

Training package

Providing Regional Climates for Impacts Studies - PRECIS

Regionalization techniques and regional climate modelling

PRECIS Workshop / Hadley Centre, Reading, U.K., 8th-10th June 2005 / Regionalization techniques



Regionalization techniques

- Objective of this session:
 - To review different methods of obtaining fine-scale information using climate models, with emphasis on regional climate models.

Contents

- Regionalization Techniques
 - Statistical
 - Dynamical
 - Statistical-Dynamical

- Suitability of these Techniques

- Regional climate models (RCMs)



What are regionalization techniques and why are they developed ?

- Impact assessors need regional detail to assess vulnerability and possible adaptation strategies
- AOGCM projections lack that regional detail due to coarse spatial resolution
- Regionalization techniques are developed to allow fine scale information to be derived from GCM output.

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There is an increasing need to better understand the processes that determine regional climate and to evaluate regional climate change information for use in impact studies and policy planning. To date, a relatively high level of uncertainty has characterised regional climate change information. This is due to the complexity of processes that determine regional climate change, which span a wide range of spatial and temporal scales, and to the difficulty of extracting fine scale regional information from coarse resolution coupled Atmosphere-Ocean General Circulation Models (AOGCMs).

Coupled AOGCMs are the modelling tools traditionally used for generating projections of climatic changes due to anthropogenic forcings. The horizontal atmospheric resolution of present day AOGCMs is still relatively coarse, order of 300-500 km, due to the centennial to millennial time scales associated with the ocean circulation and the computing requirements that these imply. GCMs projections of climate change, due to the coarse spatial resolution, lack the regional detail that impact studies need to assess vulnerability and hence possible adaptation strategies. In this connection, different techniques have been developed with the goal of enhancing the regional information provided by coupled AOGCMs and providing fine scale climate information. The approaches could be divided into three general categories, statistically based, dynamically based and an hybrid (i.e. statistical-dynamical).

Regionalization techniques

- Statistical
 - Weather generators
 - Transfer functions
 - Weather typing

- Dynamical
 - High resolution and variable resolution AGCMs
 - Regional Climate Models

- Statistical/Dynamical

Statistical Techniques

From historical data:

$$\textit{local variable} = F(\textit{large scale variable (s)})$$



$$\textit{Predicted local variable} = F(\textit{AOGCM large scale variable})$$

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Statistical Techniques

This approach is based on the construction of relationships between the large-scale and local variables calibrated from historical data. These statistical relationships are then applied to the large-scale climate variables from an AOGCM simulation to estimate corresponding local and regional characteristics

Statistical techniques categories

- **Transfer functions**
 - linear regression, piecewise interpolation, artificial neural networks
- **Weather generators**
 - Markov chain, spell length
- **Weather typing**
 - Analogue methods, classification and tree analysis

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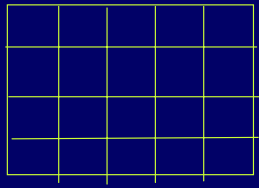


A range of statistical methods has been developed, falling into three categories:

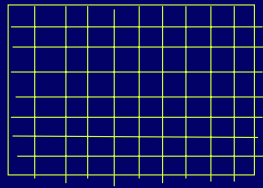
- Weather generators: statistical models of observed sequences of weather variables (Eilks and Wilby , 1999). Types of weather generators based on Markov chain approach (Bellone, 2000), spell length approach (Wilks 1999a).
- Transfer functions: relationship constructed through, for example, regression. Common techniques: linear regression; piecewise linear or non-linear interpolation (kriging tool, (Biauet al, 1999); Artificial Neural Networks (Hewitson and Crane, 1996; Hewitson, 1998)
- Weather typing: Relates weather classes to local and regional climate variations. Analogue methods (Zorita et al, 1995), Classification and Tree Analysis (CART, Lettenmaier, 1995).

High resolution and variable resolution AGCMs

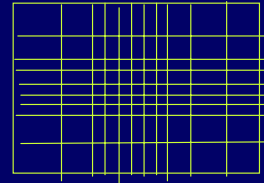
- Atmospheric GCM run with observed or AOGCM sea surface temperature as boundary conditions at the sea points.



