The Hadley Centre regional climate modelling system

PRECIS

Providing Regional Climates for Impacts Studies

DEFRA
Department for Environment, Food & Rural Affairs

DFID Department for International Development

undp

Met Office

Summary

- *The Hadley Centre has developed a regional climate model that can be run on a PC and can be applied easily to any area of the globe to generate detailed climate change predictions. The intention is to make this modelling system, PRECIS (Providing Regional Climates for Impacts Studies), freely available to groups of developing countries so that climate change scenarios can be developed at national centres of expertise.*

- *Regional climate models have a much higher resolution than global climate models and as a result provide climate information with useful local detail including realistic extreme events. Predictions using regional climate models will thus lead to substantially improved assessments of a country's vulnerability to climate change and how it can adapt.*

Funding acknowledgements

The development of PRECIS at the Hadley Centre was funded by two UK government departments: Department for Environment, Food and Rural Affairs (DEFRA) and the Department for International Development (DFID). It has also received support from the United Nations Development Programme.

1 Introduction

All parties to the UN Framework Convention on Climate Change (UNFCCC) have a requirement under Articles 4.1 and 4.8, to assess their national vulnerability to climate change. They are also required to submit National Communications, which include discussion of these vulnerabilities and how they are planning to adapt. It is important that developing countries have their own capacity to do this. Assessment of vulnerability requires an estimate of the impacts of climate change, which in turn is based on scenarios of future climate.

Scenarios are plausible future states of the climate system. They are generally derived from predictions of climate change from global climate models (GCMs) based on emission projections, indeed, in most cases the scenario is the climate model prediction. Because predictions are uncertain for several reasons, it is advisable to develop a number of possible scenarios of future climate at any location.

GCMs can provide predictions of changes in climate down to scales of a few hundred kilometres or so at best. These predictions may be adequate where the terrain is reasonably flat and uniform, and away from coasts. However, in areas where coasts and mountains have a significant effect on weather (and this will be true for most parts of the world), scenarios based on global models will fail to capture the local detail needed for impacts assessments at a national and regional level. Also, at such coarse resolutions, extreme events such as cyclones or heavy rainfall are either not captured or their intensity is unrealistically low. The best method for adding this detail to global predictions is to use a regional climate model (RCM).

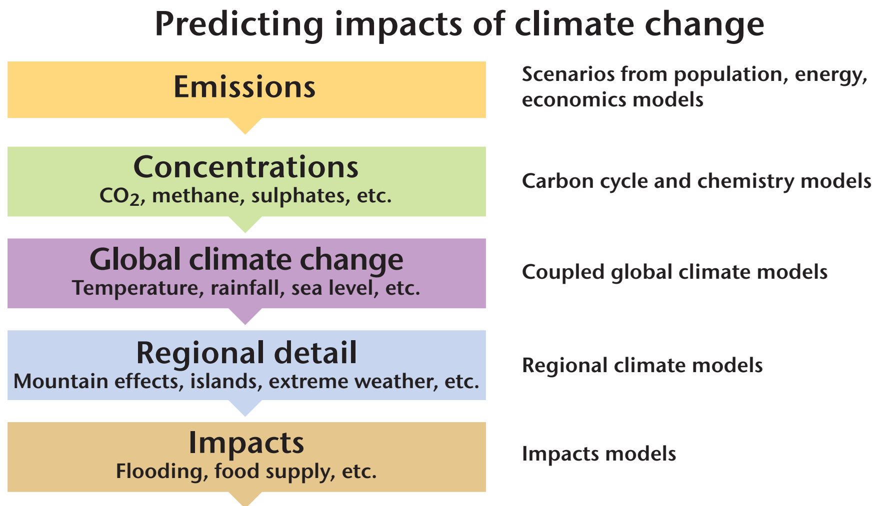
This brochure describes regional climate models and the advantages that they have over global models for providing scenarios of future climate change. It then describes PRECIS, the Hadley Centre regional climate modelling system. PRECIS runs on a PC and comprises an RCM which can be located over any area of the globe, simple interfaces to allow the user to set up and run the RCM and software (still being developed) to allow display and processing of RCM output. This is followed by sections on the current limitations on the use of RCMs and work planned to overcome these. Finally, three case studies are presented demonstrating the use of the RCM and the climate scenarios it provides.

2 Predictions of future climate change

In order to predict future climate change, we firstly need a projection of how anthropogenic emissions of the greenhouse gases (and other constituents) will change in the future. A range of emissions scenarios has been developed in the IPCC Special Report on Emissions Scenarios (SRES) and reflect a number of different ways in which the world might develop (‘storylines’) and the consequences for population, economic growth, energy use and technology.

To calculate the effect that these emissions have on the global climate we employ GCMs. They are comprehensive mathematical descriptions of the important physical elements and processes in the atmosphere, oceans and land surface which comprise the climate system (e.g. winds and ocean currents, clouds, rainfall, soils). As a result, GCMs are able to simulate the processes and interactions which define the climate of a region. They represent the broad features of current climate well and can reproduce the observed large-scale changes in climate over the recent past, so can be used with some confidence to give predictions of the response of climate to man’s current and future activities.

GCMs make predictions at a relatively coarse scale of a few hundred kilometres, but to study the impacts of climate change we need to predict changes on much smaller scales.



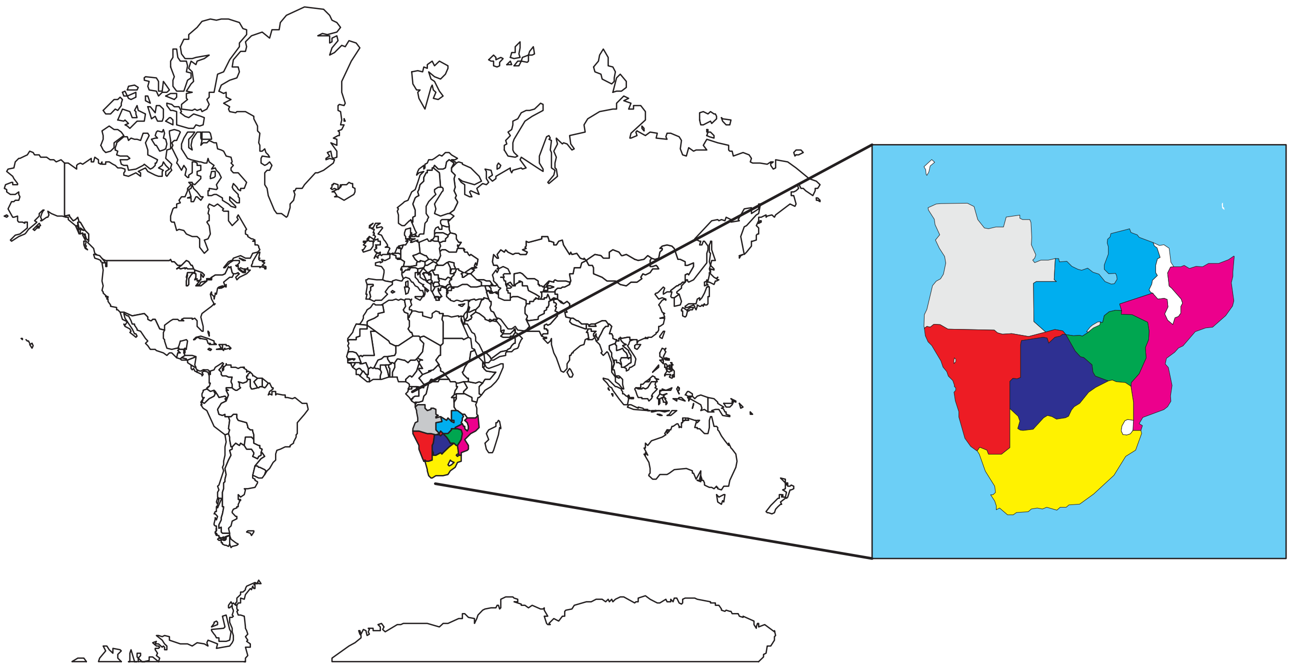
The main stages required to provide climate change scenarios for assessing the impacts of climate change.

How can we get climate change information on a smaller scale?

In order to provide predictions at the small scale needed to estimate many of the potential impacts of climate change, we need to add detail to the coarse-scale climate information provided by GCMs, and several ways of doing this have been used in the past. Interpolating between GCM grid points adds no useful information and can be misleading. Similarly a simulated future climate obtained by adding coarse-scale changes from a GCM to high-resolution observations will not contain detailed prediction of future climate.

One method of adding fine-scale information is statistical downscaling. This technique uses observations in today's climate to derive relationships between large-scale climate variables (e.g. surface pressure and atmospheric temperature), and the surface climate at point locations (e.g. precipitation measured by a rain gauge). This relationship is then applied to the GCM simulation of present-day large-scale climate, and prediction of future climate, in order to obtain the change in local-scale variable of interest. However, we cannot assume that relationships developed in the climate of the recent past will be applicable to the altered climate of the future.

