Tyndall°Centre
for Climate Change Research

# Representing the Integrated Assessment of Climate Change, Adaptation and Mitigation

Terry Barker

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## Abstract

Models, such as the UK Hadley Centre's coupled atmospheric-ocean model, have become central to the understanding of climate change. This paper is concerned with how the overall system can best be represented, whether and how the integration has been achieved, and the problems involved in the linking together of such models with energy-environment-economy (E3) and other models. Two approaches "cause & effect" and "stocks & flows" are compared and contrasted for the representation of the system. The linked system forms an integrated assessment model of climate change, its impacts on natural systems, the effects on the socio-economic system, and the how society and the economy might adapt and/or develop policies to mitigate the climate change. The role of the models is discussed in the context of the integrated assessment. The paper concludes with a discussion of some of the problems in linking the models together.

## 1 Introduction

Greenhouse gas emissions from human activity are threatening the stability of the global climate (Watson et al., 2001). Various governments and international bodies have initiated substantial research programmes to construct, develop and use coupled climate-ocean, climate change models in order to understand the extremely complex physical processes involved (e.g. the UK Hadley Centre's model). The same bodies have also, often independently, initiated research in the area of impacts of climate change on the natural environment involving complex geographical and ecosystems modelling. Finally, the driving forces leading to climate change have been also been investigated in other research programmes, involving integrated energy-environment-economy (E3) models, intended to help the formulation of equitable, efficient and effective policies to abate the greenhouse gas emissions (e.g. the European E3ME model http://www.camecon.co.uk/e3me/index.htm)). In addition to these 3 separate areas of research, reported respectively in the 3 Working Groups of the IPCC's Third Assessment Report (2001), many integrated assessment models have been developed, often with simplified versions of the large models (IPCC, 2001; EEA, 2000).

The *integration* of the knowledge embodied in these large-scale modelling programmes is a major problem in developing understanding of the adaptation to climate change and its mitigation. There are many important feedbacks in the whole system, some of which can have major effects on the costs of mitigation. For example, mitigation of greenhouse gases (GHGs), particularly $CO_2$, can often have favourable impacts by reducing emissions of other pollutants and by reducing other damaging side-effects, mainly because the burning of fossil fuels is lower. When the overall benefits and costs of climate policies are assessed, it is important to include such benefits e.g. those from reduced local and regional air pollution because under some circumstances they can be comparable in size to the direct costs of mitigation. As the main benefit of climate policies is to reduce climate change, these benefits are usually referred to in the literature as ancillary benefits (or secondary benefits).

It also important to represent these process and interactions in a simple diagram, to make understanding easier, to set each in context, and to help identify gaps in knowledge. The pressure-state-response (PSR) framework, adopted and developed by the OECD (1993) and the EEA (1998), among others, has been used by the IPCC in the Third Assessment Report (Watson et al, 2001) as a framework for the integrated assessment of climate change. This paper reviews that framework, characterized as a "cause and effect" representation, and suggests an alternative "stock and flow" representation to emphasis the physical flows, accumulation of gases and effects, and complex interactions associated with climate change.

## 2 “Cause & effect” versus “stocks & flows” in the representation of the integrated assessment system

*What is to be represented?*

The integrated assessment framework is intended to represent climate change, its causes and effects, how the human and natural systems will adapt to climate change and how it might be mitigated. The captions to the figures attached at the end of the paper describe their contents, here the issue is the effectiveness of the “cause and effect” versus the “stocks and flows” approaches to the representation of the system.

*The “cause and effect” approach*

This simple PSR framework was developed by the OECD (1993), based on an approach to organizing environmental statistics by Statistics Canada (Rapport and Friend, 1979) and has appears in many publications of international organizations. A clear account of the framework is available in www.fao.org/lead/toolbox/Index.htm. The framework starts with the idea that human activities impose *pressures* (such as pollution or land use change) on the natural environment, which can induce changes in the *state* of the environment (such as, raised concentrations of atmospheric pollutants or reduced habitat diversity). These changes in state may than lead to a socio-economic response to mitigation or remove the original pressures and reduce the environmental damage or prevent further damage. The framework was further developed by the EEA (1998) to become the Driving Force - Pressure - State - Impact - Response Framework (DPSIR) so as to provide a more comprehensive approach to analyzing environmental problems. The framework, when applied to the climate change issue can be stated:

- Driving forces, such as economic growth, produce
- Pressures on the environment, such as greenhouse gas and other emissions, which then change the
- State of the environment by inducing climate change, which then
- Impacts on the human and natural systems, causing society to
- Respond with various policy measures, such as regulations, information and taxes, which can be directed at any other part of the system.

This way of representing an integrated assessment framework can be called “cause and effect”, because it is essentially a cycle describing a sequence of causes and effects, applicable to a wide range of environmental issues. The framework adopted by the Synthesis Report (Watson et al., 2001, Figure SPM-1, p.3) of the IPCC’s Third Assessment Report is shown in Figure A. The ovals and boxes in the 4 quadrants represent changes in 4 domains: starting with the box, there is the socio-economic system, then the atmosphere, then the climate, then human and natural systems. The arrows show the direction of causes from one domain to effects in another in a clockwise cycle; one reverse arrow is shown to represent the non-climate stresses, such as changes in land use leading to deforestation, on the natural system.

The advantages of the approach are:

- Its simplicity
- A clear message giving the direction of causation.

Its disadvantages are:

- No treatment of feedbacks (to keep the figures simple)
- An overemphasis on adaptation over mitigation (adaptation is shown as modifying two causal links) although it could be argued that mitigation in fact modifies the whole chain of cause and effect.
- The impression that adaptation can manage all the impacts, e.g. on biodiversity, when adaptation can only be limited and partial and will not prevent all damage

- A boundary between "impacts on human and natural systems" and "socio-economic development paths" which is not obvious (e.g. changes in food and water resources are also partly a component of socio-economic development)
- A mixing of two different symbols for societal responses: the blue arrow and the white boxes marked "mitigation" and "adaptation", so that it is not clear why both are included
- Mixing of stocks and flows (emissions and concentrations) in one of the quadrants.

This last point is perhaps the most important in conceptualizing the climate change problem. The distinction between stocks, i.e. what exists at a moment of time, and flows, i.e. change over a period of time, is basic in the understanding and conceptualization of systems and their behaviour. The DPSIR framework appears to treat variables that seem to relate to stocks ("pressure" and "state") as conceptually on a par with variables that seem to relate to flows ("driving forces", "impacts" and "responses"). This can be particularly confusing in representing the climate change issue because a critical concept is the flow of emissions of greenhouse gases (a flow) into the atmosphere, accumulating as concentrations (a stock). Figure A has both emissions and concentrations in one of the quadrants. This may be confusing because it looks as though anthropogenic emissions may be causing climate change, when the science tells us that it is concentrations that are important in the long term. The links between emissions and concentrations are in fact much more complicated than at first sight because of the different atmospheric lives of the different greenhouse gases and the possibilities of their interactions with other components of the atmosphere, e.g. water vapour.