GCM
O(300)km



High res. AGCM
O(100) km



Variable res. AGCM
50 km to '100s' km

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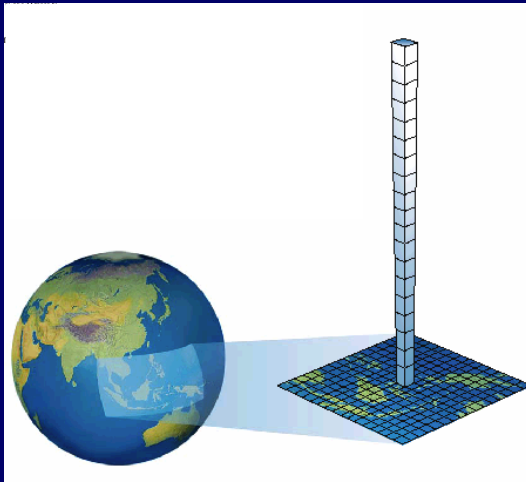


High resolution and variable resolution AGCMs.

Though simulations of many centuries are required to fully integrate the global climate system, for many applications regional information on climate or climate change is required for at most several decades. Over these time scales AGCM simulations are feasible at resolutions of the order of 100 km globally, or 50 km locally with variable resolution models. This suggests identifying periods of interest within AOGCM transient simulations and modelling these with a higher resolution or variable resolution AGCM to provide additional spatial detail.

An atmospheric GCM is run for a specific period of interest with boundary conditions of surface temperature and ice concentrations specified at sea points. Boundary conditions are derived from observations or taken from global coupled climate model experiments.

Regional Climate Models (RCMs)



Limited area models driven at the boundaries by GCMs or analyses data.

Resolution of 50km and below

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The nested regional climate modelling technique consists of using initial conditions, time-dependent lateral meteorological conditions and surface boundary conditions to drive high-resolution RCMs. The driving data is derived from GCMs (or analyses of observations) and can include GHG and aerosol forcing. A variation of this technique is to also force the large scale component of the RCM solution throughout the entire domain.

To date, this technique has been used only in one-way mode, i.e. with no feedback from the RCM simulation to the driving GCM. The basic strategy is thus to use the global model to simulate the response of the global circulation to large scale forcings and the RCM to a) account for sub-GCM grid scale forcings (e.g. complex topographical features and land cover inhomogeneity) in a physically-based way; and b) enhance the simulation of atmospheric circulations and climatic variables at fine spatial scales.

Suitability of regionalization techniques

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Comparing the suitability of downscaling techniques

- **Consistency** at regional level with global projections
- **Physical plausibility** and realism
- **Appropriateness** of information for impact assessment
- **Representativeness** of the potential range of future climate change
- **Accessibility** for use in impact assessments

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The suitability of each of these techniques to be used to construct climate scenarios for use in policy-relevant impact assessment can be assessed according to five criteria adapted from Smith and Hulme (1998):

1. *Consistency* at regional level with global projections. Scenario changes in regional climate may lie outside the range of global mean changes but should be consistent with theory and model-based results.
2. *Physical plausibility and realism*. Changes in climate should be physically plausible, such that changes in different climatic variables are mutually consistent and credible.
3. *Appropriateness* of information for impact assessments. Scenarios should present climate changes at an appropriate temporal and spatial scale, for a sufficient number of variables, and over an adequate time horizon to allow for impact assessments.
4. *Representativeness* of the potential range of future regional climate change.
5. *Accessibility*. The information required for developing climate scenarios should be readily available and easily accessible for use in impact assessments.

