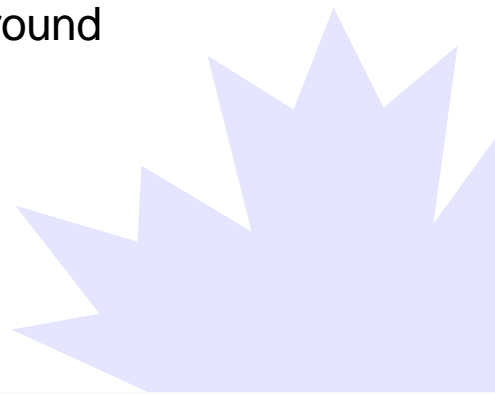


Climate Change Scenarios

Background



This presentation contains an overview of the different scenario construction methods available and the advantages and disadvantages of each.

The IPCC Task Group on Scenarios for Climate Impacts Assessment provides an excellent summary of the techniques available as well as outlining the current IPCC recommendations and reporting standards. The guidelines are available for download (pdf file) from: <http://ipcc-ddc.cru.uea.ac.uk>.

References cited in these notes:

Carter, T.R., Parry, M.L., Harasawa, H. & Nishioka, S. (1994): IPCC Technical Guidelines for Assessing Climate Change Impacts and Adaptation. UCL/CGER, 59pp.

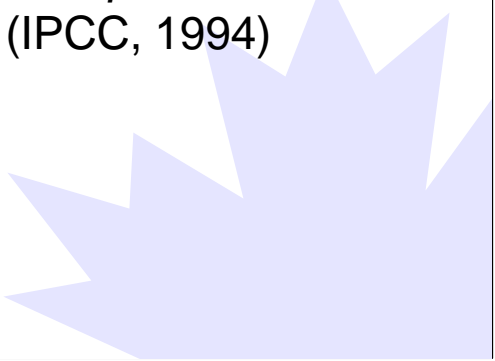
IPCC-TGCIA, (1999): Guidelines on the use of scenario data for climate impact and adaptation assessment. Version 1. Prepared by Carter, T.R., Hulme, M. and Lal, M., Intergovernmental Panel on Climate Change, Task Group on Scenarios for Climate Impact Assessment, 69pp.

Parry, M.L. & Carter, T.R. (1998): Climate Impact and Adaptation Assessment. Earthscan, 166pp.

Smith, J.B. & Hulme, M. (1998). Climate Change Scenarios. Download from:
http://www.vu.nl/english/o_o/instituten/IVM/pdf/handbook_climat.pdf

What are climate change scenarios?

“coherent, internally consistent and plausible descriptions of possible future states of the world” (IPCC, 1994)



Although this scenario definition was put forward in an IPCC technical report in 1994, not all climate change impacts studies have adhered to this definition.

This was particularly apparent during the preparation of the IPCC Second Assessment Report (published in 1996) when it was realised that it is very difficult to draw any conclusions about the impacts of climate change when all manner of scenarios have been used and applied in different ways. An IPCC workshop on regional climate change projections for impacts assessment was held in 1996 and as a result of this meeting the IPCC Task Group on Scenarios for Climate Impacts Assessment (TGCIA) was formed. The main role of this group was to consider the strategy for the provision of regional climate change information with a particular focus on IPCC Third Assessment Report.

The work of this group has resulted in the establishment of the IPCC Data Distribution Centre (operational since 1998), as well as the IPCC guidelines on the use of scenario data for climate impact and adaptation assessment, available online since 1999 (<http://ipcc-ddc.cru.uea.ac.uk>).

This basic scenario definition includes the main requirement - that scenarios be internally consistent, i.e., changes in the climate variables should be related in a consistent manner, e.g., changes in precipitation are reflected in the cloud/radiation values.

Scenario criteria:

- straightforward to obtain
- simple to interpret and apply
- estimate a sufficient number of climate variables on a spatial and temporal scale that allows for impacts assessment
- physically plausible
- spatially compatible
- consistent with the broad range of global warming projections
- reflect the potential range of future regional climate change
- representative of the range of uncertainty of projections

The basic scenario definition (see previous slide) has been expanded by the IPCC TGCIA and this slide outlines the criteria with which scenarios should conform. These criteria are taken from the TGCIA Guidelines (Carter *et al.*, 1999) - for further details please consult the guidelines (download from <http://ipcc-ddc.cru.uea.ac.uk>). These guidelines represent part of an initiative to improve consistency in the selection and application of scenario data in climate impact and adaptation assessment.

The criteria listed here have been put together from these guidelines (Carter *et al.*, 1999) as well as from earlier reports (Carter *et al.*, 1994; Parry and Carter, 1998; Smith and Hulme, 1998).

The scenarios should contain a sufficient number of variables to be of use to impacts researchers. The basic set of climate variables should consist of maximum and minimum temperature, precipitation, radiation/cloud, specific/relative humidity or vapour pressure and wind speed.