The most proven method for obtaining detailed predictions, which the Hadley Centre has helped to pioneer, is to use a regional climate model, essentially a higher-resolution version of a GCM covering a limited area of the globe. This is driven by large-scale predictions from the GCM to provide high-resolution simulations for a particular area of interest.



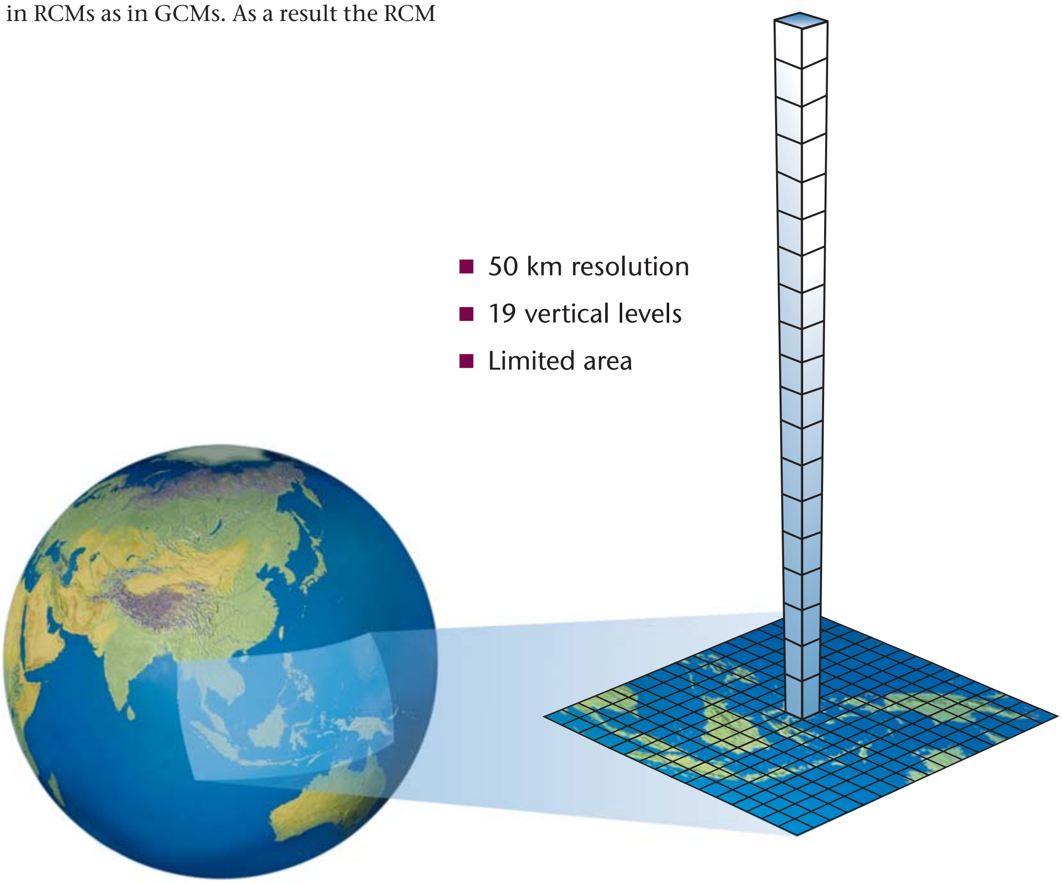
Schematic representation of countries included in a typical domain of a regional climate model.

3 What is a regional climate model?

A regional climate model (RCM) has a high resolution (typically 50 km, compared to 300 km in a GCM; see diagram below) and covers a limited area of the globe (typically 5,000 km x 5,000 km; roughly the size of a box around Australia). It is a comprehensive physical model, usually of the atmosphere and land surface, containing representations of the important processes in the climate system (e.g. clouds, radiation, rainfall, soil hydrology) as are found in a GCM. An RCM does not generally include an ocean component; this would increase complexity and need more computing power; in any case, most applications for impacts' assessments require only land-surface or atmospheric data. At its boundaries, an RCM is driven by atmospheric winds, temperatures and humidity output from a GCM. RCM predictions of ideally 30 years (e.g. the period 2071-2100) are needed to provide robust climate statistics, e.g. distributions of daily rainfall or intraseasonal variability.

The Hadley Centre uses the same formulation of the climate system in RCMs as in GCMs. As a result the RCM provides high-resolution climate change predictions for a region generally consistent with the continental-scale climate changes predicted in the GCM.

The third generation Hadley Centre RCM (HadRM3) is based on the latest GCM, HadCM3. It has a horizontal resolution of 50 km with 19 levels in the atmosphere (from the surface to 30 km in the stratosphere) and four levels in the soil. In addition to a comprehensive representation of the physical processes in the atmosphere and land-surface, it also includes the sulphur cycle. This enables it to estimate the concentration of sulphate aerosol particles produced from SO_2 emissions. These have a cooling effect as they scatter back sunlight and also produce brighter clouds by allowing smaller water droplets to form. The IPCC SRES emission scenarios show substantial changes in SO_2 emissions in the future, so it is important that the RCM can calculate their effect.

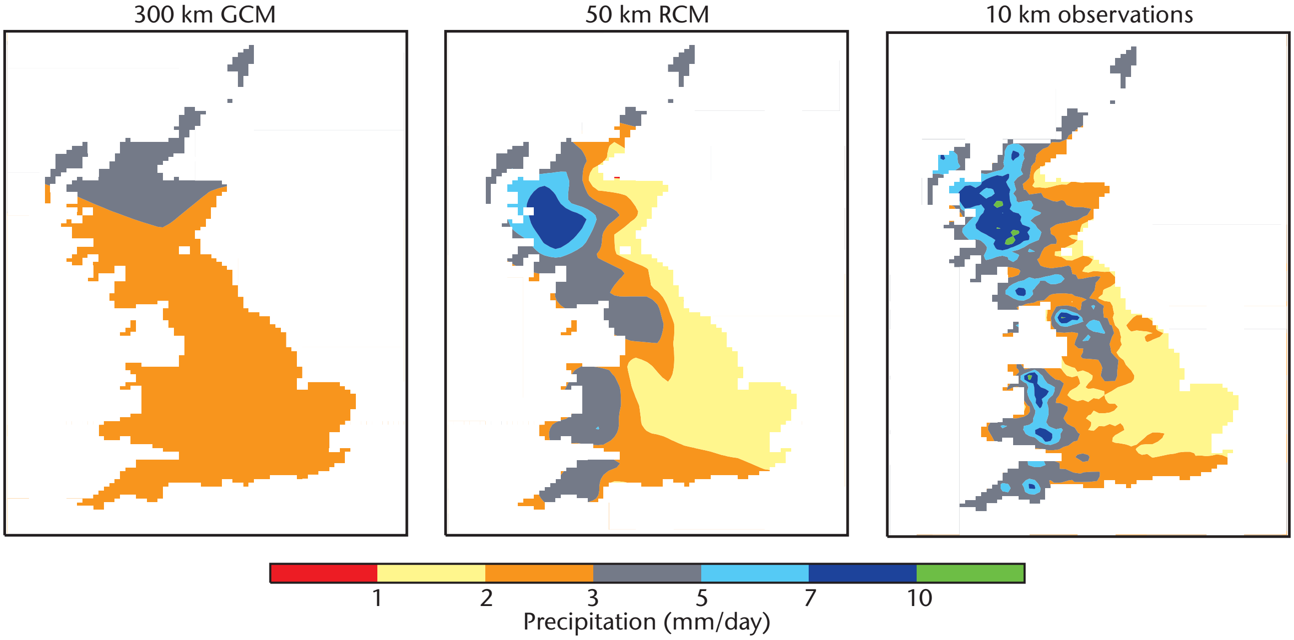


Schematic diagram of the resolution of the Earth's surface and the atmosphere in the Hadley Centre regional climate model.