Suitability of regionalisation techniques

Method	Strengths	Weaknesses
Statistical	<ul style="list-style-type: none"> • High resolution • Computationally cheap 	<ul style="list-style-type: none"> • Dependent on empirical relationships derived for present-day climate • Few variables available • Not easily relocatable
High-res AGCMs	<ul style="list-style-type: none"> • High (very high) resolution • Can represent extremes 	<ul style="list-style-type: none"> • Dependent on surface boundary conditions from couple model • Computationally expensive • <i>(Have to parameterise across scales)</i>
Regional models	<ul style="list-style-type: none"> • Physically based • Many variables • RCM: easily relocatable 	<ul style="list-style-type: none"> • Dependent on driving model & surface boundary conditions • Possible lack of two-way nesting • Computationally expensive • <i>(Have to parameterise across scales)</i>

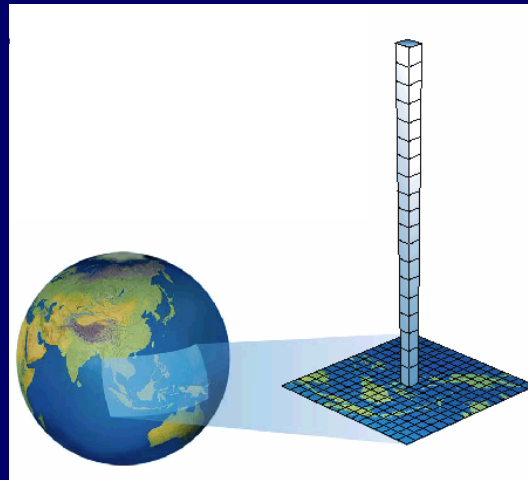
Regional climate models in more detail

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What is a Regional Climate Model?

- Comprehensive physical high resolution climate model that covers a limited area of the globe
- Includes the atmosphere and land surface components of the climate system (at least)
- Contains representations of the important processes within the climate system
 - e.g. clouds, radiation, precipitation, soil hydrology



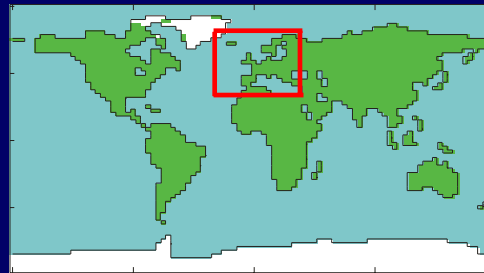
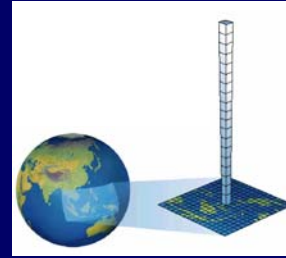
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A Regional Climate Model (RCM) is a high resolution climate model that covers a limited area of the globe, typically 5,000 km x 5,000 km. RCMs are based on physical laws represented by mathematical equations that are solved using a three-dimensional grid. The typical horizontal resolution of an RCM is 50 km. Hence RCMs are comprehensive physical models, usually including the atmosphere and land surface components of the climate system, and containing representations of the important processes within the climate system (e.g., cloud, radiation, rainfall, soil hydrology). Many of these physical processes take place on much smaller spatial scales than the model grid and cannot be modelled and resolved explicitly. Their effects are taken into account using parametrizations by which the process is represented by relationships between the area or time averaged effect of such sub-grid scale process and the large scale flow.

The nesting methodology

- A RCM is a limited area Model (LAM), similar to those used in NWP
- LAMs are driven at the boundaries by GCM or analysis data . . .