They should be physically plausible - combinations of changes in different variables should be physically consistent.

They should be spatially compatible - changes in one region are physically consistent with those in another region and with global changes.

They should be consistent with the broad range of global warming projections 1.0 - 3.5°C by 2100, or 1.5 - 4.5°C for a CO₂ doubling.

The only way that a realistic range of possible impacts can be estimated is if the scenarios reflect the potential range of future regional climate change, as well as the uncertainty in the predictions.

Scenario Types

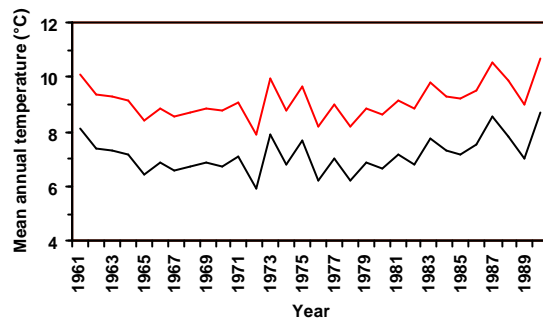
- Synthetic
- Analogue
- Global Climate Model (GCM)

There are 3 basic scenario types and to a certain extent they reflect the history of climate change scenario construction since the construction methodology has developed in line with the type of data available.

Simplest scenarios are synthetic, or arbitrary, whilst those from GCMs are most complex.

Synthetic Scenarios

Incremental changes in meteorological variables



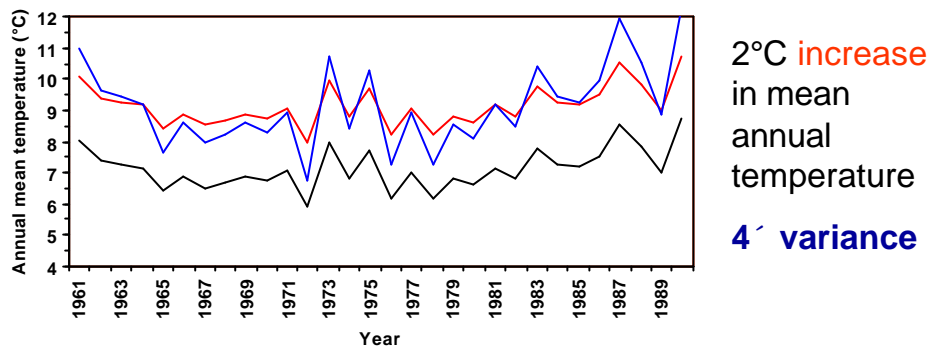
Annual mean temperature:
Toronto, 1961-1990

Increase of 2°C

In synthetic scenarios an arbitrary change in a particular variable is applied to an observed time series. In this example, an increase of 2°C is applied to the annual mean temperature time series for Toronto. The new time series (shown in red) exhibits all the same characteristics of the original (black) but is just 2°C warmer.

Synthetic Scenarios

Also possible to incorporate changes in variance



It is possible to incorporate changes in variance as well as changes in mean values. In this example the annual mean temperature time series for Toronto has had a 2°C increase applied and its variance has been quadrupled (blue). The following algorithm was used (Mearns *et al.*, 1991):

$$X_{\text{new}} = \mu + \delta^{1/2}(X_t - \mu)$$

$$\text{and } \delta = \sigma_{\text{new}}^2 / \sigma^2$$

X_{new} is the new value of the climate variable (e.g., monthly mean January temperature for year t);

μ is the mean of the time series (e.g., the mean of the monthly mean January temperatures for a series of years)

δ is the ratio of the new to the old variance of the new and old time series

X_t is the old value of climate variable (e.g., the original monthly mean January temperature for year t)

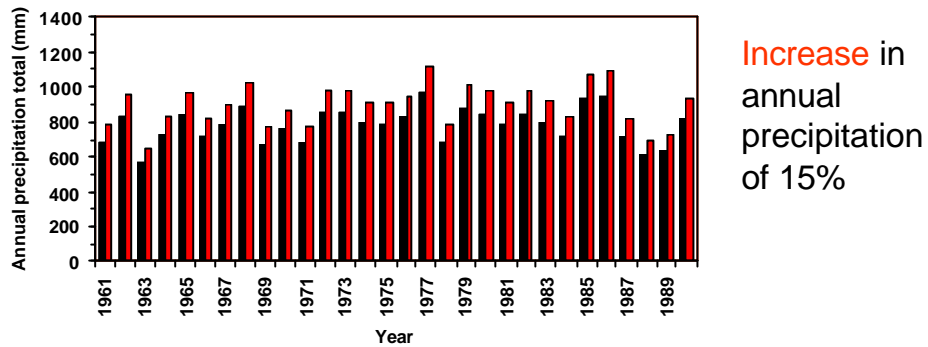
σ_{new}^2 is the new variance

σ^2 is the old variance

Mearns, L.O., Rosenzweig, C. & Goldberg, R. (1991): Changes in climate variability and possible impacts on wheat yields. Paper presented at the Seventh Conference on Applied Climatology, September 1991, Salt Lake City, Utah.