4 What are the advantages of a regional climate model?

4a RCMs simulate current climate more realistically

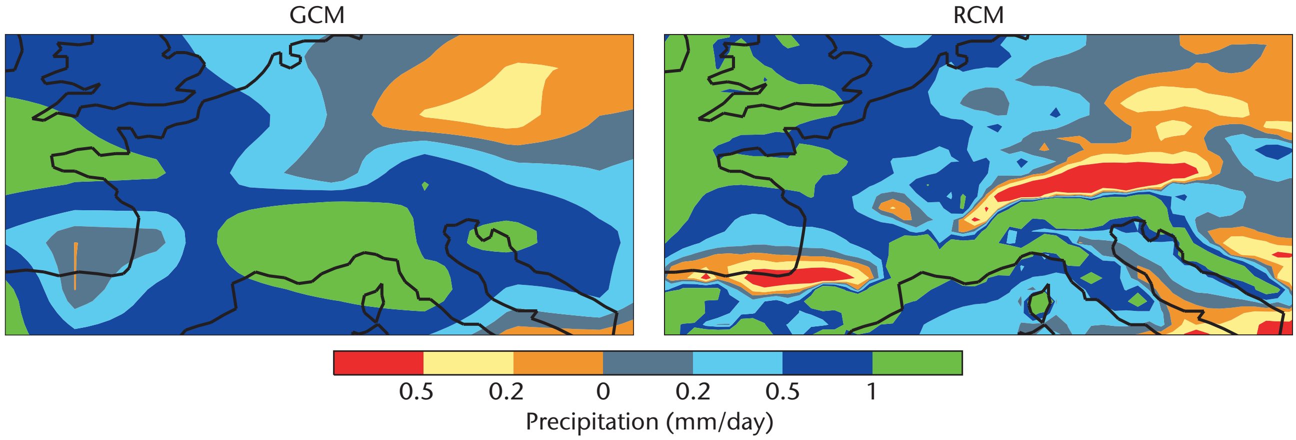
Where terrain is flat for thousands of kilometres and away from coasts, the coarse resolution of a GCM may not matter. However, most land areas have mountains, coastlines etc. on scales of a hundred kilometres or less, and RCMs can take account of the effects of much smaller scale terrain than GCMs. The diagram below shows simulated and observed precipitation over Great Britain. The observations clearly show enhanced rainfall over the mountains of the western part of the country, particularly the north west. This is missing from the GCM simulation, which shows only a broad north–south difference. In contrast to the GCM, the 50 km RCM represents the observed rainfall pattern much more closely.



Patterns of present-day winter precipitation over Great Britain. Left, as simulated with the global model. Middle: as simulated with the 50 km regional model. Right, as observed.

4b RCMs predict climate change with more detail

The finer spatial scale will also be apparent, of course, in predictions. When warming from increased greenhouse gases changes patterns of wind flow over a region then the way mountains and other local features interact with this will also change. This will affect the amount of rainfall and the location of windward rainy areas and downwind rain-shadow areas. For many mountains and even mountain ranges, such changes will not be seen in the global model, but the finer resolution of the RCM will resolve them. The diagram at the top of the next page shows how the RCM predicts that winter precipitation over the Pyrenees and Alps, two mountain ranges in Europe, will decrease substantially between now and the 2080s. The GCM for the same period shows there to be little change, or even an increase in rainfall over these areas.

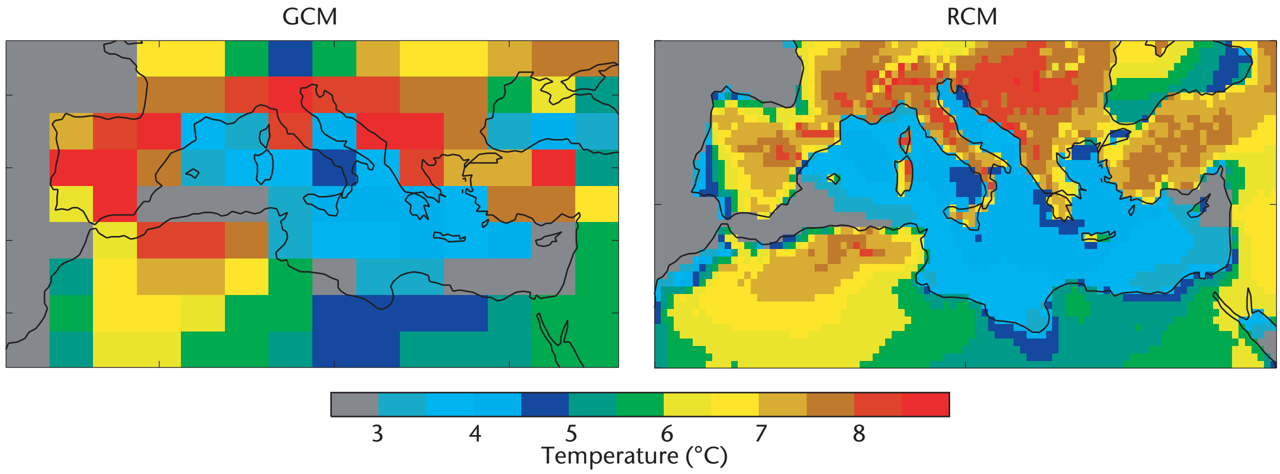


Predicted changes in winter precipitation over central/southern Europe between now and the 2080s. Left, from the global model. Right, from the regional model. The areas of red (where precipitation has decreased by more than 0.5 mm/day) indicate large reductions over the Alps and Pyrenees predicted by the RCM, but not the GCM.

4c RCMs represent smaller islands

The coarse resolution of a GCM means than many islands are just not represented and hence their climate is predicted to change in exactly the same way as surrounding oceans. However, the land surface has a much lower thermal inertia than the oceans so will warm faster. If it has any significant hills or mountains, these will have a substantial influence on rainfall patterns. In an RCM, many more islands are resolved, and the changes predicted can be very different to those over the nearby ocean.

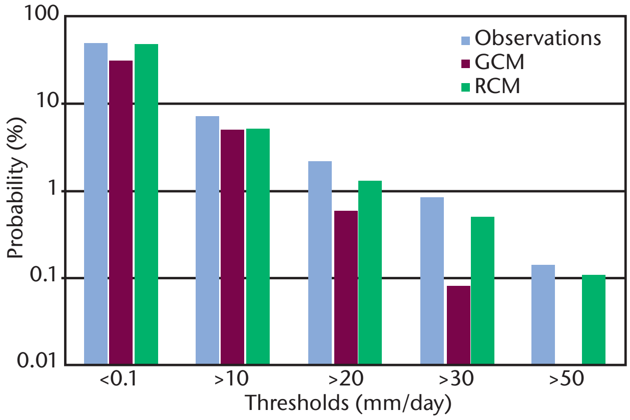
As an example, the diagram below shows the Hadley Centre GCM prediction of summer temperature change in and around the Mediterranean. Even large islands such as Corsica, Sardinia and Sicily are not seen by the GCM, and hence they appear to warm at the same rate as the sea. In contrast, in the corresponding RCM simulation these islands are resolved and are seen to warm faster than the surrounding ocean, as might be expected. Hence, impacts based on the GCM will be in error. (Of course some islands will not even be resolved at a resolution of 50 km, and await the use of the RCM at a higher resolution.)



Predicted changes in summer surface air temperatures between the present day and the end of the 21st century. Left, from the global model. Right, from the regional model.

4d RCMs are much better at simulating and predicting changes to extremes of weather

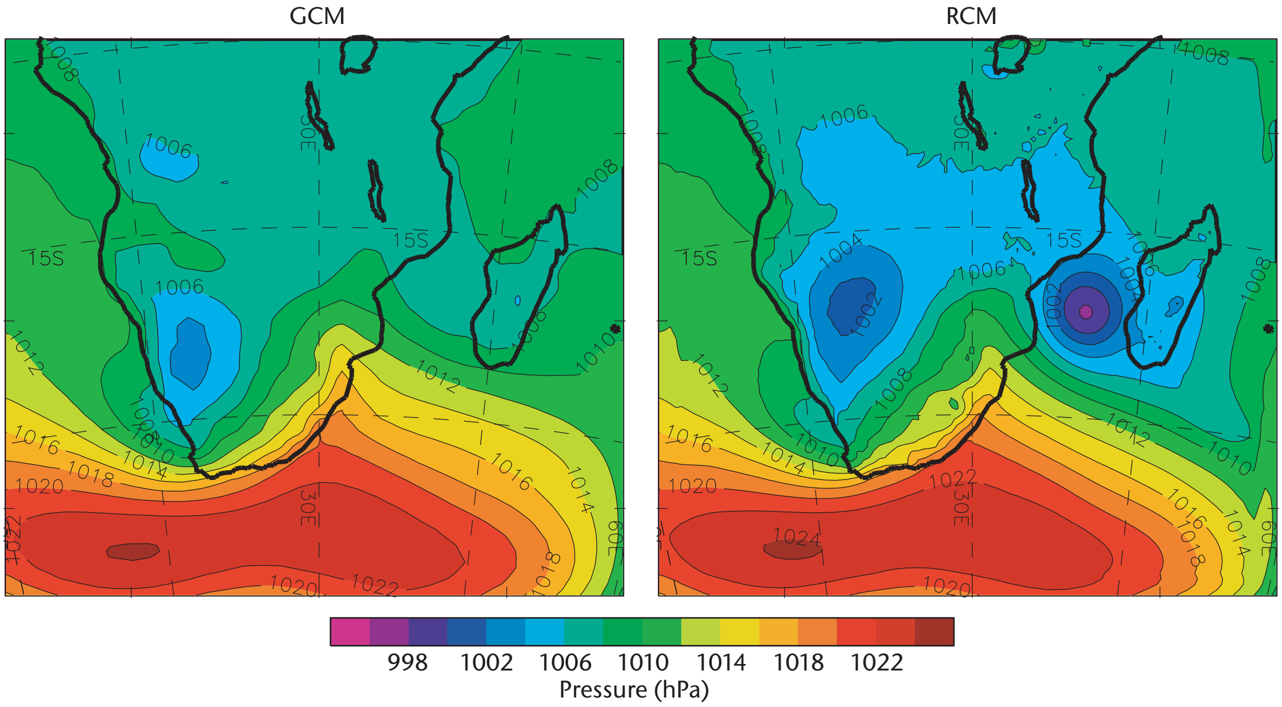
Changes in extremes of weather, for example heavy rainfall events, are likely to have more of an impact than changes in annual or seasonal means. RCMs are much better than GCMs at simulating extremes. The diagram to the right shows the probability of daily rainfall over the Alps being greater than a number of thresholds up to 50 mm. It is clear that the GCM-simulated probability does not agree well with observations, whereas the RCM simulation is much more realistic. For this reason, RCM predictions of changes in extremes in the future are likely to be very different to, and much more credible than, those from GCMs.