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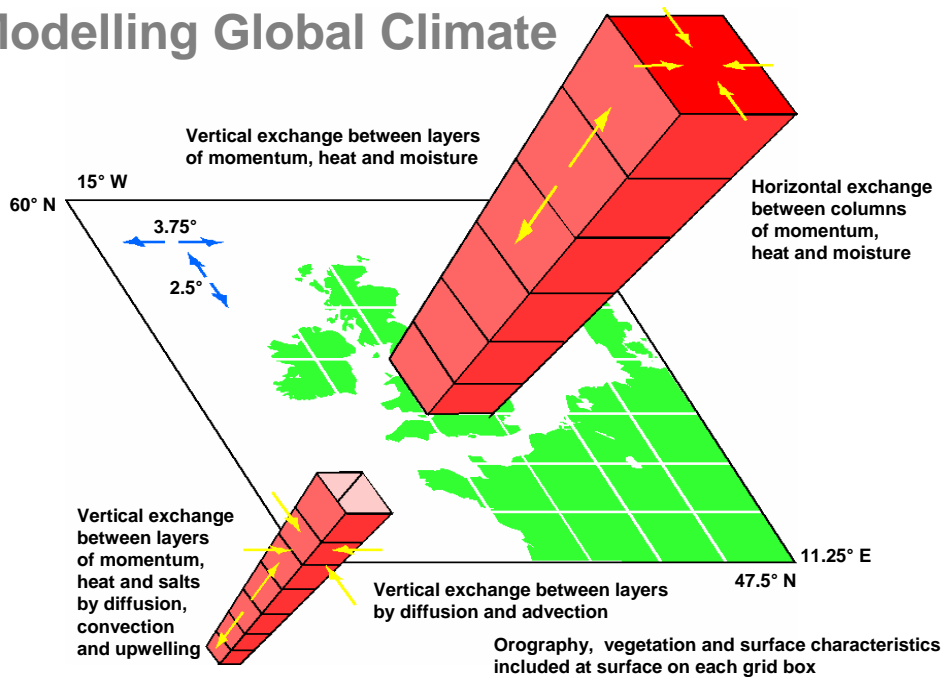
RCMs are effectively Limited Area Models run in a climate mode. The Limited Area Model pre-dates the RCM as it was used for weather forecasting, the mechanism was already in place. However climate is a different problem to weather forecasting! As one might expect, weather forecast LAMS are dealing with an initial value problem and care is taken not to allow the boundary information to reach the region of interest. However, in climate modelling, the initial state is quickly forgotten by the model and the boundary conditions are more important. In addition, more care has to be paid to issues in the physics schemes – such as those regarding soil hydrology and other processes characterised by longer timescales.

Deviations between an RCM and its driving model tend to be bigger:

- towards the middle of the terrain
- Towards the surface (effect of local forcings greatest).
- When the driving circulation is weak (summer), with the local convective effects and land-surface processes are more important.

Forcing the RCM with re-analysis data allows isolation of the model physics errors.

Modelling Global Climate



Modelling climate

- Representation at finite resolution and timestep
 - grid point and spectral methods
- Solve (integrate) governing differential equations
- *Prognostic variables*
 - take information from timestep to timestep
- Other quantities diagnosed – *diagnostic variables*
- Sub-model coupling or prescribed boundary conditions

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Climate models attempt to represent the evolution of the atmosphere, and other sub-components of the Earth system, using a (necessarily limited) amount of information. There are two types of model in use: grid point models, where the values of the model variables are held on the vertices of a grid whose resolution can be specified, and spectral models, where fields are represented by a superposition of waves of differing frequency and the limitation is on the frequency of the waves represented.

The models evolve in time through numerical solution of the differential equations governing the system of interest. Model runs are sometimes referred to as “integrations”, because the aim is integrate the equations, for the prevailing conditions; this has to be done in some approximate way for a finite updating interval or “timestep”. In gridpoint models, values at adjacent grid points are used to calculate the required spatial derivatives. The timestep should in general be chosen so that information propagating across the grid cannot travel across more than one gridbox in each timestep – effectively, higher resolutions require smaller timesteps.

Model variables that are solved for directly are known as “prognostic” variables. For a model of the atmosphere they are typically wind, surface pressure and some representation of temperature and moisture. (There are neat ways of representing temperature and moisture which when used together allow, for example, partition of moisture into water vapour and liquid water phases). Prognostic variables are treated in a physically consistent manner from timestep to timestep. Other variables are “diagnosed”, that is, derived directly or indirectly from the prognostic variables at each model timestep.

PRECIS uses a grid-point model. Models covering the whole of the globe using a latitude/longitude grid can have problems at high latitudes (near the poles), where the model grid-points become close together, so filtering of the fields is performed at high latitudes. (This is not a problem in spectral models; these however have a large computational overhead in conversion between grid-point space and spectral space.)

The atmosphere of course is dependent on other systems for its “boundary conditions”. These systems may be represented by another model, running simultaneously, with passage of information between the two – this is known as coupling. These other models have their own prognostic variables. Alternatively, the variables required at the boundaries may be supplied by prescribed fields – constant or with a seasonal cycle.