Synthetic Scenarios

.... also similar approach with other variables....



Arbitrary changes can be applied to any climate variable. Here annual precipitation totals at Toronto are increased by 15%.

Synthetic Scenarios

ADVANTAGES:

- simple to apply
- relative sensitivities of impacts can be explored by using the same synthetic scenarios

DISADVANTAGES:

- arbitrary, so seldom represent physically plausible changes
- may be inconsistent with the uncertainty range of global changes

The main advantage of synthetic scenarios is their simplicity. They can also be used to explore the relative sensitivities of different impacts models by using the same synthetic scenarios in a number of different models.

However, these scenarios do not conform to the scenario criteria outlined earlier - they are not physically plausible changes and, unless the changes are derived from GCM results they are unlikely to be consistent with the uncertainty range of global changes.

However, they do have some uses....

Synthetic Scenarios

But they can provide valuable information about:

- sensitivity
- thresholds or discontinuities of response
- tolerable climate change

Synthetic scenarios are useful for exploring the sensitivity of a particular exposure unit allowing its response per unit change in climate to be determined. Thresholds or discontinuities of response that might occur under a given magnitude or rate of change can also be determined - i.e., levels above which the nature of the response changes (a threshold above which changes in a particular variable are no longer beneficial - e.g., effect of increases in temperature on crop growth). The magnitude or rate of climate change that a modelled system can tolerate without major disruptive effects can also be determined by using synthetic scenarios.

Analogue Scenarios

Assumption: climate will respond in the same way to a unit change in forcing despite its source and even if boundary conditions differ

Based on the identification of recorded climate regimes which may resemble the future climate in a given region

- spatial
- temporal

In analogue scenarios the fundamental assumption is that climate will respond in the same way to a unit change in forcing despite its source or the boundary conditions in place at the time.

Analogues can be either spatial and temporal - in both cases we are looking for a recorded climate regime which may resemble the future climate at the location in question.

Spatial Analogues

Parry and
Carter, 1988



Identify regions today which have a climate analogous to that anticipated in the study region in the future

But

approach restricted by frequent lack of correspondence between other non-climatic features of the two regions

In the spatial analogue approach we are attempting to identify regions which have a climate that is similar to that projected for the study region in the future.

In this example, taken from Parry and Carter (1988), the analogue regions for one GCM-derived $2\times\text{CO}_2$ scenario (from the Goddard Institute for Space Studies) are illustrated (global-mean warming between 1.5°C and 4.5°C).

However, this approach is generally restricted since the non-climatic conditions of the two regions are not similar, e.g., soil type, day length etc.

Parry, M.L. & Carter, T.R. (1988): The assessment of effects of climatic variations on agriculture. In: Parry, M.L., Carter, T.R. & Konijn, N.T. (eds) *The Impact of Climatic Variations on Agriculture*. Volume 1: Assessments in Cool Temperate and Cold Regions; Volume 2: Assessments in Semi-Arid Regions. Kluwer, Dordrecht, The Netherlands, pp. 11-96.

Temporal Analogues

Use climate information from the past as an analogue of possible future climate

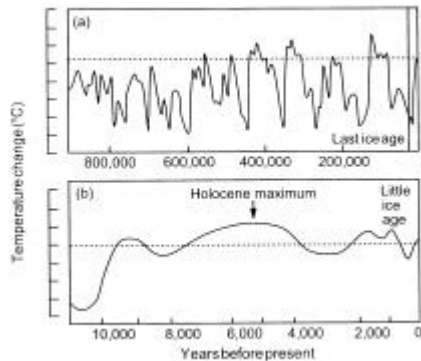
- Palaeoclimatic
- Instrumental



In the case of temporal analogues we are looking into the past for a climate at a given location which resembles the projected future climate for that location. Here we can make use of palaeoclimate information, or the actual observed instrumental record.

Palaeoclimatic Analogues

Use of information from the geological record - fossils, sedimentary deposits - to reconstruct past climates



IPCC, 1990

Three main periods of interest:

- **mid-Holocene**, 5-6k BP, 1°C warmer
- **last (Eemian) interglacial**, 125k BP, approx. 2°C warmer
- **Pliocene**, 3-4m BP, 3-4°C warmer

In palaeoclimatic analogues, information from the geological record (fossils, pollen, floral and faunal remains etc.) is used to build a picture of what the climate was like in the past by knowing the conditions under which particular tree species etc. currently flourish. This gives an indication of what the climatic conditions (e.g., temperature and precipitation regimes) were likely to have been like.