The frequency of winter days over the Alps with different daily rainfall thresholds. Blue bars, observed. Red bars, simulated by the GCM. Green bars, simulated by the RCM.

4e RCMs can simulate cyclones and hurricanes

The impact of a hurricane (severe tropical cyclone, typhoon), such as Hurricane Mitch that hit Central America in October 1998, can be catastrophic. We do not know if hurricanes will become more or less frequent as global warming accelerates, although there are indications that they could become more severe. The few hundred kilometre resolution of GCMs does not allow them to properly represent hurricanes, whereas RCMs, with their higher resolution, can represent such mesoscale weather features. This is clearly illustrated below, where the pressure pattern for a particular day simulated by a GCM and that simulated by the corresponding RCM are shown. At first glance, the two pressure patterns look very similar, but a closer examination shows one crucial difference; there is a cyclone in the Mozambique Channel in the RCM which is absent in the driving GCM.

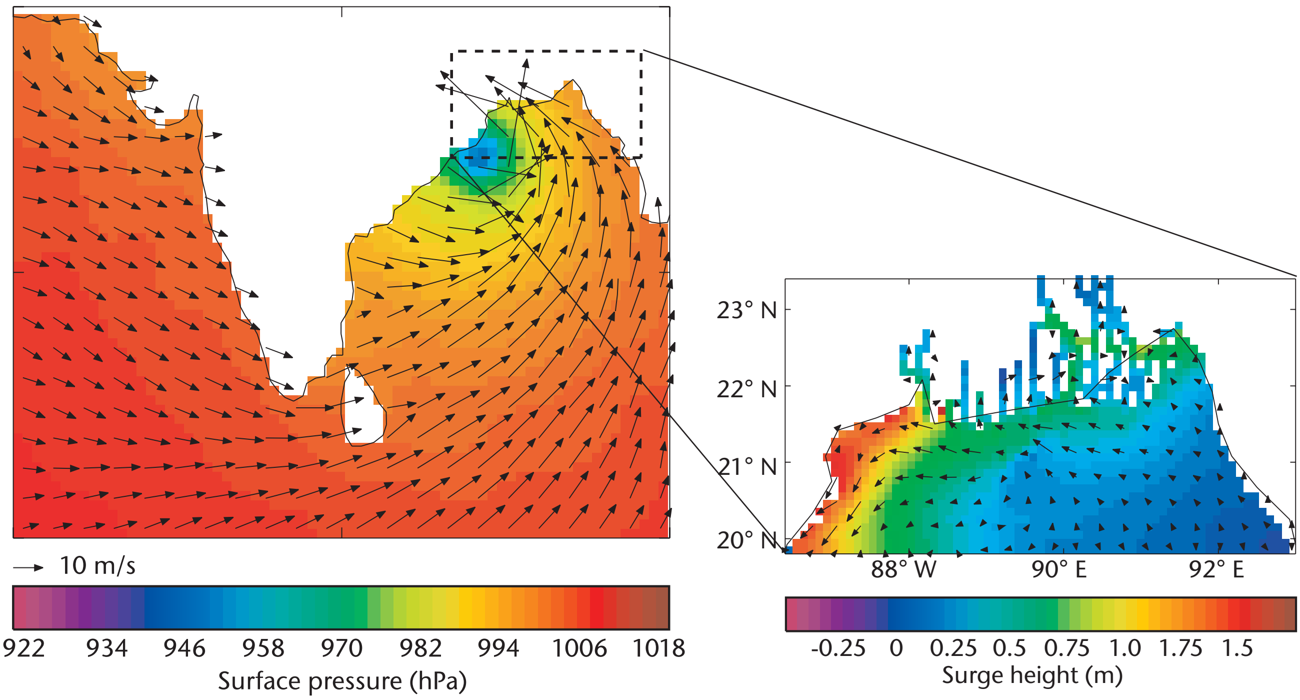


A tropical cyclone is evident in the mean sea-level pressure field from the RCM (right) but not in the driving GCM (left) for the corresponding day (from an RCM over southern Africa, developed by the Hadley Centre in collaboration with the University of Cape Town).

4f RCM data can be used to drive other models

In many cases, output from a climate model is used to drive other models, such as those simulating coastal flooding by short-lived extreme sea-level events, known as storm surges. Although GCM data can be used for this, the resolution is insufficient to provide realistic simulations. The higher resolution of the RCM allows it to drive such a model, which can predict how the frequency and intensity of storm surges might change. As an example, the RCM simulation of a cyclone in the Bay of Bengal is shown below, together with the corresponding storm surge in the Ganges delta modelled using RCM data. As previously mentioned, GCMs do not simulate severe tropical cyclones, and hence would fail to simulate the corresponding storm surges.

Of course, changes in high-water events, which could lead to coastal flooding, will also be strongly influenced by sea-level rise. This is not predicted by the RCM, and therefore comes from GCM predictions. While we have confidence in the global mean predictions of sea-level rise, and can use them in impacts studies, we currently have much less confidence in the regional details.



A cyclone in the Bay of Bengal simulated by the Hadley Centre RCM and the resulting high water levels in the Bay of Bengal. The latter were simulated using a coastal shelf model developed by Proudman Oceanographic Laboratory.

5 PRECIS – Providing Regional Climates for Impacts Studies

There is a growing demand from many countries for regional-scale climate predictions. Yet at present, developing, setting up and using a regional model over a specific area of the globe requires a considerable amount of effort from an experienced climate modeller. In addition, RCMs (like GCMs) are usually run on large computing installations, such as the Cray T3E at the Met Office in the UK. Both these factors effectively exclude many developing countries from producing climate change predictions and scenarios. The Hadley Centre has developed an efficient way of meeting the demand for RCM predictions. It has configured the third-generation Hadley Centre RCM so that it is easy to set up and can be run over any area of the globe on a relatively inexpensive fast PC. This, along with software currently being developed to allow display and processing of the data produced by the RCM, will form PRECIS.

The intention is to make PRECIS freely available for use by developing country scientists involved in vulnerability and adaptation studies conducted by their governments, such as those to be reported in National Communications to the UNFCCC. It is assumed that scientists in a group of neighbouring countries can work together so that they can configure the model over their own region and run their own regional climate change predictions; the advantages of this are discussed in the box below. The PRECIS RCM needs to be driven at its boundaries by data from a GCM and this will also be supplied, corresponding to a range of emissions scenarios. National climate change scenarios can then be created locally for use in impact and vulnerability studies using local knowledge and expertise. Some training courses would be run, and user-friendly supporting software and online help will be provided to allow local groups of countries to use PRECIS largely independently.

This project will lead to much more effective dissemination of scientific expertise and awareness of climate change impacts than could be achieved by simply handing out results generated from models run in developed countries. Later in this report we show some case studies of RCM predicted climate changes over India and over southern Africa. We also show an example of how data from the PRECIS RCM has been used to look at the impact of climate change on water resources over southern Africa. A sample display of PRECIS configured for a southern Asian region is provided on the next page.