Lateral Boundary conditions



- Relaxation method (PRECIS)
 - Large scale forcing over a lateral buffer zone
- Spectral nesting
 - Large scale forcing of low wave number components
- Issues
 - Spatial resolution of driving data
 - Updating frequency of driving data

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The difference in resolutions of the driving and regional model grids should not be too great – experiments have suggested a maximum factor of 12.

Another important issue concerning the Lateral Boundary conditions is the interval of updates of the large-scale driving fields. Model lateral boundary conditions are needed at each time step and are usually linearly interpolated (in time) from two adjacent large-scale field updates. In most models this updating interval is between 3 and 12 hours. This allows some representation of the diurnal cycle.

Sea Surface Boundary conditions

Two methods of supplying SST and ice-extent and thickness:

- Using a coupled AOGCM
 - Need good quality simulation of SST and sea ice in model

- Using observed values
 - For the present-day simulation.
 - For future climate need add to the observed values the changes in SST and ice from a coupled GCM

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Most RCMs developed to date include representations of the atmosphere and the land surface only. As a result they need to be supplied with surface boundary conditions over the oceans which consist of sea-surface temperatures (SSTs) and, where appropriate, information about the extent and thickness of sea-ice. (In some cases the land-surface model also requires a boundary condition of temperature of the bottom soil layer.) If this information is taken directly from a coupled GCM then its coarse resolution means that there could be quite large regional errors in the data and for coastal points and inland seas they may have to be interpolated or extrapolated which could lead to even larger errors locally. An alternative is to use observed values (at higher resolution) for the GCM and RCM simulations of present-day climate and then obtain values for the future by adding on changes in the SSTs and sea-ice extent and thickness from a coupled GCM.

RCM physical formulations

	Advantages	Disadvantages
Different physics	Optimal physics for each resolution	Difficult to interpret GCM and RCM differences
Same physics as driving GCM	Maximum compatibility	Consistency of behaviour over a range of resolutions

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Errors in regional climate simulations derive both from the lateral boundary forcing and the model formulation (Noguer et al, 1998).

In general there are two approaches regarding the formulation of an RCM:

- Use of different formulations for the nested and driving models. Advantage: each model is developed and optimised for the respective resolution (and region in the case of the RCM). Disadvantage: any differences in the GCM and RCM could be caused by the different formulations and so it is less clear that the RCM prediction can be interpreted as a high-resolution version of the GCM prediction.
- Use of the same formulation in the nested and driving model. Advantage: maximum compatibility. Disadvantage: consistency of model behaviour over a range of resolutions.

Sources of errors in RCMs

- The RCM adds fine detail to the large-scale and shouldn't deviate from it.
- Two sources of error:
 - Deriving from driving fields
 - Derived from internal model physics.

Simulation length

- Minimum
 - 10 years to reasonably study the mean climate
- Preferably
 - 30 years to study higher order statistics, climate variability, extremes, etc

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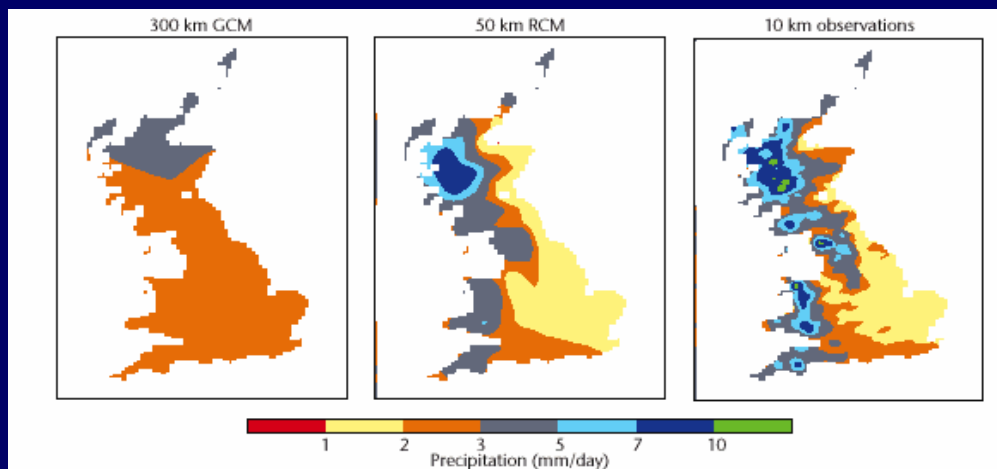
In a study with a previous version of the Hadley Centre RCM, Jones et al. (1997) have shown that a 10-year simulation captures about half of the variance of the true regional climate change response (i.e. that obtained with a simulation of infinite length). This should thus be regarded as the minimum length needed to obtain an estimate of the climate change signal. To capture 75% of the variance of the true signal a 30-year simulation is required. In a more recent study Huntingford et al. (2002) showed that with 20-30 year simulations changes in extreme precipitation were only statistically significant under a large climate change.