*The "stocks and flows" approach*

This paper proposes an alternative approach that focuses on stocks and flows in representing the interacting systems, with

- the quadrants representing different systems as stocks, "states of the world" or bodies of knowledge
- the arrows in the figure representing flows from one system affecting another, and
- the direction of the arrows representing the direction of cause and effect.

Figure B shows the integrated system in a stocks and flows approach, with adaptation and mitigation measures affecting certain flows. In contrast with Figure A the ovals and box represent domains as systems rather than as changes in key variables and the arrows represent flows and effects between the systems rather than simple cause and effect directions. Several of the arrows represent measurable flows, such as emissions of greenhouse gases and aerosols into the atmosphere. The positioning of the ovals and the box has been changed to reflect the fact that two of them are mainly concerned with the atmosphere and so are better placed above the other two, which are mainly concerned with the surface of the earth.

The advantages of the approach are:

- A clear distinction between stocks and flows, necessary for understanding the science
- A one-to-one representation of two key flows between systems, i.e. (1) anthropogenic emissions and (2) the enhanced greenhouse effect (higher radiative forcing)
- The possibility of a logical depiction of adaptation and mitigation as the narrowing of flow arrows
- A clearer depiction of mitigation at the start of the cycle, reducing uncertainties and risks throughout the cycle world-wide, in contrast with adaptation at the end of the cycle, mainly affecting the eventual outcome of climate change impacts at a local level
- The possible depiction of the key concept of ancillary benefits, shown as reduced damages of air pollution (the problem of putting such benefits into the "cause and effect" figure is that ancillary benefits are not a "smaller" cause of damages, but simply lower damages)
- A close identification of the systems represented by the domains with the underlying scientific disciplines and modelling systems. For example the coupled atmosphere-ocean (AO) models are of the climate system and project changes in air temperature and sea level rise, and the energy-environment-economy (E3) models are of human behaviour and project emissions of greenhouse gases and aerosols.

- The explicit inclusion of the effects of socio-economic development on natural systems that is NOT via climate change directly, e.g. changes in land use leading to loss of biodiversity, as represented by the "non-climate-change stresses" arrow.

Its disadvantages are:

- A full diagram with feedbacks is too complex to be understood easily as a stand-alone figure
- There is a difficulty in separating "natural systems" from "human society" in that humans are also part of the natural system.

The last point is serious and worth as discussion. Humans are part of the natural system, but they have changed it intensively and extensively through burning, changes in land use away from forestry and prairie towards agriculture and urban use, and more recently through atmospheric emissions. If a natural system is juxtaposed with human society, the contrast suggests that the natural system is somehow one without such human interference. However, the distinction is useful and clearly underlies much of the analysis of the impacts of climate change and other human interventions on the natural system, e.g. as described in IPCC TAR WGII Report. The natural system is seen as the uncontrolled and unregulated part of the natural environment, e.g. the natural conditions that lead to the spread of tropical diseases, such as higher winter temperatures.

The "stocks and flows" figure can be easily be extended and refined to give a much more comprehensive picture of the climate change issues, in a series of 10 figures, which builds up the various systems and their main interactions. These figures are appended to this paper and are also given in a separate presentation, with the explanation of each figure given in the notes.

*Conclusions on representing climate change and human society*

Both approaches have their advantages, but the "cause and effect" framework seems more appropriate as a description of human interference with natural systems rather than as a description of the non-human system interactions also covered in the figures. The driver-pressure-state-response causal chain works well when the driver is a social group, but not when the driver is an outcome of a complex physical system, such as the radiative forcing of greenhouse gas concentrations, with multiple interactions and time-scales. The physical systems do not respond with choice and motivation; and the pressure-state relationships are complex and intrinsic parts of all the systems being represented. The "stocks and flows" figure has the advantage that it is conceptually more logical. Several of the complexities inherent in the climate change problem can be explained by developing the figure into a series of component figures, as shown in the 10 figures of the attached presentation.

## 3 Integrated Assessment of Climate Change and the IPCC's Third Assessment Report (TAR)

*The state of the art*

The current state of knowledge on these issues is assessed in the Intergovernmental Panel on Climate Change's (IPCC) Special Report on Emissions Scenarios (Nakicenovic et al, 2000), the Third Assessment Report (IPCC, 2001) including post-SRES mitigation scenarios. These reports and studies are concerned with human interference in the climate. (Working Group I (WGI) reports on the scientific basis of climate change), WGII on the impacts of climate change on natural and human systems, particularly over the next 100 years and adaptation to the impacts and WGIII on mitigation). However, the current state of science as represented in these reports does not yet allow the quantification of such a fully integrated assessment (Watson et al., 2001). Figures A and B above representing the integrated assessment of climate change as discussed above are more conceptual aids for thinking about the issues rather than a description of an actual modelling system, including "state of the art" models.

The main way in which consistency have been achieved in the results reported in the TAR is by running the different modelling systems on a set of common scenarios based on the 6 illustrative marker scenarios in SRES (Nakicenovic et al., 2000). This has been done for versions of the coupled AO models and for the E3 models, but not for most of the modelling of climate change impacts. None of the potential feedbacks between the systems in Figure B has been formally modelled in the large systems, with the exception of the link back from the higher temperatures of sea water to atmospheric concentrations of GHGs (sea water absorbs less $CO_2$ at higher temperatures).

*The role of models*

The prevailing and overarching methodology in the analysis of climate change, adaptation and mitigation involves the use of large-scale computable models of physical, biological, technical and economic processes. The models are required to

- Incorporate scientific knowledge in widely different areas with varying degrees of reliability
- Manage the huge amounts of data needed for modelling at different spatial scales (e.g. global, national and local) and different time scales with solutions for the next 100 years
- Maintain consistency in definitions and identities, over regions and time periods at different levels of aggregation
- Allow for easy and reproducable computation of solutions based on different sets of assumptions, e.g. those associated with the SRES scenarios.

A basic distinction between the processes and systems being modelled is between those simulating physical and biological systems and those involving human choice. If human choice is involved, as in land use change or emissions of GHGs as a result of economic activities, then there may be opportunities and options for behaviour of people and social groups to change.

Atmosphere-Ocean (AO) modelling on a large scale is needed to represent complex climate interactions. The value of this modelling is because the more detailed and the more reliable are the projections, by region, locality, season and year, the better the information for adaptation and mitigation.

*Energy-environment-economy (E3) modelling*

Large-scale E3 modelling is needed for climate change mitigation for four reasons.