Using PRECIS for groups of countries

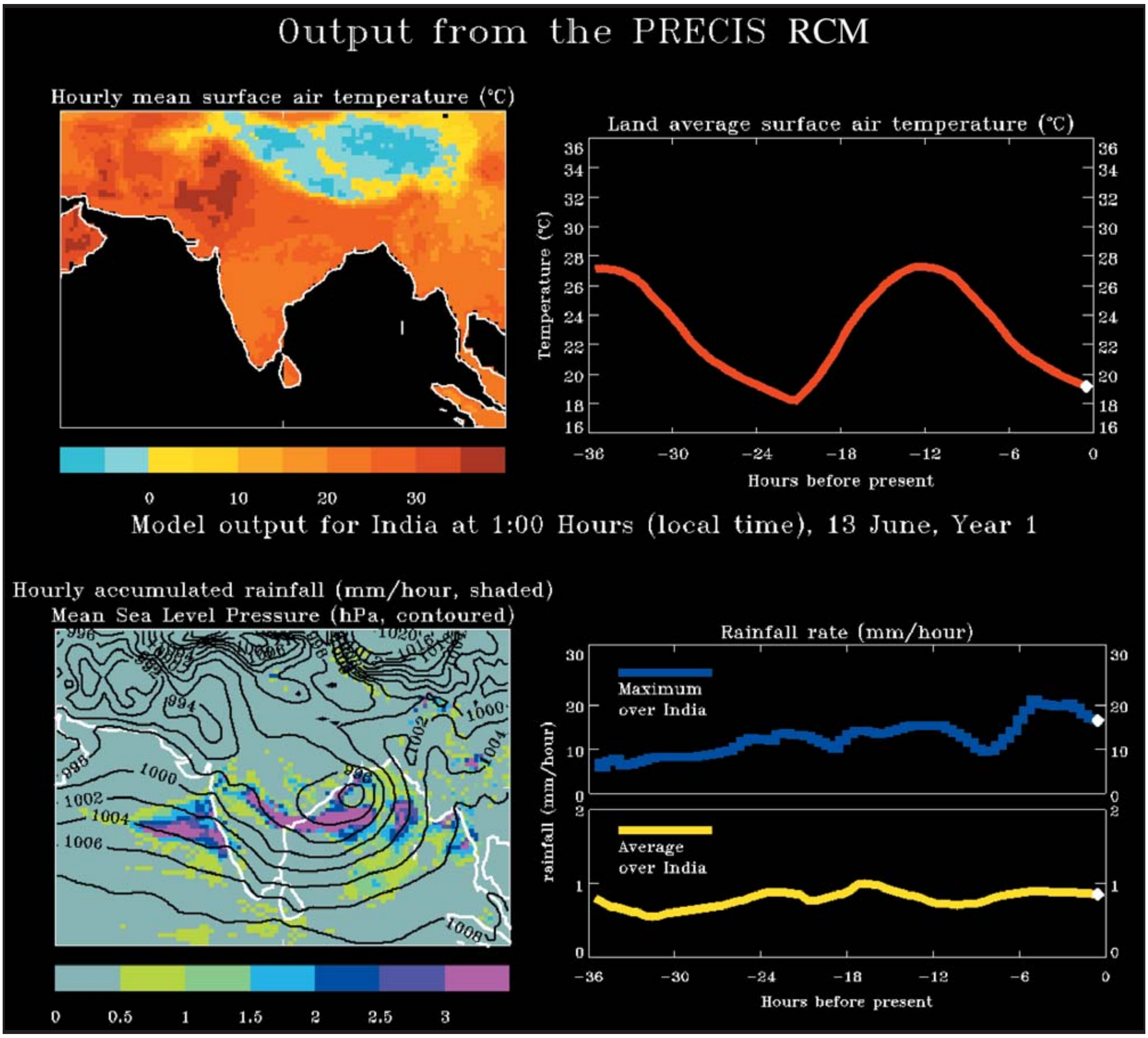
PRECIS will usually cover regions encompassing several countries who may find it useful to work together. Because an RCM is driven by a GCM field at its boundary, there is a strip about 400 km wide where adjustment between the two models is taking place, and where RCM data is not useable. Hence the minimum working area is 5,000 km x 5,000 km for it to be efficient, which will generally be big enough to cover a number of countries (for example the southern African domain used in the case studies).

There are distinct advantages to countries working together, in order to explore the range of uncertainty in climate predictions. Uncertainty in predictions arises from three distinct causes: uncertainty in future emissions, uncertainty in how the climate will respond to emissions, and natural variability (see box on page 12, *Uncertainties in climate change predictions*). To quantify the range of uncertainty in predictions it is desirable that many RCM experiments should be run, covering:

- a range of SRES emissions scenarios (e.g. B1, B2, A2, A1FI), to cover the uncertainty in future emissions;
- a range of climate models from the main modelling centres, to cover the uncertainty in climate response;
- different initial conditions, to quantify the uncertainty due to natural variability;
- different time periods (e.g. 2041–2070, 2071–2100), but if this is not possible, then the later period (2071–2100) should be modelled, and patterns of change for earlier periods can be scaled from this.

While these could all be done by one country, it is obviously much more efficient and quicker for the work to be shared and results exchanged.

Training on the use of PRECIS would be more efficient in groups of people from several countries rather than being done individually. This would also promote collaboration between countries in a region. Lastly, many impacts models will extend over a large area, and the impacts can be calculated just as easily for a whole region as for a single country. The new GEF-funded programme, AIACC (Assessments of Impacts of and Adaptation to Climate Change in Multiple Regions and Sectors, www.start.org/Projects/AIACC/aiacc.html) is based on groups of countries, as in many cases they have similar vulnerabilities and face similar impacts from climate change.



Example output monitoring the PRECIS RCM running over a southern Asian region showing (from top left, clockwise): surface temperature over the region's land areas averaged for the model time displayed; a time-series of average temperature over India for the model's previous 36 hours (the diurnal cycle can be clearly seen); maximum and area average rainfall over India for the same 36-hour period and a map of rainfall and surface pressure isobars for the model time displayed.

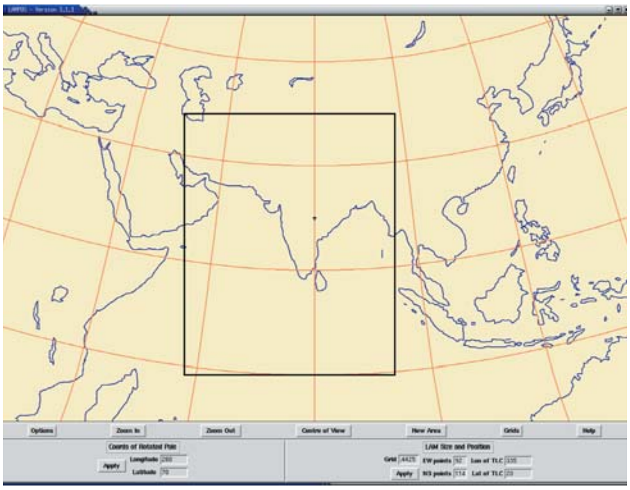
6 How do we use PRECIS?

Once PRECIS is installed on the PC and started, the user is presented with a graphical menu (shown below left) which allows the domain (area) of the model to be specified by choosing an appropriate central point and drawing a rectangular box around it (below right). It also asks the user to specify the length of simulation (10, 20 or 30 years) and the particular GCM driving fields to be used (for example, SRES A2 emissions scenario). The user will also have to decide what quantities from the model output should be saved, and how often. In principle, all the model quantities, at every grid point, from the surface to 30 km in the atmosphere, could be saved at every time step. However, this would produce an enormous amount of data that would be almost impossible to store on a PC.

The interface to the PRECIS RCM. The first row of buttons start graphical interfaces (the first is shown on the right) to set up the model for the chosen region. The button on the second row starts a graphical interface to define the data the model will display when running and will archive. The bottom button starts (or restarts, if necessary) the RCM simulation.

The model prediction can then be started, and the model will step forward every five minutes of model time (about four seconds of real time), calculating the new state of the climate system at each step. During the prediction run the output can be monitored in a number of ways; for example, displaying a map showing rainfall or temperature patterns every model hour, or plotting a graph of temperature over a single grid square covering an area of interest (see page 9). Some technical parameters can also be displayed so that any problems can be quickly identified. If the prediction run is stopped part way through (either deliberately or because of a power failure, for example) then it can be easily restarted without loss of data.

In addition to making data from the RCM predictions available for impacts assessments, it can be valuable in its own right to publish this information (with some simple analyses) in the form of maps and diagrams. For example, maps of changes in quantities (such as maximum and minimum temperature, rainfall, soil moisture) for each of the four seasons and as an annual average, for the period 2071-2100, can be easily generated by the RCM user (see case studies for examples). Further analysis can generate quantities such as change in number of days with heavy rainfall, with temperatures greater or less than a given threshold, or changes in the number of droughts. In the UK, we have found that, when combined with information on the current observed climate, a short booklet can be produced which is not only a source of information, but which can have the effect of making the issue of climate change more visible to government and other stakeholders.



Setting up the domain for PRECIS.

PRECIS: some technical details

PRECIS will be supplied on a CD-ROM. It should be installed on a PC having the recommended minimum specification of a 1 GHz processor, 512 Mb of memory, 60 Gb of disk space and a tape drive to allow off-line storage of input and output data. A PC running the easily installed Linux operating system is required. A PC having 1.4 GHz Athlon processor takes approximately 4–6 months to carry out a 30-year simulation. This would produce 150 Gb of data, giving a comprehensive description of the simulated climate. This run time seems long, but is actually comparable to the time taken for climate predictions made on supercomputers at large climate modelling centres.