Added value of RCMs

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RCMs simulate current climate more realistically



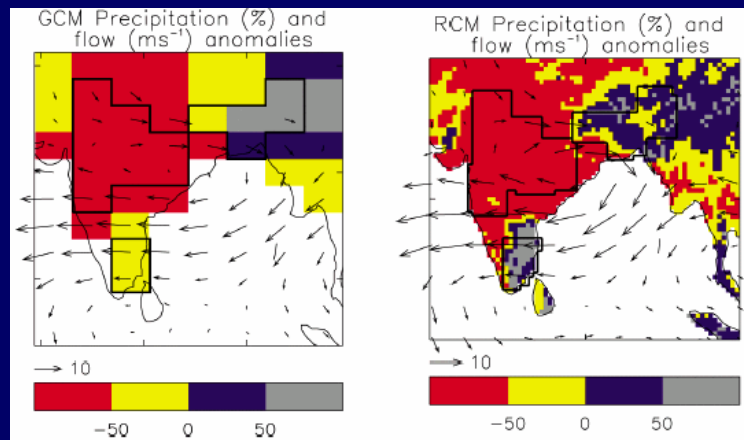
Patterns of present-day winter precipitation over Great Britain

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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 shows simulated and observed winter 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.

RCMs simulate current climate more realistically



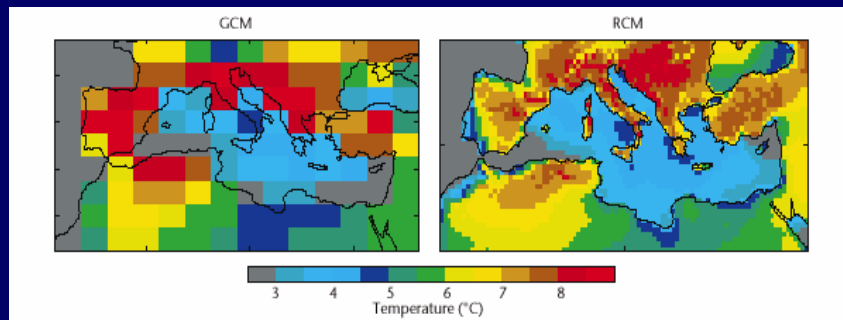
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Each field is the difference in the break and active composite precipitation as a percentage of the full mean. Overlaid are the 850 hPa wind anomalies (break composite minus active composite, units m/s). Regions marked where observed ratios are $< -50\%$ (central India) and $> -50\%$ (Tamil Nadu and north-eastern India) according to Hamilton (1997). From Hassell and Jones, 1999).

This shows that the RCMs capture observed precipitation anomalies in the break phases of the South Asia monsoon that were absent from the driving GCM.

RCMs represent smaller islands



Projected changes in summer surface air temperature between present day and the end of the 21st century.

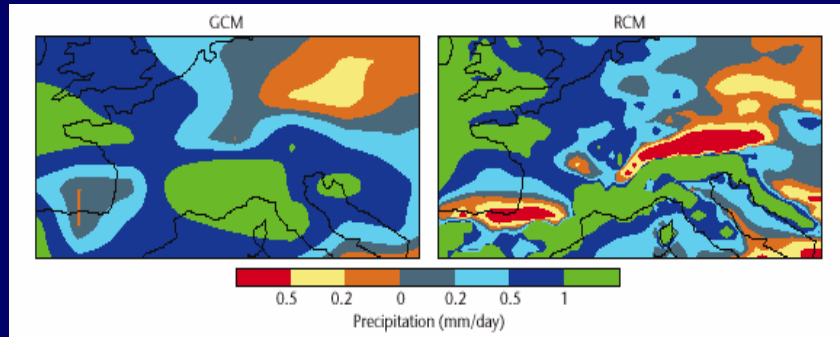
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The coarse resolution of a GCM means that many islands are just not represented and hence their climate is predicted to change in exactly the same way as surrounding oceans. However, the land surface has a much lower thermal inertia than the oceans 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 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.)

