C relative to 1990. Furthermore, the rate of global-mean temperature increase over the period 1990 to 2100 is estimated by ESCAPE in all cases to be greater than 0.1°C per decade.

These projections of future global-mean temperature enable us to return to the issue of sustainable targets for climate change raised earlier.[65] Figure 20 shows, for each of the five scenarios, the rate of global-mean temperature change (per decade) as a function of the absolute temperature increase. By the end of next century the BaU-90, CTAX and EC-AP scenarios will have exceeded both the thresholds

[65]For many vulnerable regions the targets may well be lower. For example, even 1°C of warming, if accompanied by increased aridity, would be critical in parts of semi-arid Africa.

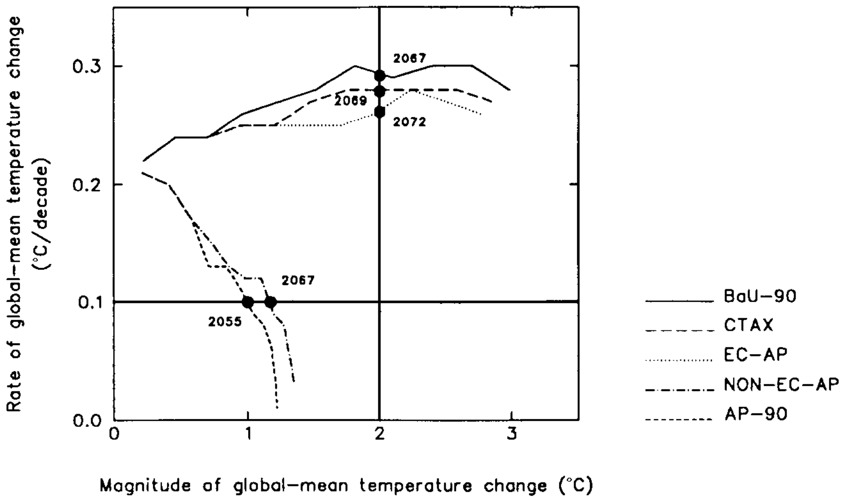

Figure 20. Projections of global-mean temperature change from 2000 to 2100 (relative to 1990) related to the rate of change.

The horizontal and vertical lines indicate the global climate change targets recommended by the AGGG (see text) and the years indicate when these targets are crossed for each scenario.

defined earlier, ie more than 2°C absolute global warming at a rate greater than 0.1°C per decade. BaU-90 exceeds the 2°C threshold in 2067; the CTAX and EC-AP scenarios delay this occurrence by less than five years. Even the AP-90 and NON-EC-AP scenarios continue to exceed the rate of change threshold until the last decades of next century, by which time the rate of warming has declined to below 0.1°C per decade.

Conclusions

Calculations with the integrated climate assessment model ESCAPE show that future climate change, the magnitude of which is not yet well known, cannot be avoided over the next century. This is because of the future climate change commitment which arises both from past emissions of greenhouse gases and because of the inertia within the global development path which the world is currently pursuing. To restrict future climate change to within the rates and magnitudes of global-mean temperature and sea level change suggested earlier as being compatible with sustainability, will require a major jolt to the foreseeable economic and technological development pathway of the world.

The impacts within the EC of a sea level rise resulting from climate change are clearly negative. Countries like France, Italy, Denmark and Germany are especially vulnerable and both damage costs or adaptation costs are likely to be high.[66] For other sectors of the European economy, however, a climate change may have contrasting impacts, both beneficial and detrimental. Within the agricultural sector, for instance, Greece, Italy, Spain and Portugal are likely to be faced with higher costs, while increased yields are possible in other countries of the EC. Overall, we conclude that climate change will have adverse effects for the southern countries of the EC, mainly due to sea level rise and water shortages, and to a lesser extent because they become less attractive as tourist resorts. The northern countries of Europe might realize net benefits from the impact of climate change, mainly because of the increase in agricultural yields, and to a lesser degree because of a reduction in energy requirements for the heating sector and an increased suitability for tourism. Although this North–South contrast is visible from the ESCAPE results, the impact indicators need to be

[66]Very small benefits may arise, however, from increased wetlands and nature reserves in some coastal areas.

incorporated into robust economic evaluations to identify the most appropriate policy options. At present the impact costs associated with sea level rise appear to outweigh other benefits, and the net effect of climate change within the EC seems likely to impose costs.[67]

A number of different scenarios have been designed and evaluated with ESCAPE. With respect to global-mean warming, IPCC's Business-as-Usual scenario (BaU-90) exceeds both of the two suggested thresholds: the absolute temperature change and its rate of change. Even for the Accelerated Policies scenario (AP-90), the rate of temperature change over the coming decades may present problems for ecosystem and societal adaptation. The AP-90 scenario would, however, be the minimum requirement needed to return climate and sea level change close to sustainable magnitudes by the end of the 21st century.

To illustrate the limited scope for the EC acting alone to directly reduce future warming, we considered the EC-AP scenario where only the EC follows an accelerated policy future. In this case, global-mean warming by 2100 is reduced by 0.2°C (about 5%). Of course, there are other indirect ways in which an accelerated climate change policy implementation in the EC would reduce future warming.[68] The introduction of a global carbon tax in the CTAX scenario, rising from zero in 1990 to US $10 per barrel (or 65 ECU/ton C) in 2000, would lead to approximately 6% lower CO_2 emissions by 2100, corresponding to CO_2 concentrations and global-mean temperature change 4% lower than BaU-90. Introducing this tax for the EC alone, however, would not significantly contribute to a reduction of CO_2 concentrations.

Coping with climate change will be an essential problem for the EC in the decades ahead, since the likelihood of some climate change cannot be avoided in the near future. Whichever global scenario may be realized, the rate of global temperature increase seems likely to be above 0.1°C per decade for the coming 60 years. Although not pretending to represent a comprehensive climate change impact analysis, ESCAPE enables some of the effects of a climate change within the EC to be estimated. More importantly, the model framework is particularly effective in illustrating both the extent of policy intervention which is necessary to substantially reduce future global warming and the linkages which exist between energy, climate and land use systems. The uncertainties at each stage are large, however, and new assessments may substantially modify the conclusions of our ESCAPE analysis described here. At least we hope the ESCAPE framework will illustrate for students, researchers and policy makers the urgent demand for improved understanding of climate change and its impacts.

[67] *Op cit*, Ref 4.
[68] For example, by sending a signal to other nations that the EC was prepared to implement policies aimed at prevention, the likelihood increases of policies aimed at emissions reduction being introduced elsewhere. Such geopolitical considerations are not modelled in ESCAPE.