There are three periods of global warmth which are of interest: the mid-Holocene, the last (Eemian) interglacial and the Pliocene. We need to look for large-scale (i.e., global or hemispheric) warmth (since we are seeing increasing temperatures at the global scale as a result of the enhanced greenhouse effect) and then examining the climatic conditions at the regional scale of interest.

Palaeoclimatic Analogues

Caveats:

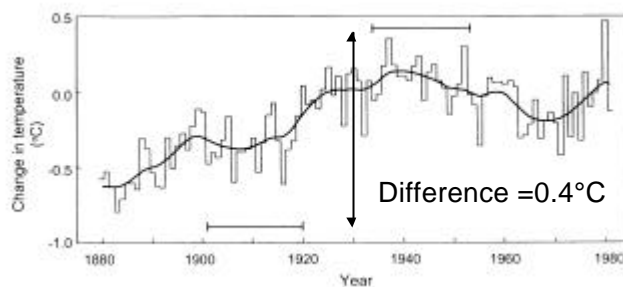
- changes in the past unlikely to have been caused by increased GHG concentrations
- data and resolution generally insufficient
- uncertainty about the quality of palaeoclimatic reconstructions
- higher resolution (and most recent) data generally lie at the low end of the range of anticipated future climatic warming

However, there are some problems when it comes to using palaeoclimatic analogues as scenarios of climate change. Generally, the data coverage and spatial resolution are insufficient to construct scenarios of use to impacts researchers. There may also be problems with accurate dating of some of the samples. The better quality data are generally most recent and therefore lie at the low end of the range of anticipated future warming. Although the temperature changes associated with the Pliocene are more in line with future projections, the quality of the data from this period is insufficient for scenario use.

The main problem with palaeoclimatic analogues is that the changes in the past are unlikely to have been caused by increased greenhouse gas concentrations. It is more likely that they were due to orbital variations (i.e., changes in the earth's orientation to and path around the sun). Hence, we cannot be certain that we will see the same regional climate conditions associated with similar increases in global-mean temperature.

Instrumental Analogues

Past periods of observed global-scale warmth used as an analogue of a GHG-induced warmer world



Lough et al., 1983

Difference between the regional climate during the warm period and that of the long-term average, or of a similarly selected cold period

Instrumental analogues are generally of more use in scenario construction since climate data from the observational record is being used for scenario construction and therefore scenarios are available at the time and space scales required and since the data has actually been observed we know that it is internally consistent and physically plausible.

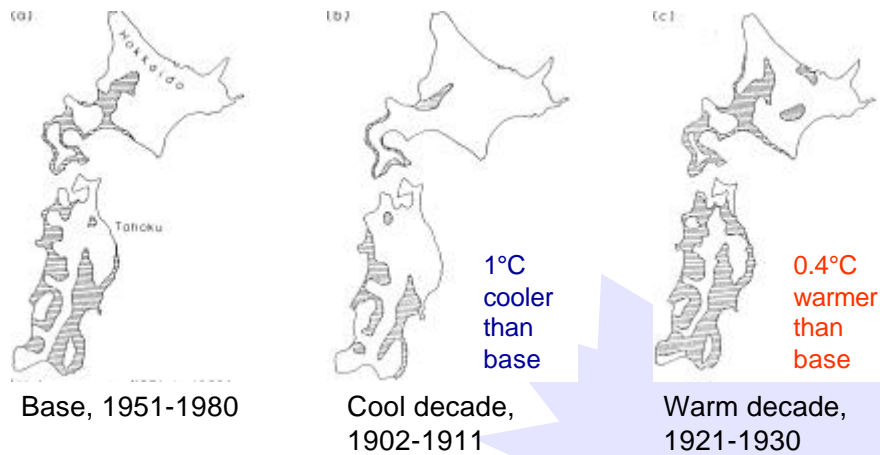
In instrumental analogues past periods of warmth in the historical record are used as scenarios for the future. These past warm periods are identified on the global or hemispheric scale by comparing a warm period with the long-term average, or a cooler period.

In the example here, taken from Lough *et al.*, 1983, the maximum warming in the Northern Hemisphere temperature record (0.4°C) is calculated by comparing the warmest (1934-1953) and coldest (1901-1920) twenty-year periods available at the time of the study.

Lough, J.M., Wigley, T.M.L. & Palutikof, J.P. (1983): Climate and climate impact scenarios for Europe in a warmer world. *Journal of Climate and Applied Meteorology*, 22, 1673-1684.

Instrumental Analogues

Example of use as scenarios in impacts studies:
rice-growing areas in Japan



This slide illustrates the application of analogue scenarios in a study examining the effects of climate change on rice production in Japan (Nishioka *et al.* 1993). The rice-growing area can be described using effective accumulated temperatures (i.e., degree days) above a threshold value of 10°C during the July and August period. Expansion and contraction of this area relative to the 1951-1980 baseline can be seen with the application of warm and cool decade scenarios, respectively.