- The global requirement for mitigation. Most countries, if they were to act on their own to reduce their emissions, would have a negligible effect in mitigating global warming. To be effective, action has to be global and substantial to achieve a reduction of around 11 to 52% below 1990 levels by 2030 for stabilisation of GHG concentrations at 450ppm.
- The economy-wide nature of GHG emissions. The emissions are an unwanted byproduct of economic activity, such as the burning of fossil fuels for heat, light and power and the clearing of forests. However, energy can be produced from a variety of sources, some with very low carbon contents, and used in a variety of ways, offering the possibility of even lower levels of emissions. Consumption can also be much less carbon-intensive than at present.
- The absence of a cost-effective end-of-pipe technology to remove the $CO_2$ from emissions. This implies that fiscal policies are more suited to GG abatement than regulation. A range of fiscal options are available (carbon/energy tax, $CO_2$-emission permits, energy-saving R&D and other incentives).
- The desire by policy makers and business to assess the effects of the policies on costs, employment, equity and industrial competitiveness.

*General equilibrium and time-series cross-section econometric models*
Most of the research effort has gone into the development of Computable General Equilibrium (CGE) models for the economy component of the E3 models (e.g. the Worldscan (CPB, 1999) component of the IMAGE integrated assessment model), and this methodology dominates the field. CGE models incorporate parameters based on expert views or literature surveys without embedding these priors into a formal estimation system; CGE models usually use one year's data, even where time-series are available, to make long-term projections into the future without consideration of the time-series properties of the data. The alternative to CGE modelling is the econometric time-series cross-section simulation models, but they are in general less developed. Examples of global econometric models are OPEC's World Energy Model (Ghanem et al, 1998) and the LBS world model EGEM (Mabey et al., 1997) (no longer maintained). Econometric models are those based directly on formal methods of statistical inference involving cross-section and/or time-series data to estimate the parameters of the model.

Such economy models have been developed into E3 models by linking them with energy and GHG emissions models (e.g. as in IMAGE) or by constructing fully integrated E3 models (OWEM and EGEM referenced above).

*Linking AO and E3 models*
These models are very large, they can take a long time to solve and they work on different, often inconsistent spatial and temporal scales (e.g. AO models may work on a uniform grid whereas E3 models use a country group spatial aggregation). Therefore they have to be linked together somehow in an encompassing Integrated Assessment Model (IAM).

*Problems in constructing IAMs*
Quantified and rigorous IAM has become a discipline in itself with its own journals[1], academic experts and professional practitioners. IAMs have been built as tools for teaching and understanding the problems, as well as for use in quantifying detailed scenarios, such as the SRES marker scenarios. Since the IAM cannot actually integrate the component models in real time because they are too complex, too large and/or too slow in solution, reduced from have to be developed to capture the salient features of the component models.

Therefore if a model is to fit within such an IAM framework, it has to be capable of providing 3 types of solution, a task incumbent on the modelbuilders themselves, rather than the architect of the IAMs. These are

1. The *elaborated solution* at the full level of detail
2. The *reduced solution* composed of reduced form equations calibrated on a series of elaborated solutions, but capable, given a set of key inputs of an independent solution of the key outputs of the model
3. The *prescribed solution*, a set of solutions of the elaborated model providing values of key outputs given the values of the key inputs, e.g. those of the SRES scenarios.

There are 5 problematic areas in constructing such IAMs.

- Building the reduced forms of the elaborated models

This is a major task for the modelbuilder and the IAM architects. The reduced forms fit into the IAM, so they include any feedbacks judged necessary for the IAM. Sometimes the feedback mechanisms in the model will be unimportant for the model, unreliable and poorly quantified, but essential for the IAM, so a close dialogue between the modelbuilder and the IAM modellers will be advisable.

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[1] Amongst others there are*: Environmental Impact Assessment Review, Environmental Modeling and Assessment, Human Choice and Climate Change Tools for Policy Analysis,* and *Integrated Assessment*

- Managing the repeated updating of the elaborated models

Typically the various component models will be periodically revised and updated independently, sometimes with substantial effects on the quantitative results or on the structure of the model. If the updates also include revised reduced and prescribed solutions, then the incorporation of the updated model in the IAM will be much easier.

- Establishing protocols for linking the reduced form models together

The linking of large models is difficult, time-consuming and often academically unrewarding. It requires a deep understanding of the models to be linked. It can be an unending task because the underlying models get revised as the linkages are developed. The use of reduced form solutions is intended to overcome some of these problems, partly by putting the primary burden for constructing the reduced form on the team constructing the elaborated model. Special component software will help to establish protocols and procedures, e.g. the required inputs and outputs for each component model.

- Identifying overlaps and gaps in the IAM and resolving them

This is a major task, almost entirely undertaken by the team preparing the IAM. There is the possibility that some of the component models will overlap and provide two or more inconsistent solutions for the same output variables. Priorities will have to be established and differing approaches reconciled.

- Directing and managing the development of the IAM

The building of an IAM is similar to that of a physical building. A number of components are brought together in an overall framework and if the building is successful, they interact efficiently. The problems faced by the builders of an IAM are such that they can only be overcome effectively by a multidisciplinary team under strong leadership. The director of the team has to be capable of reconciling differences in approach in the component models, identifying potentially weak links and gaps and replacing or filling them, if necessary from within the resources of the IAM team.

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## Figure A: A "Cause and Effect" Integrated Assessment Framework for Climate Change with Adaptation and Mitigation