Hadley Centre GCM fields of global quantities which are required to drive the PRECIS RCM will also be supplied on CD-ROMs or tapes and may be available online. Online support will consist of a web site and mailing list, both maintained by staff at the Hadley Centre. These will provide users with details of the current status of the project, provide hints and answer queries, enable users to exchange data and methods and supply updates and modifications to the model.

Included on the standard release CD-ROM will be:

- executables and source of the PRECIS RCM and control code;
- software to set up, control and monitor the PRECIS RCM;
- software to automatically archive data produced by PRECIS;
- software to process the generated data, e.g. to form multi-annual means, distributions or time-series from the archived data;
- software to display the processed data.
- software to extract data in a form that can be used by impact models;
- HTML pages providing guidance on setting up and using PRECIS.

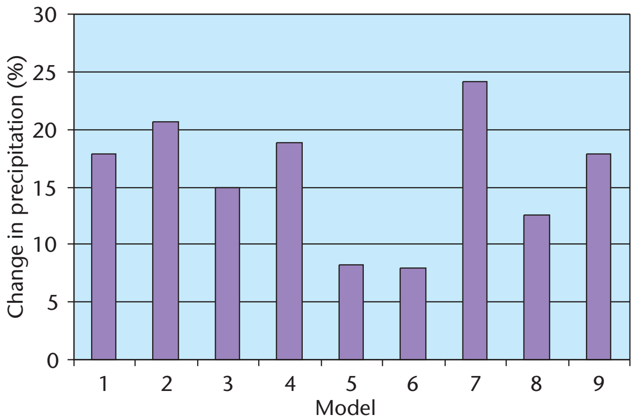
7 Limitations of RCMs for climate change scenarios

In common with other techniques, regional climate models do not yet provide all the solutions for generating climate change scenarios. There will be errors in their representation of the climate system and their resolution will not be sufficient for some applications. In addition, there are two main limitations to their use in conjunction with GCMs.

Predictions from an RCM are dependent on the realism of the global model driving it; any errors in the GCM predictions will be carried through to the RCM predictions. This limitation is shared by all techniques for generating realistic climate scenarios.

Because different GCMs represent the climate system in different ways, predictions that they make at a regional scale can be very different (see right). As there is currently no assessment available of the quality of the GCM predictions, ideally an RCM should be driven by predictions from a range of GCMs to explore uncertainty. However, there are many practical problems yet to be solved before it is easy to do this. Firstly, interfacing RCMs with a range of GCMs is a complex technical issue which is only now beginning to be addressed. Secondly, the data requirements of RCMs are very substantial and these have to be planned for before running a GCM experiment. Thirdly, the data volumes are currently expensive to archive and time-consuming to transfer. Fourthly, the computing resources needed to run an RCM driven by a large number of GCMs are substantial.

Ways in which these limitations are being addressed are discussed later.



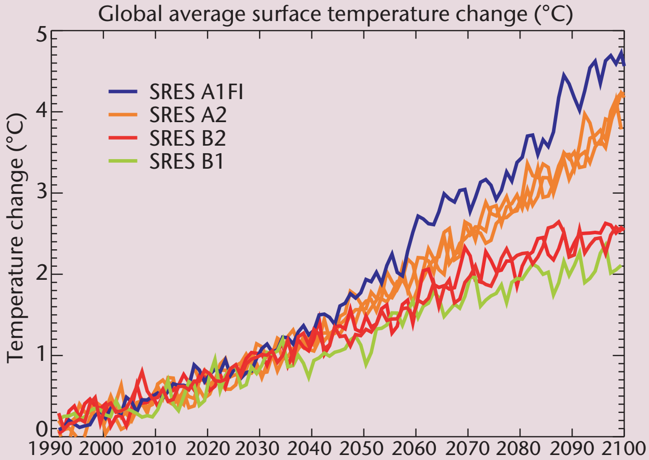
Area averaged changes in summer rainfall for the period 2071-2100 over southern Asia as predicted by nine coupled models forced by the A2 emissions scenario (taken from Chapter 10 of the Scientific Basis of the IPCC Third Assessment Report). In other areas predictions can show much greater differences in magnitude and even sign.

Uncertainties in climate change predictions

When assessing the impacts of climate change and the vulnerability of a country, it is important to use not just one climate scenario but a number which attempt to cover the range of uncertainty. Uncertainty arises from three main causes; the magnitude of future emissions, the response of climate to these emissions, and natural variability.

A. Future emissions

As we do not know how emissions of greenhouse gases will increase in the future, we have driven the Hadley Centre GCM with emissions which would result from four storylines, developed in the IPCC Special Report on Emissions Scenarios (SRES), which essentially cover the range of uncertainty. These are labelled A1FI, A2, B2 and B1 in order of decreasing emissions. The resulting global temperature changes range from about 2 °C to 5 °C, representing the uncertainty due to future emissions, and are shown below.



The evolution of global mean surface temperature from 1860–2100 as simulated by the latest Hadley Centre coupled model. Observed changes in greenhouse gases are used to drive the model up to 1990, and thereafter four SRES emissions scenarios are used, as shown. The three orange and two red lines refer to the evolution in the simulations using the same emissions scenario but different initial conditions.

B. The response of the climate system

Because we have an imperfect understanding of the way the earth's climate system works, no climate model can give an accurate prediction of climate change. We do not know what the true uncertainty in predictions is, but we can make an estimate of this by taking predictions from a range of climate models. For example, the global mean temperature change resulting from A2 emissions ranges from 4.7 °C in the most sensitive model reported in the IPCC Third Assessment Report Technical Summary to 2.7 °C in the least sensitive.

At a regional level, the spread in predictions from GCMs can be even larger. However, the 2001 IPCC Scientific Assessment has shown that agreement between GCMs on regional-scale seasonal-mean changes has improved. For example, models show consistency in relative warming in three-quarters of world land regions and in the sign of precipitation change in two-thirds of regions. Consistency is better at mid- and high-latitudes.

C. Natural variability

A further type of uncertainty, very different from those above, comes from the natural variability of climate. For a given period in the future, natural variability could conspire to either add to the underlying man-made change, and thereby make conditions even more pronounced, or could subtract from it, to make it less pronounced. Because we cannot predict natural variability, and are unlikely to be able to do so for some time, we have to live with this uncertainty by quantifying it. This is done by running the climate model with different initial conditions. Results over the eastern part of England, using this technique, show that a predicted decrease in summer rainfall by the middle of the century of 16% (averaged over four model runs) could be as much as 27% or as little as 2% depending on whether natural variability tended to give drier or wetter conditions.

8 Further developments

Although PRECIS is a major step forward in making climate modelling more readily accessible, developments over the next few years are expected to improve it further. Some of these anticipated developments are as follows:

1. The global models used to drive the RCM and the RCM itself will continue to be improved. Three main areas will be addressed:

   increasing resolution in both the atmosphere and ocean;

   improving the representation of processes in the atmosphere (e.g. clouds) and in the ocean (e.g. eddies);

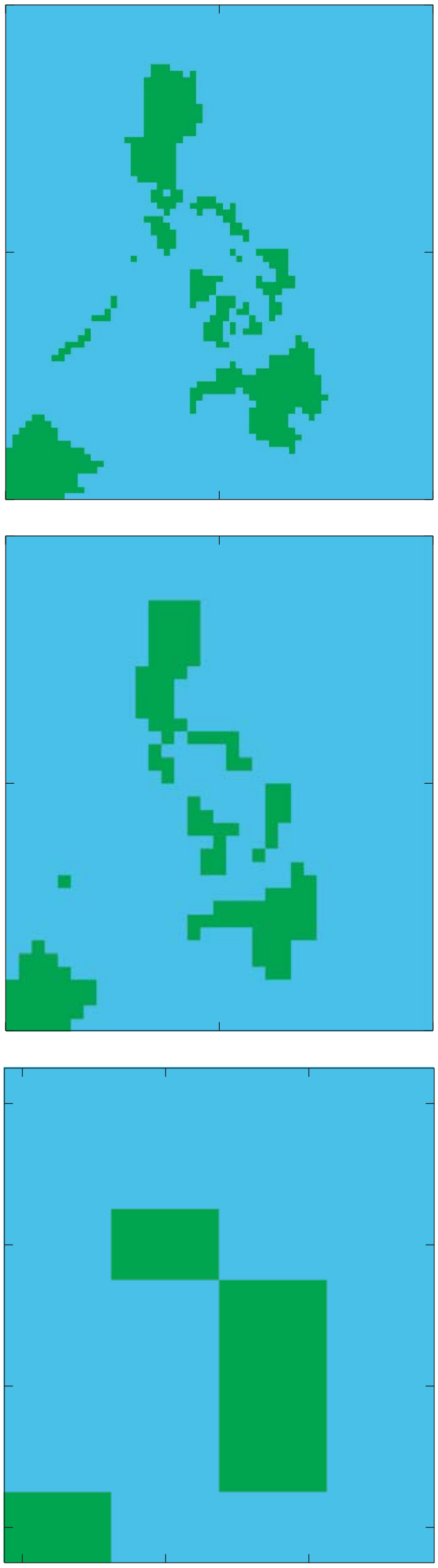
   including new processes that provide feedbacks onto climate (e.g. the carbon cycle, atmospheric chemistry).