Nishioka, S., Harasawa, H., Hashimoto, H., Ookita, T., Masuda, K. & Morita, T. (eds) (1993): The potential effects of climate change on Japan. CGER/NIES, 96pp.

Instrumental Analogues

ADVANTAGES

- data available on a daily and local scale
- scenario changes in climate actually observed and so are internally consistent and physically plausible

DISADVANTAGES

- climate anomalies during the past century have been fairly minor cf. anticipated future changes
- anomalies probably associated with naturally-occurring changes in atmospheric circulation rather than changes in GHG concentrations

Instrumental analogues may be used to construct scenarios of climate change to represent the low end of the anticipated future range of warming. We know that the data are generally at the time and space scales required by impacts researchers and since these conditions have actually been observed we know that the scenarios are internally consistent and physically plausible. However, the scenarios which can be derived from using observed data do lie at the low end of the range of anticipated future warming, so their use is limited. More importantly, the anomalies which have been seen during the first half of the last century at least are likely to be associated with naturally-occurring changes in the atmospheric circulation (e.g., changes in state of the North Atlantic Oscillation) rather than due to changes in atmospheric composition. Hence, we cannot be certain that climate will respond in the same way to increases in greenhouse gases and that we will see similar patterns as a result of this increase compared those resulting from changes in atmospheric circulation.

Scenarios from GCMs

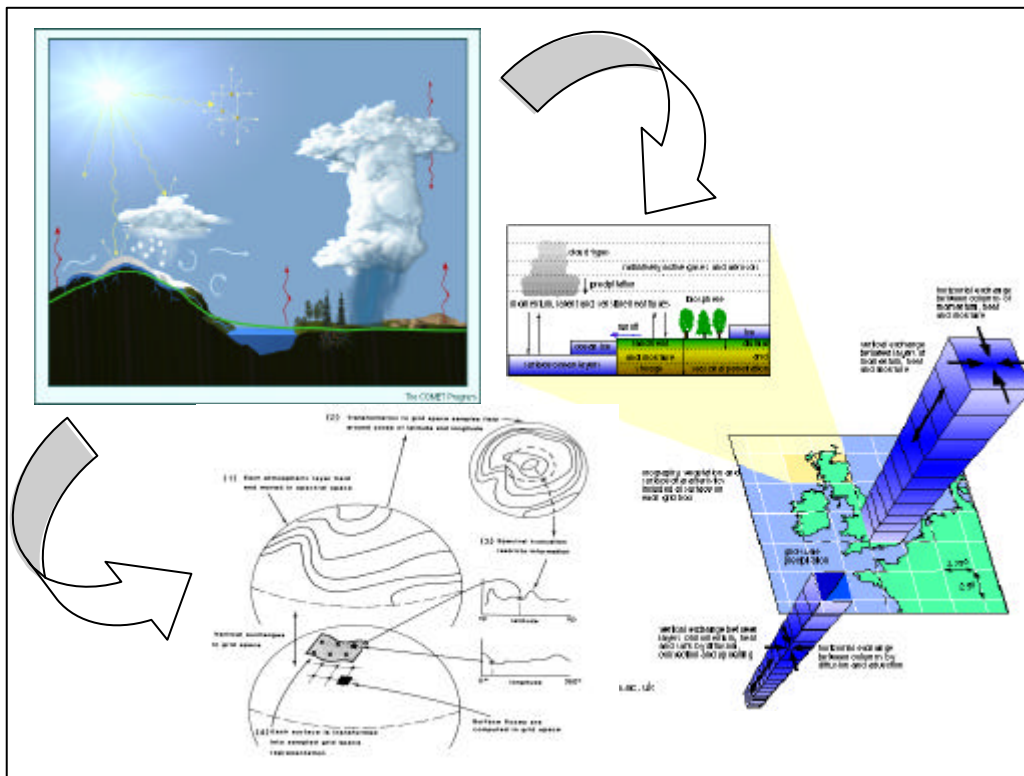
“...only credible tools currently available for simulating the physical processes that determine global climate” (IPCC)

Currently able to simulate large-scale features of the present climate quite well, but at the regional scale they may fail to reproduce even the seasonal pattern of current climate.

It has been recognised for some time that global climate models are the only credible tools currently available for simulating the physical processes that determine global climate. Experiments with these models have been ongoing since the 1970s, but it is only really in the last 10-15 years that the information from them has been used for climate change scenario construction.

These models attempt to represent the atmospheric and oceanic processes in mathematical form and so they provide internally-consistent information which is physically plausible and spatially compatible.

GCMs are able to simulate the large-scale atmospheric and oceanic features of climate reasonably well but at smaller spatial scales their performance is not as good and this has implications for the way in which scenarios are constructed from GCM data.



This slide attempts to give an indication of the complexity of global climate models. The atmospheric and oceanic processes are represented in mathematical form either in spectral or grid-form space. In spectral GCMs (the majority of models take this form) horizontal movement is considered to be in the form of waves, whilst in grid-form models grid boxes are used with exchanges occurring between adjacent boxes, both horizontally and vertically.