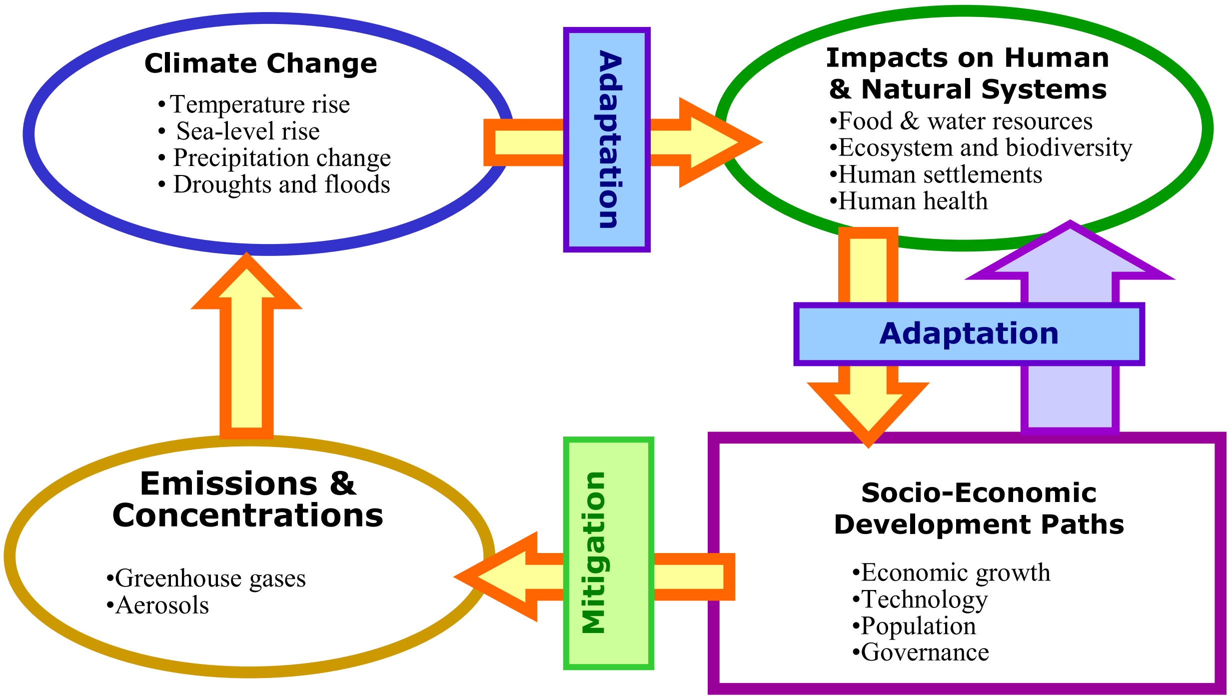

Figure A shows the linkages between changes in human society and climate change as a set of "causes and effects" in a driver-pressure-state-response methodology. More formally, it provides a schematic and simplified representation of an integrated assessment framework for considering anthropogenic climate change. The figure shows changes in four ***domains*** in the quadrants i.e. (1) ***human society***, i.e. the socio-economic system with development paths described in the SRES (this is shown in a box to indicate that it is different in that choices and options are available that may change the whole system) (2) ***atmospheric gases*** with concentrations of greenhouse gases, aerosols and precursors (3) ***the climate system*** undergoing Climate Change as a result of higher concentrations and radiative forcing, and (4) ***human and natural systems*** including all plants and animals.

The arrows show a full clockwise cycle of ***cause and effect*** between the domains. Each socio-economic development path explored in the SRES, including development of the industrialized countries, has driving forces that can be grouped into the areas of population, economic growth, technology and governance. These driving forces give rise to emissions of greenhouse gases, aerosols and precursors, with $CO_2$ being the most important. The emissions accumulate and interact in the atmosphere as concentrations and disturb the natural balances, depending on physical processes such as solar radiation, cloud formation and rainfall. The aerosols also give rise to air pollution, e.g. acid rain, that damage human and the natural systems (not shown). The long-term effect is to change the global climate system (higher radiative forcing i.e. the enhanced greenhouse effect) with temperature rise leading to sea level rise and more global precipitation change. These climate changes, in turn, have impacts on natural systems through more storms, floods, droughts. Thawing of permafrost, avalanches, landslides, reduced snow cover affecting food and water security, ecosystems and biodiversity, and human health and settlements. There is a possibility of some feedback between the changes in these systems and the climate (not shown), such as albedo effects from changing land use, and other, perhaps larger interactions between the systems and atmospheric emissions, e.g. effects of changes in land use (again not shown). These changes will ultimately have effects on human society in the form of different socio-economic development paths e.g. by weakening food and water security. The reverse blue arrow indicates the societal response to climate change impacts. The effects of development of emissions can be modified by *mitigation* as shown in the box superimposed on the arrow. The effects of climate change on natural and human systems and therefore on the impacts on socio-economic development can be modified by *adaptation*, also shown in the figure.

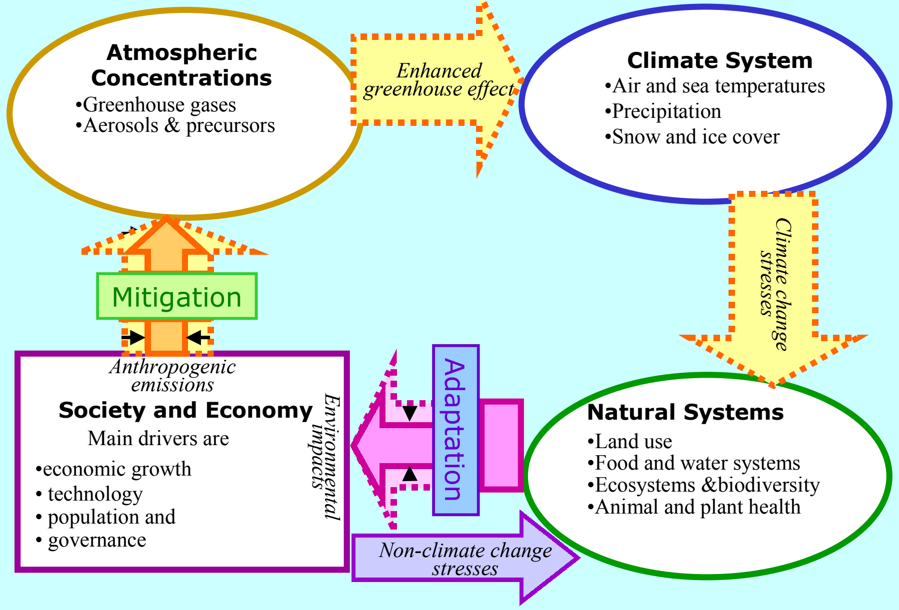

Figure B: An Integrated Assessment Framework for Considering Climate Change with Adaptation and Mitigation

Figure B provides an integrated assessment framework for considering climate change using the "stocks and flows" approach, although it is a simplified and schematic representation that omits several interactions and feedbacks.

The figure shows four domains in each corner: (1) ***society and the economy*** with their socio-economic development paths, with the main driving forces of economic growth, technology, population and governance, (2) the anthropogenic emissions leading to ***atmospheric concentrations***, (3) the ***climate system*** affected by the concentrations, and (4) the ***natural systems*** stressed by climate change and socio-economic development. Each system contains complex interactions and feedbacks, with the possibilities of extreme events, critical threshholds and shocks. The arrows show the main ways in which the systems affect one another as a clockwise series of flows. The economy gives rise to ***anthopogenic emissions*** that accumulate in the atmosphere. The concentrations give rise to the ***enhanced greenhouse effect***, which affects the behaviour of the climate system. ***Climate changes*** take the form of higher average temperatures, sea level rise and more extreme events , such as floods and droughts. These impact on natural systems with ***environmental impacts*** on human society and the economy.

***Adaptation*** will take place by human society in response to the environmental impacts of climate change on human and natural systems. The adaptation will be both autonomous, such as households protecting their dwellings from local flooding, and via government initiatives, such as more flood defences in areas threatened by higher sea levels. These adaptation actions will also help to reduce (but not entirely avoid) some of the impacts of climate change. ***These actions provide benefits but also entail costs. Net climate change costs are the adaptation benefits less adaptation costs, plus the costs of the unavoided impacts.*** The figure also shows that ***mitigation*** of GHG emissions is unlike adaptation in that it reduces emissions at the start of the cycle and through the cycle. This is important because there are many unknowns and uncertainties in the effects and feedbacks; in consequence mitigation reduces risks of dangerous outcomes much more than adaptation.. Mitigation reduces anthropogenic emissions at source and this explains the narrowing of the mitigation arrow and other arrows throughout the flow chart, including that for adaptation, compared to the figure without adaptation and mitigation. Mitigation reduces concentrations, then the climate change, then the impacts of climate change and finally the required adaptation. ***The primary benefit of mitigation is avoided climate change, but it also has costs*** (e.g. higher energy costs) ***and ancillary benefits*** (not shown) (e.g. in the form of reduced air pollution such as improvements in human health from reductions in air-borne fine particles (smog and dust), or more rural employment in biomass projects).