2. The current resolution of the RCM is 50 km. A 25 km resolution version of this has already been developed and is currently being evaluated. In the next three years, a 10 km RCM is planned for application to smaller domains. This will improve the realism of the models further allowing more geographic detail to be resolved and better simulation of extremes. The extra detail is demonstrated clearly when resolving the islands of the Philippines at 50 km and 25 km (see right). Unfortunately, an RCM with twice the resolution will be four to eight times slower, so the practical application of higher-resolution models awaits faster PCs or the use of PC clusters (networked PCs providing a parallel processing facility).

3. A regional ocean model developed for shelf seas forecasting will be coupled to the atmospheric RCM to provide a coupled regional modelling system. Taken with improvements in GCMs, this will allow direct predictions of regional sea-level rise and storm surges as well as providing high-resolution regional ocean climate scenarios consistent with those from the atmospheric RCM.

4. Software will be provided to allow PRECIS to use data from other centres' GCMs. It is important that the uncertainty from the different regional responses in different GCMs is explored, which could be done by using them to drive the PRECIS RCM. This is currently not possible as software to reformat the data from these GCMs is not available and, in many cases, the data themselves are not available. The uncertainty in the coarse-resolution GCM predictions over any region can currently be explored by obtaining data from the IPCC DDC or using, for example, the SCENGEN generator.

5. Just as climate modelling centres develop independent GCMs, many of them also develop RCMs, and these can give a spread of predictions. It is hoped that some of these can be compared over the next two to three years and the results gained will lead to a first estimate of the uncertainty in predictions of detailed climate changes. This is currently being started in Europe under a European Commission funded project, PRUDENCE.

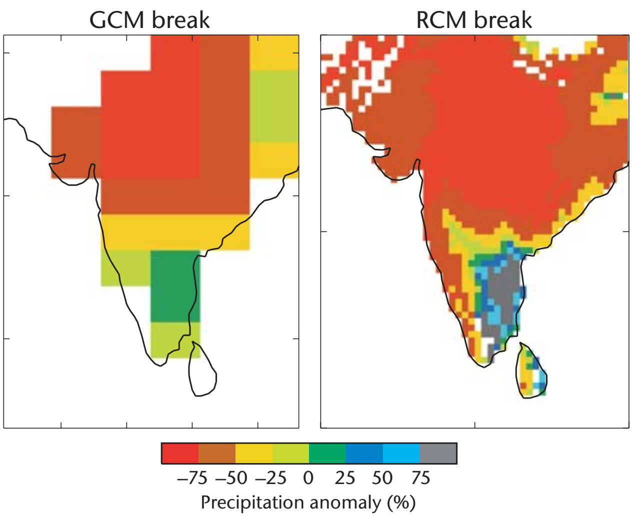


The representation of the Philippines in RCMs with resolutions of 25 km and 50 km, and in the GCM (400 km resolution).

Case study: Application of an RCM to the Indian subcontinent

The single most important factor in the annual agricultural cycle of south Asia is the rainfall brought on by the summer monsoon. At the continental scale, mean summer season rainfall is fairly constant from year to year but high spatial and temporal variability leads to localised flooding or even drought conditions. Within a given monsoon season phases of low activity occur, termed break periods, as do periods of high activity, termed active periods. The typical precipitation distributions during these regimes are in anti-phase: break periods are associated with dry conditions over most of the region apart from south-east India and Bangladesh whereas active conditions bring heavy precipitation only over central India. These phenomena create significant climatic impacts throughout the whole region.

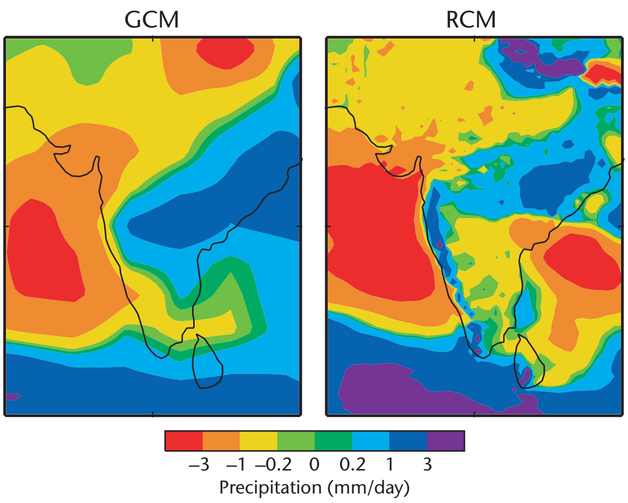
To examine how faithfully the RCM represents the Indian summer monsoon, the previous Hadley Centre RCM was used to simulate the climate of the region for the present day. Both the RCM and its driving GCM simulate realistic mean synoptic flow conditions and the main features of the monsoon season precipitation, including the break and active precipitation anomalies over central India. However, only the RCM captures the observed precipitation anomalies over the south as shown below.



Precipitation anomaly during break periods in the GCM (left) and RCM (right) control simulations expressed as a percentage of the summer monsoon season (JJAS) mean. Sea points and areas of low daily rainfall (<1mm/day) are not shaded. (The RCM was developed in collaboration with the Indian Institute of Technology).

This is due to its ability to simulate extreme daily rainfall events associated with westward tracking weather systems passing over the region. The RCM is able to simulate these cyclones, preferentially in break periods as observed, and their interaction with the mountains rising steeply from the eastern coast produces the extreme rainfall. In contrast the GCM simulates weaker depressions, fewer in break periods and no enhanced rainfall over south east India. We can therefore attribute the better simulation in the RCM to an interaction between more skilfully resolved weather systems, in both structure and frequency, with the much more realistic fine-scale topography.

The RCM and the GCM were also used to predict climate change by the middle of the century. The predicted changes in mean monsoon rainfall in the two models are broadly similar but there are substantial regional differences. For example, over much of the Western Ghats mountain range (which runs up the west coast of India) and in parts of southern India the global model predicts a decrease in rainfall whereas the local effect seen in the RCM is actually an increase (see below). Conversely, over a large area of central India the RCM predicts decreases, most markedly over the east coast, where the GCM indicates increases. Given that the RCM better represents the influence of the topography and the sub-seasonal variations in monsoon precipitation, we have more confidence in its predictions of these regional changes.

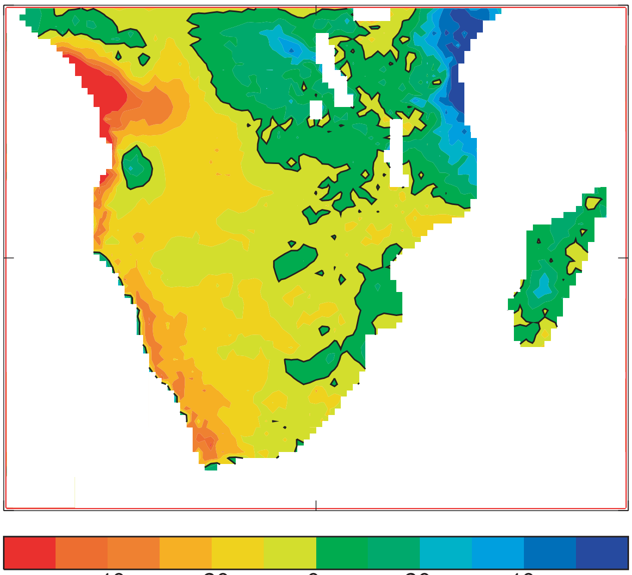


Predicted changes in monsoon precipitation over India, between the present day and the middle of the 21st century from the GCM (left) and from the RCM (right).

Case study: Application of the PRECIS RCM to southern Africa

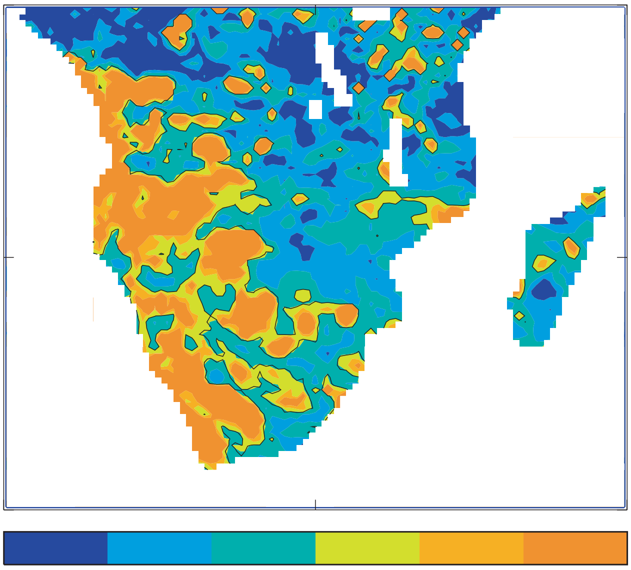
Because water is a limited resource in many sub-Saharan African countries, this region may be very vulnerable to human-induced climate change. Hence, the PRECIS model has been applied to this region in order to derive high-resolution climate change predictions.