A good introduction to climate modelling is given in:

McGuffie, K. & Henderson-Sellers, A. (1997): A climate modelling primer. Second edition. John Wiley and Sons, 253 pp.

Scenarios from GCMs

Two types of experiment:

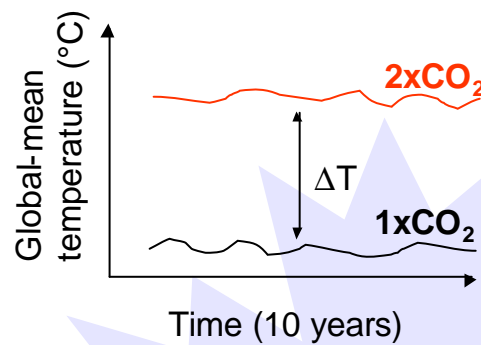
- equilibrium
- transient
 - ‘cold start’
 - ‘warm start’



Two types of experiment have been undertaken using global climate models. In earlier models, a three-dimensional atmospheric model was coupled to a very simple representation of the ocean (a ‘swamp’ or ‘slab’ ocean). Equilibrium experiments were undertaken with these GCMs since the role of the oceans was not well represented. Advances in computing technology resulted in the development of GCMs which could be run in ‘transient’ mode. In these GCMs a full 3D model of the ocean was coupled to that of the atmosphere and so the rate of change as well as the magnitude of the climate change could be modelled since the oceanic processes were well represented. Earlier transient experiments, in which no representation of historical forcing was included, are known as cold start experiments and those which do include a representation of historical forcing are known as warm start experiments. These different types of GCM experiments mean that there is a range of methodologies for constructing scenarios from GCM information.

Scenarios from GCMs

Equilibrium experiments examine the equilibrium response of the global climate following an abrupt increase in atmospheric CO₂ concentration



A step change in atmospheric composition is unrealistic. Equilibrium experiments straightforward to conduct and useful for model diagnosis and development.

In equilibrium experiments the GCM is run until a steady-state, or equilibrium, climate is achieved. A step change in atmospheric composition is then imposed, usually a doubling or quadrupling of the atmospheric CO₂ concentration, and the model run again until an equilibrium climate is again achieved. A limited amount of data is available from these experiments - usually of the order of 10 years for each of the 'control' and 'perturbed' simulations. 'Control' refers to the climate obtained using the 1xCO₂ forcing and 'perturbed' to the climate resulting from the step change in atmospheric composition, usually in response to a doubling of CO₂ (i.e., 2xCO₂).

In order to construct a climate change scenario using equilibrium experiment results, the data available from the control and perturbed simulations (usually 10 years) are averaged and then the difference (or ratio in the case of precipitation) between the two simulations is calculated (perturbed - control, or perturbed/control for precip). This is usually undertaken for the whole global data set at once and a *change field* results. *Change field* is usually used to mean a *climate change scenario*. This is the simplest way of constructing a climate change scenario.

The global-mean temperature change resulting from a CO₂ doubling is also known as the *climate sensitivity* and this is used to give an indication of how sensitive the GCM is to a change in forcing.

Since the role of the oceans is not included in these models, it is not possible to obtain any information about the rate of change; it is also not possible to associate any timing with this equilibrium climate without referring to a simple climate model.

Scenarios from GCMs

Transient experiments:

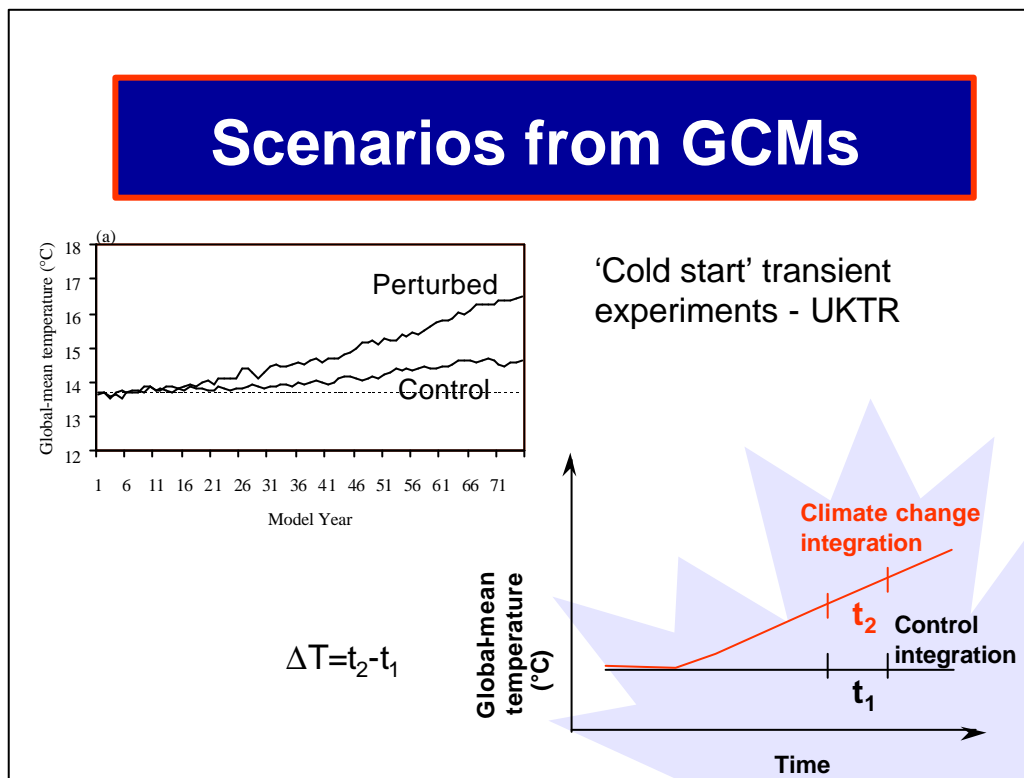
- continuous, time-dependent change in GHG concentrations
- more realistic representation of the oceans
- provide information on the rate as well as the magnitude of climate change
- most recent experiments have discriminated between regional sulphate aerosol loading and GHG forcing