A stocks and flows approach

Figures 1 to 10 provide an integrated assessment framework for considering climate change using the "stocks and flows" approach. The figures can be seen as representing the body of knowledge in the IPCC SRES, the TAR and the post-SRES mitigation scenarios, in as much it concerns human interference in the climate and its effects over the next 100 years. Note however that the state of scientific knowledge does not yet allow for a fully integrated quantified assessment.

Figure 1 The principal domains

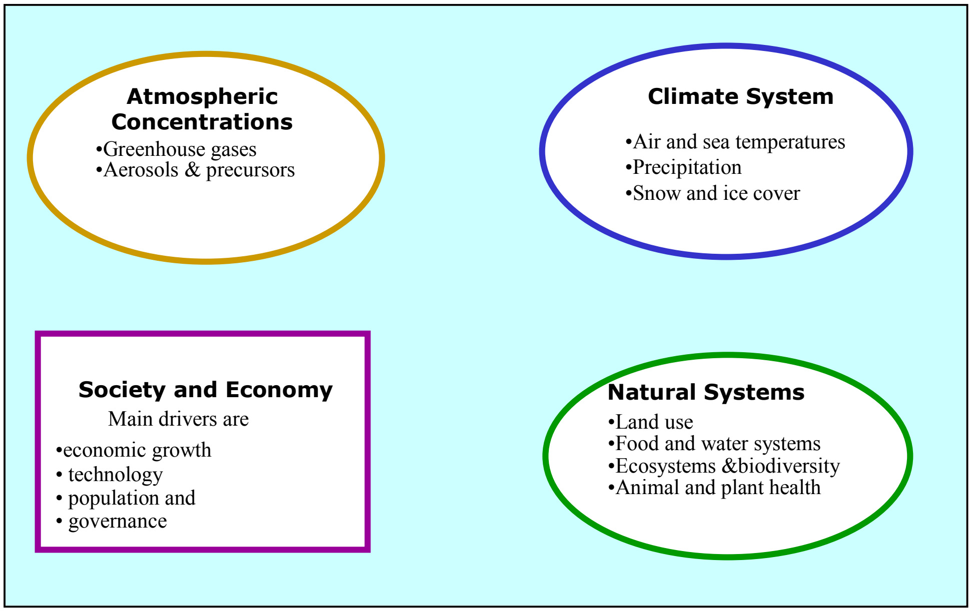

Figure 1 shows four domains in each corner: (1) ***society and the economy*** with their socio-economic development paths, such as those described in the SRES projections with the main driving forces of population growth, energy use, economic growth, technological change and land-use change, (2) the anthropogenic emissions leading to ***atmospheric concentrations***, (3) the ***climate system*** affected by the concentrations, and (4) the ***natural systems*** stressed by climate change and socio-economic development. The domains represent different parts of the world in the past and the future. Each system contains complex interactions and feedbacks, with the possibilities of extreme events, critical thresholds and shocks.

Figure 2 Different development paths give rise to (1) different levels and mixes of anthropogenic emissions that accumulate and (2) other environmental stresses on human and natural systems

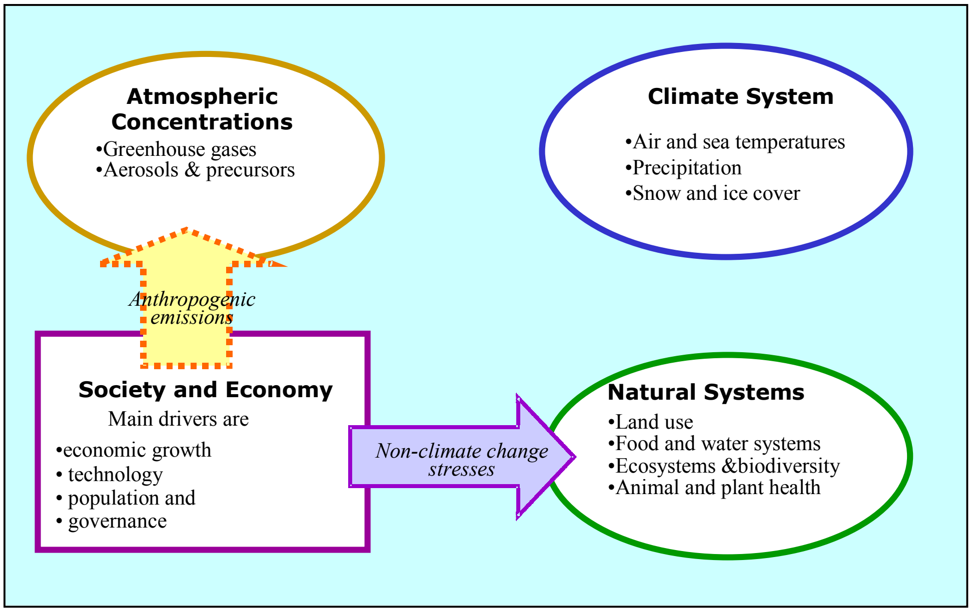

Figure 2 shows how society and the economy interact with the atmosphere and natural systems. Each socio-economic development path explored in the SRES, including development of the industrialized countries, gives rise to ***anthropogenic emissions*** of GHGs and aerosols and imposes ***non-climate-related stresses*** on the natural system, such as effects of changing land use or use of fresh water.

Figure 3 – Atmospheric concentrations lead to the enhanced greenhouse effect and effects on human and natural systems e.g. damage from air pollution and acid rain