RCMs predict climate change with more detail



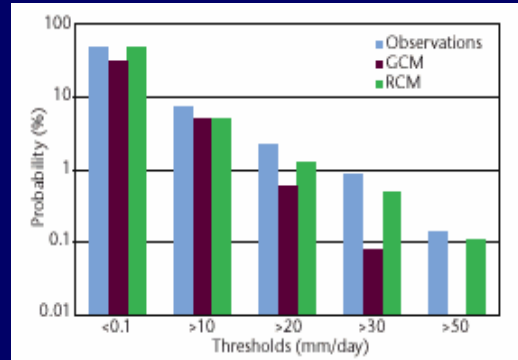
Projected changes in winter precipitation between now and 2080s.

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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 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.

RCMs simulate and predict changes in extremes more realistically



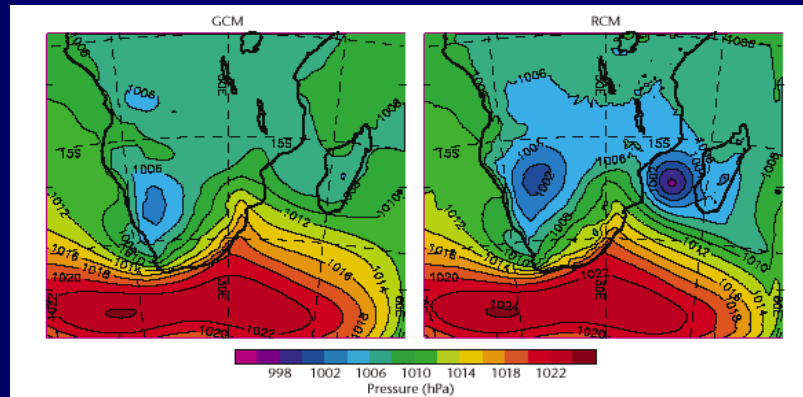
Frequency of winter days over the Alps with different daily rainfall thresholds.

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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 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.

RCMs can simulate cyclones and hurricanes



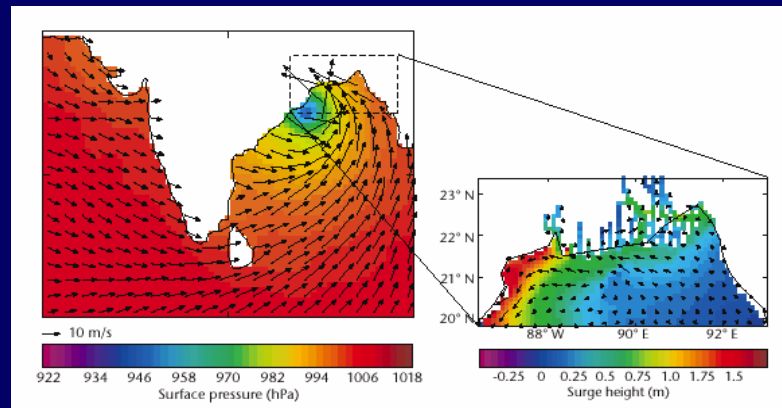
A tropical cyclone is evident in the RCM (right) but not in the GCM

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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 in the Figure, 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 though there is one crucial difference; there is a cyclone in the Mozambique Channel in the RCM which is absent in the driving GCM.

Data can be used to drive other models



A cyclone in the Bay of Bengal simulated by an RCM and the resulting high water levels in the Bay simulated by a coastal shelf model.

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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 in the Figure, 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.

Summary of regionalization techniques

- Used to add fine scale details to a GCM projection
- Several methods are available, with different strengths and weaknesses
- PRECIS is a physically-based and computationally accessible regional climate model

End of session

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