Once it became feasible to couple a three dimensional ocean model to the 3D atmosphere model and to run experiments without incurring huge computing costs, it was possible to run transient GCM experiments.

In these experiments, the ocean and atmosphere models are usually run separately (the 'spin-up' process) and then coupled together. The coupled model is then usually run for a number of years to ensure that it is operating properly and once this has been ascertained, then the climate change experiment (the 'perturbed' experiment) is started. A 'control' experiment is also run in which there is no imposed forcing.

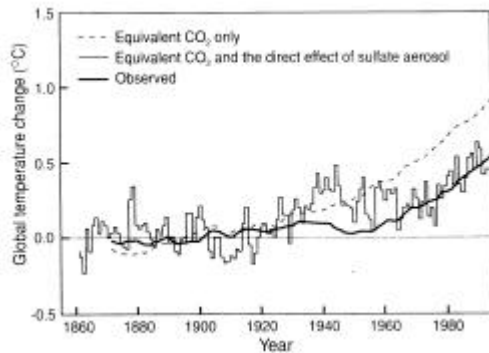
Since the role of the oceans is included through the use of a 3D ocean model it is possible to include continuous, time-dependent changes in greenhouse gas concentrations and thus to obtain information on the rate as well as the magnitude of climate change. The most recent transient experiments have discriminated between the negative forcing (cooling) of regional sulphate aerosol loading and the positive forcing (warming) of greenhouse gases.

Scenarios from GCMs



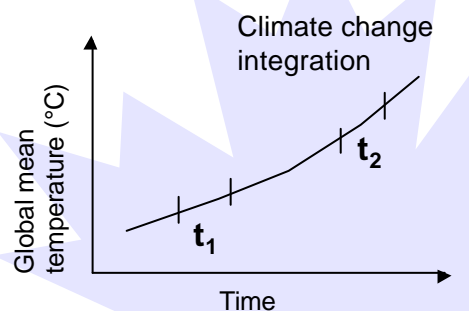
In the earliest transient experiments a number of problems were identified and these influenced the way in which scenarios were constructed from these experiments. These experiments became known as ‘cold start’ experiments since there was a lag in the response of climate to the imposed forcing. The example shown here is from the first transient experiment undertaken at the UK Meteorological Office, UKTR. It is apparent from the figure that it takes about 20 years after the start of the climate change experiment before there is any appreciable difference between the perturbed and control simulations. This lag in response is due partly to the thermal inertia of the oceans. This cold start problem makes it difficult to associate calendar dates with the climate change simulation which should theoretically have been possible with these type of experiments. ‘Climate drift’ is apparent in the control run - here it amounts to about a 1°C increase above the mean value of the first 10 years of the control simulation by the end of the experiment (75 years in this example). This drift is in part due to errors caused when coupling the atmosphere and ocean models together which increase over time. It may be that the interactions/feedbacks etc. between the atmosphere and ocean are not completely/correctly specified and over time the errors build up and the climate drifts away from reality. There may also have been insufficient spin up of the coupled model, implying that climate wasn’t in equilibrium when the climate change experiment was started. The recognised method of constructing scenarios from cold start experiments is to select a time period in the climate change simulation (here t_2) and to select the corresponding time period in the control simulation (t_1) and then to take the difference or ratio between these two periods. By selecting the same time periods in the control and perturbed simulations it is assumed that the magnitude of the climate drift is the same in each. Long-term variability is also assumed to be similar.