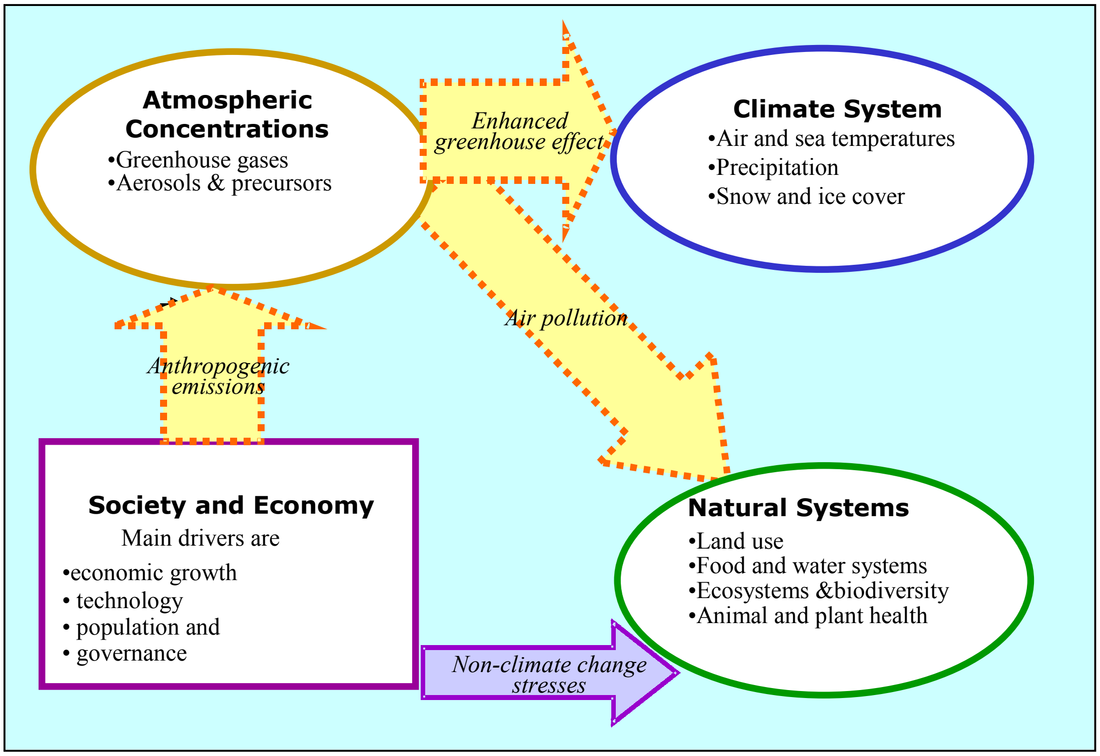

Figure 3 shows how these emissions accumulate in the atmosphere, giving an ***enhanced greenhouse effect*** and disturbing the natural balances, depending on physical processes such as cloud formation and rainfall. The aerosols contribute towards ***air pollution*** and acid rain that damage the natural systems, e.g. forest die-back and acidification of fresh-water lakes.

Figure 4 – Air temperature and sea level rises imply e.g. higher risks of floods and droughts

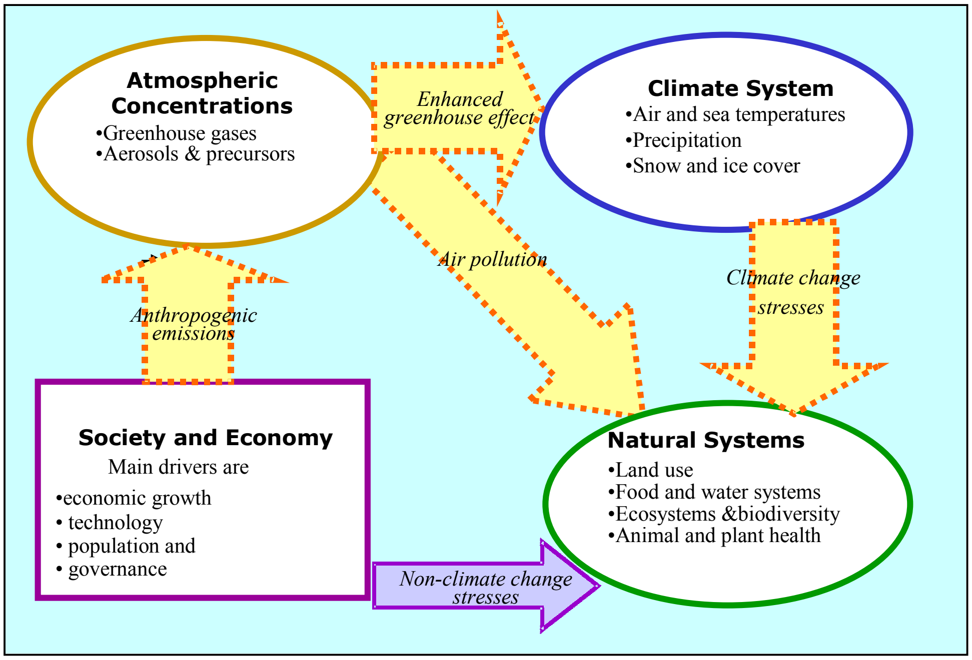

Figure 4 shows that the long-term effect is to raise air temperatures and sea levels and these, in turn, cause ***climate change stresses*** on natural systems. These add to the effects of air pollution and to non-climate change-related stresses leading to

- loss of land through sea level rise
- more floods and droughts
- stress on food and fresh-water provision
- loss of biodiversity
- changes in animal and plant health

Figure 5 Various feedbacks and interactions modify the effects

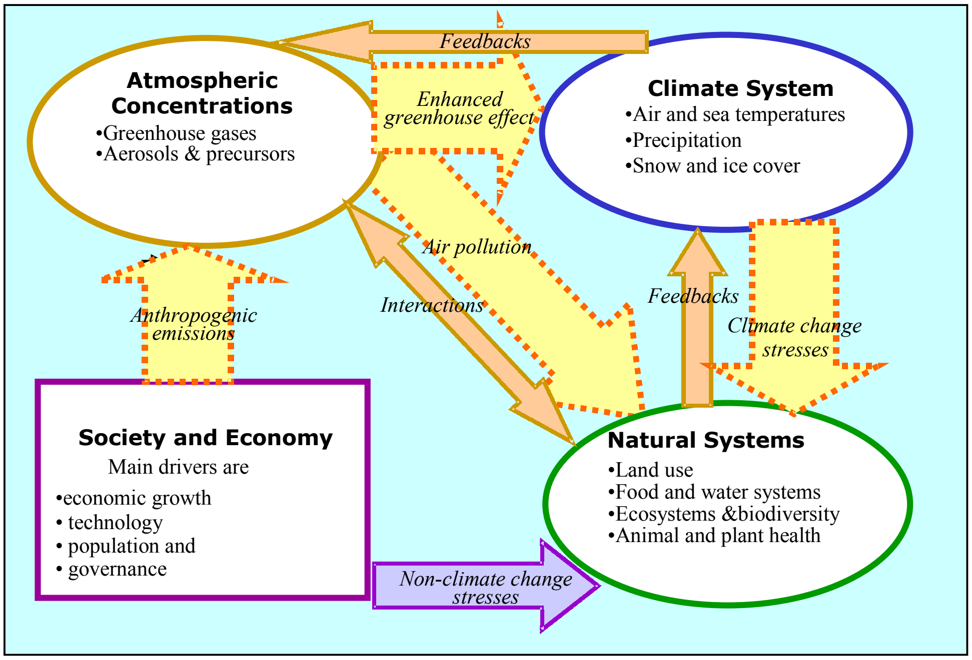

Figure 5 shows three feedbacks and interactions between the systems. There is a feedback from the sea temperature rise to atmospheric concentrations, because the sea absorbs less CO2 at higher temperatures. There is also a possibility of some ***feedbacks*** from the changes in the natural systems to the climate, such as albedo effects from changing land use, and other perhaps larger ***interactions*** between the natural systems and atmospheric concentrations, e.g. as a result of changes in land use.