Under the SRES A2 emissions scenario the RCM predicts an average surface warming over the subcontinent of 3.8 °C in summer and 4.1 °C in winter by the 2080s. It also predicts a reduction in rainfall over much of the western and subtropical subcontinent, and wetter conditions over eastern equatorial and tropical southern Africa during summer when most rain falls (see below).



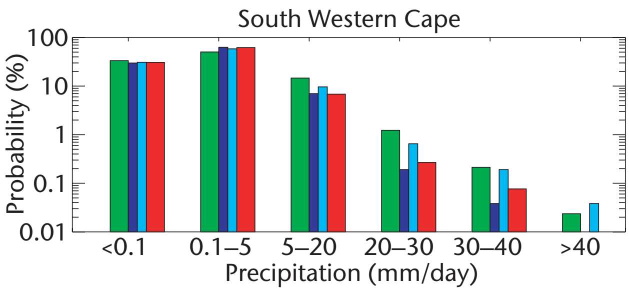
Change in mean summer (DJF) precipitation over southern Africa for the 2080s relative to the present-day for the A2 emission scenario.

Much of southern Africa experiences a high degree of intra- and interannual rainfall variability, and the region is particularly susceptible to floods and drought. The predicted decrease in summer rainfall over the western half of the subcontinent, specifically Angola, Namibia and South Africa, is associated with a decrease in the number of rain-days, as well as a small reduction in the intensity of rainfall falling on any given rain-day. In contrast, the increase in rainfall over Tanzania and the Democratic Republic of Congo is related to an increase in the intensity of rainfall rather than a change in the number of rain-days. In the fields of hydrology and civil engineering, a common means of examining extreme rainfall is in terms of return periods. For example, structures such as bridges and dams are designed to withstand the largest precipitation event anticipated within a particular period (e.g. the one in 20-year flood event). An analysis of the amount of rainfall associated with the one in 20-year flood event, shown here, indicates that rainfall may become more extreme over large areas of Mozambique, Zimbabwe, Zambia, Tanzania and the Democratic Republic of Congo, whereas less extreme rainfall is predicted over western regions.



Summer rainfall return periods for the 2080s, under the A2 emissions scenario, with respect to the present-day 20-year rainfall return values. Values less than 20 imply that the present-day extreme precipitation event is more likely in the future scenario, and vice versa.

During winter most of southern Africa is dry. However, the south western-region of South Africa receives its rainfall during this season due to the passage of cold fronts. The diagram below shows that the RCM captures the frequency of winter (JJA) heavy rainfall days much better than the GCM. It also shows the RCM prediction that there will be fewer heavy rainfall days in the future.



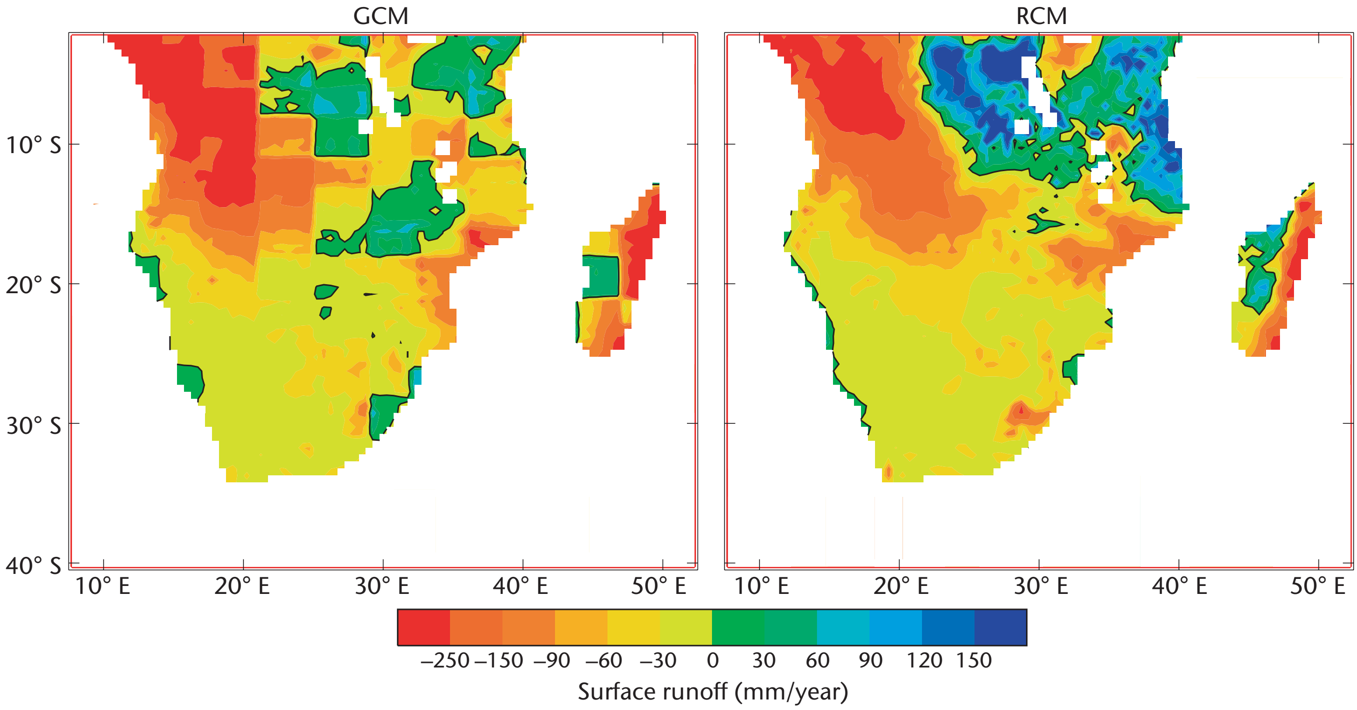
The probability of different amounts of daily precipitation for the South Western Cape in winter for the current climate, from observations (green), the GCM (dark blue) and the RCM (light blue). It also shows the climate of the 2080s as predicted by the RCM for the A2 emissions scenario (red).

Case study: Impacts of climate change on hydrology and water resources in southern Africa

Predictions of changes in climate resulting from the A2 emissions scenario, taken from both the Hadley Centre global model and the PRECIS RCM, have been applied by the University of Southampton to a hydrological model of southern Africa. This operates on a spatial resolution of half a degree, containing about 100 river catchments over the area shown, and uses data on precipitation, temperature, windspeed, humidity and net radiation from the climate models. The changes in mean monthly climate between the modelled recent climate (1961–90) and the end of the century (2071–2100) were applied to an observed monthly climatology for 1961–90, as input to the hydrological model. The model simulates a 30-year time series of daily surface runoff, which is summed over the whole catchment to calculate river flow, although data are only output for each month.

The diagram below shows the change in annual average surface runoff across southern Africa, between the recent climate and that of the 2080s, using input climate data from the GCM and from the PRECIS RCM. The pattern of change broadly follows that in rainfall, but with larger areas showing a reduction in river flows than in rainfall, because of the increased evaporation in the warmer future climate. On a broad scale, as expected, the results using the GCM and RCM agree. River flows generally decrease south of 20° S by 30% or more (although of course absolute amounts are small in these arid regions) and in the west between 20° S and the equator large decreases in river flows are evident. In other parts of the region modelled, for example Tanzania and the Democratic Republic of the Congo, the spatial pattern and magnitude of change predicted by the RCM is very different from that in the GCM. Some areas which show little or no increase in river flows using GCM predictions, show substantial increases in river flows under RCM predictions. Hence the impact assessment and adaptation policy based on GCM predictions could be in error.

The University of Southampton model also uses projections of population, etc. to calculate each country's water stress (availability of water per capita). They find that, in all the countries which will be stressed by the end of the century (for example, South Africa, Zimbabwe and Swaziland), climate change adds substantially to this stress.



The change in annual average surface runoff between the recent climate and that predicted for the 2080s as calculated from GCM predictions (left) and from RCM predictions (right). (Nigel Arnell, University of Southampton)

The Regional Modelling Group at the Hadley Centre

The model development work was carried out by a number of scientists, past and present, at the Hadley Centre: James Murphy, Maria Noguer, David Hassell, Debra Hudson (current visiting scientist from the University of Cape Town), Simon Wilson, Ruth Taylor and Balakrishnan Bhaskaran (past visiting scientist from the Indian Institute of Technology, Delhi). The head of the Regional Modelling group is Richard Jones, John Mitchell heads the Climate Prediction Group and the Climate Prediction Programme is managed by Geoff Jenkins.

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