Scenarios from GCMs



$$\Delta T = t_2 - t_1$$

'Warm start' transient experiments, e.g., CGCM1 and models available from IPCC DDC



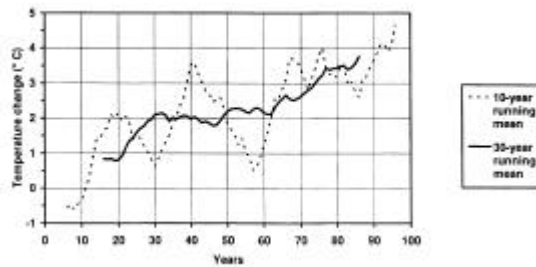
The most recent transient experiments are known as warm start experiments since they include a representation of the forcing which has occurred over the historical period. Hence, there is no lag in the climate response to the forcing imposed in the climate change experiment. Most of these warm start experiments are also flux corrected: this means that corrections have been calculated from control experiments to prevent the climate from drifting away from a realistic state. These corrections are then applied throughout the climate change experiment, with the assumption that the same correction will be required. As the modelling of the atmosphere-ocean interactions improves the need for these flux corrections is lessened.

All of the models available from the IPCC Data Distribution Centre (<http://ipcc-ddc.cru.uea.ac.uk>) are warm start transient experiments.

More data are generally available from these models (partly in response to the demands from impacts researchers) and monthly time series generally exist from about 1900 to 2100 for most models. Since a representation of the observed historical forcing is included, it is possible to associate calendar dates with the climate change integrations. The larger amount of data also means that scenarios can be calculated using longer periods (previously about 10 years of data were used since this is what was available). For scenario construction from these type of experiments, 30 years of data are generally used from two time periods selected from the climate change simulation. One of these time periods represents the baseline climate (currently 1961-1990) and the other some period in the future, e.g., 2040-2069, to represent the 2050s. A 30-year mean field is calculated for each time period and the difference (or ratio) between the baseline and future time period is then calculated (i.e., $t_2 - t_1$, or t_2/t_1).

Scenarios from GCMs

Why are 30-year periods used in scenario construction?



Carter et al., 1996

There is a large amount of inter-decadal variability in time series of, e.g., temperature and precipitation, from GCMs. If decadal periods are used for developing scenarios then the resulting change fields for a given time window may be unrepresentative of the long-term trends.

Why are 30-year periods used in scenario construction? This is a compromise between trying to capture the climate change signal without losing too much of the variability in the model results over time. Scenarios constructed from earlier transient experiments generally used only 10 years of data since this is what was available. The figure above illustrates that using such a small data set may not be advisable. In a study shown above scenarios of climate change were constructed for Finland (Carter *et al.*, 1996). The figure shows a comparison of 10-year and 30-year running means of the change between the GFDL control and climate change simulations for spring temperature. As is apparent, there is a large amount of inter-decadal variability in this time series, so much so that if decadal periods are used for developing scenarios in this instance, then the resulting change fields for a given time window may be unrepresentative of the long-term trends.

Carter, T.R., Posch, M. & Tuomenvirta, H. (1996): The SILMU scenarios: specifying Finland's future climate for use in impact assessment. *Geophysica*, 32, 235-260.

Which GCM?

- Vintage
 - Resolution
 - Validity
 - Representativeness of results
- (Smith and Hulme, 1998)

There are lots of GCM experiments available from which scenarios can be constructed, so how do you go about choosing which ones to use? Smith and Hulme (1998) put forward a number of criteria which should be considered when considering which experiments to select.

1. Vintage: more recent experiments are generally better than earlier ones. More recent experiments are generally higher resolution and have better parameterisations of sub-grid scale processes. However, an increase in resolution doesn't necessarily mean that a particular model is automatically better than an older one.
2. The resolution of some GCM experiments may not be sufficient for use in scenario construction. As in (1) more recent experiments are generally of higher resolution, but this doesn't mean that the model is necessarily better than an earlier one.
3. Validity: GCMs which simulate present-day climate most faithfully are considered to be more reliable than GCMs which have problems simulating the features of current climate. By comparing GCM performance with observed data an indication is obtained of those models which are more successful than others. However, this success will depend on the region size and also on the climate variable. It is probably better to think in terms of excluding experiments where the performance of the model is unacceptably poor - especially at estimating the features of climate that are of critical importance for the impacts application. There are lots of intercomparison projects underway and referring to the results of these will help in model selection.
4. Representativeness of results: GCMs can display large differences in estimates of regional climate change, so where several GCMs are to be selected, it is prudent to choose models that show a range of changes in the key climate variable.

The IPCC Data Distribution Centre

<http://ipcc-ddc.cru.uea.ac.uk>

Criteria for archiving GCMs at the DDC:

- an IS92a-type forcing scenario
- historically forced (warm start) integrations
- integrations with and without sulphate aerosol forcing and extending to 2100
- data in public domain and models documented
- models which have been included in intercomparison exercises such as AMIP and CMIP