Figure 6 – Changes in the natural systems alter socio-economic development

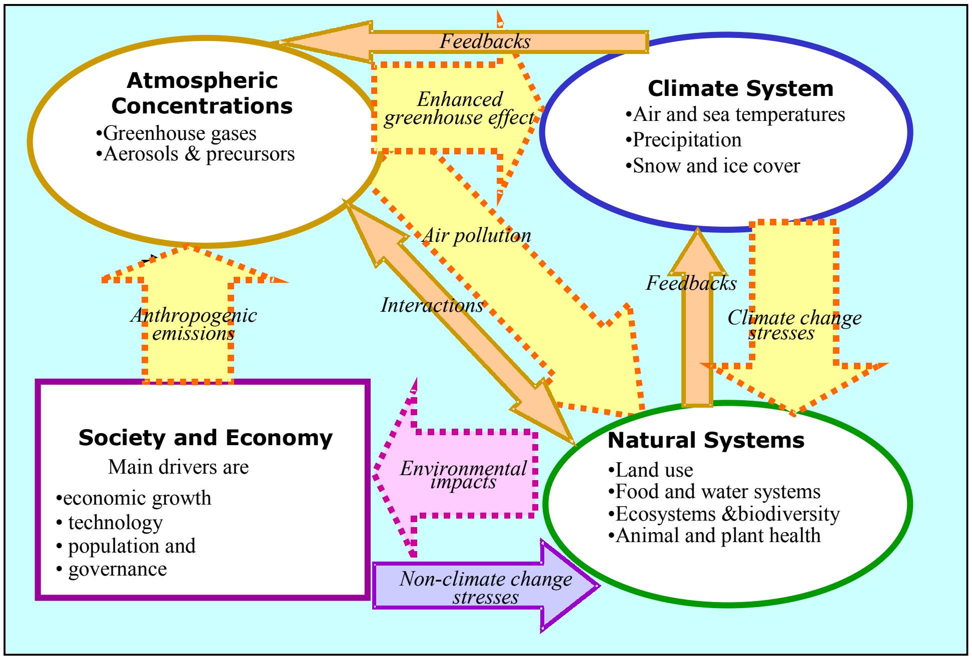

Figure 6 shows how these changes will ultimately have ***environmental impacts*** on society and the economy and on socio-economic development paths. This completes the clockwise cycle of effects, with the environmental impacts affecting the main drivers of the anthropogenic emissions, namely economic growth, technology, population and governance.

Figure 7 – Adaptation reduced the environmental impacts of climate change

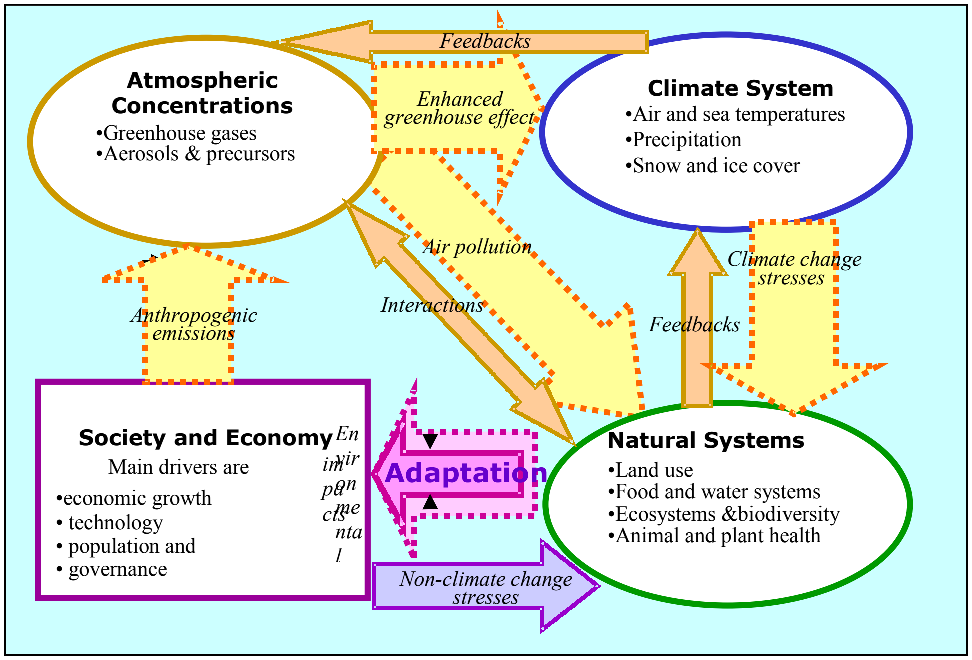

Figure 7 shows how ***adaptation*** can be included in the integrated assessment. Adaptation will take place by human society in response to the environmental impacts of climate change on human and natural systems. The adaptation will be both autonomous, such as households protecting their dwellings from local flooding, and via government initiatives, such as more flood defences in areas threatened by higher sea levels. These adaptation actions will also help to reduce (but not entirely avoid) some of the impacts of climate change, shown by the narrowing of the adaptation arrow. ***These adaptation actions provide benefits but also entail costs. Net climate change costs are the adaptation benefits less adaptation costs, plus the costs of the unavoided impacts.***

Figure 8 – Immediate mitigation effect – reduced emissions

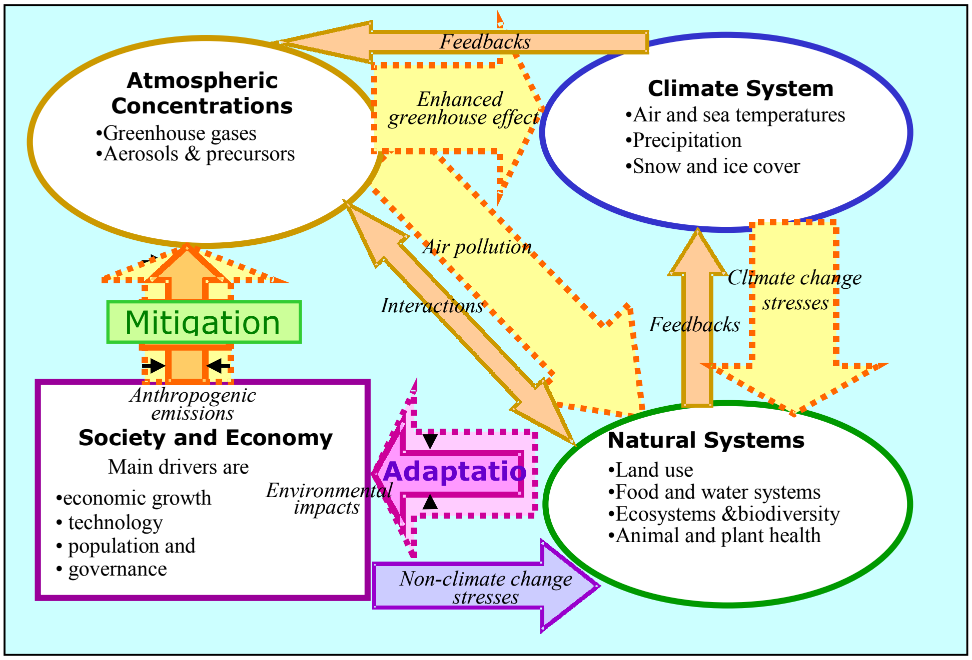

Figure 8 shows that ***mitigation*** of GHG emissions is unlike adaptation in that it reduces emissions at the start of the cycle. The immediate effect of mitigation is to reduce anthropogenic emissions at source and this explains the narrowing of the mitigation arrow. ***The primary benefit of mitigation is avoided climate change, but it also has costs*** (e.g. more energy-saving research and development or higher energy costs).

Figure 9 – Mitigation then reduces the greenhouse effect and local air pollution

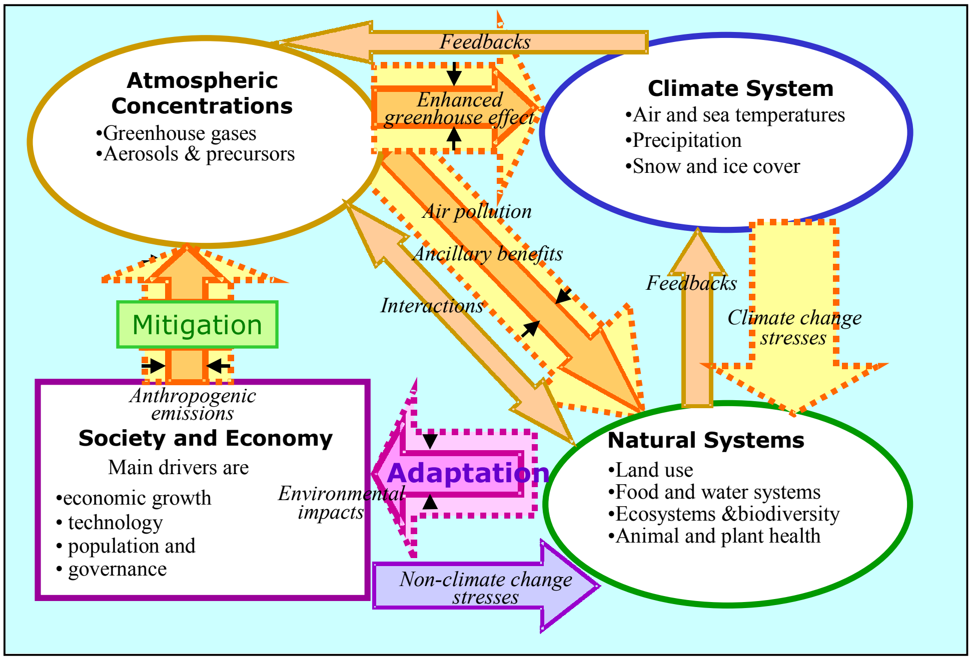

Figure 9 shows how ***mitigation*** of GHG emissions then reduces climate change by reducing the enhanced greenhouse effect (i.e. lessening radiative forcing). It also illustrates the ***ancillary benefits*** of mitigation by showing how the air pollution effects on natural systems are reduced by mitigation. An example of such a benefit of reduced air pollution is the improvement in human health from reductions in air-borne fine particles (smog and dust).

Figure 10 – Mitigation also reduces climate change stresses and finally reduces the need to adapt

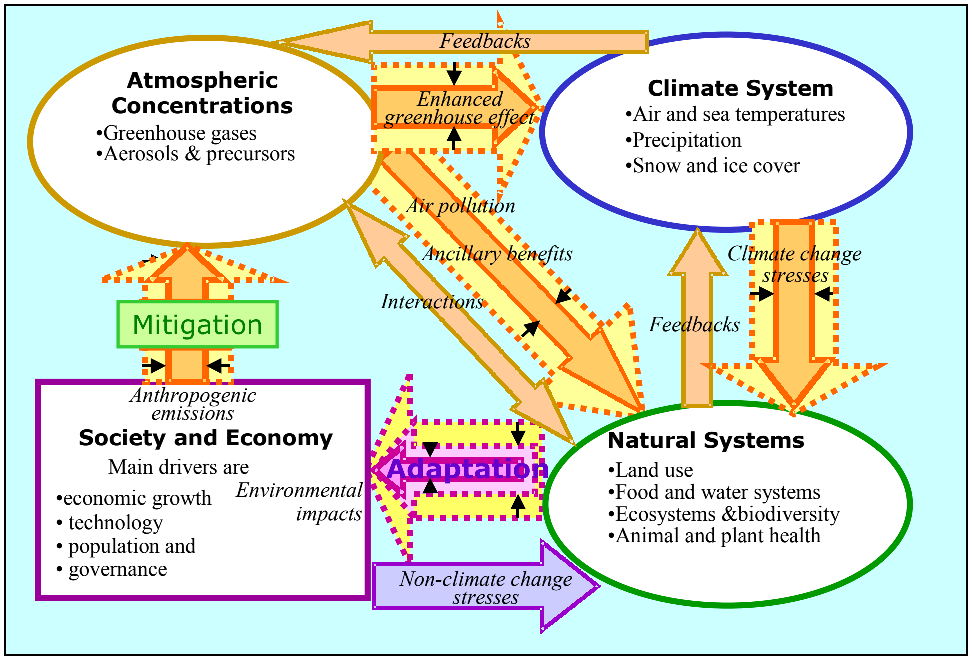

Figure 10 shows that ***mitigation*** of GHG emissions also reduces the impacts of climate change i.e. the temperature rise, sea level rise and incidence and intensity of extreme events such as droughts and floods. It also further reduces the impacts of the natural systems on human society , reducing the need to adapt.

The figure also illustrates that mitigation is unlike adaptation in that it reduces emissions at the start of the cycle and throughout the cycle. This is important because there are many unknowns and uncertainties in the effects and feedbacks; in consequence ***mitigation reduces risks of dangerous outcomes much more than adaptation***. Mitigation is also unlike adaptation in that mitigation is a global problem with local implications, but requiring global action, whereas adaptation is mainly a local problem.

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for Climate Change Research

The inter-disciplinary Tyndall Centre for Climate Change Research undertakes integrated research into the long-term consequences of climate change for society and into the development of sustainable responses that governments, business-leaders and decision-makers can evaluate and implement. Achieving these objectives brings together UK climate scientists, social scientists, engineers and economists in a unique collaborative research effort.

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