Guidelines for Use of Climate Scenarios Developed from Regional Climate Model Experiments

by

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1. INTRODUCTION

For many regional and local applications, users of climate model results have long been dissatisfied with the inadequate spatial scale of climate scenarios produced from coarse resolution global climate model (GCM) output (Gates, 1985; Robinson and Finkelstein, 1989; Lamb, 1987; Smith and Tirpak, 1989; Cohen, 1990). This concern emanates from the perceived mismatch of scale between coarse resolution GCMs (100s of km) and the scale of interest for regional impacts (an order or two orders of magnitude finer scale) (IPCC, 1994; Hostetler, 1994). For example, mechanistic models used to simulate the ecological effects of climate change usually operate at spatial resolutions varying from a single plant to a few hectares. Their results may be highly sensitive to fine-scale climate variations that may be embedded in coarse-scale climate variations, especially in regions of complex topography, coastlines, and in regions with highly heterogeneous land surface covers.

There are now techniques available for generating high resolution climate information, but some tend to be complex and/or computationally expensive. It is also not always straightforward which techniques one should use, or whether high resolution information is even necessary for approaching certain types of impacts problems.

The purpose of this guidance material is to provide researchers in climate impacts with the background material, and descriptions of procedures for evaluating, producing, and using high resolution climate scenarios. We also provide recommendations for when and how to use such scenarios. While we will present overview material on all downscaling or regionalization methods, we will focus our more detailed discussions on regional modelling.

This guidance paper is not meant to be a manual or recipe book for actually producing regional climate model (RCM) simulations. It is assumed that impacts researchers who are not climate modelers, will be working with regional climate modelers who have the expertise for generating such simulations. What we hope to do is inform the impacts researcher on choices that can be made among techniques, on strengths and weaknesses of techniques, on what the regional modelling community feels we know about the quality of simulations and on what degree of confidence we have in the results of regional models compared to global coarse scale models.

In this guidance document we present in part 2 background information on the different methods of developing high resolution scenarios, in part 3 examples of how such scenarios have been used up till now, and in part 4 a general discussion of the uncertainty of spatial scale in relation to the many other uncertainties in climate impacts work. In part 5 we then go on to explain the current thinking on the "added value" of high resolution information, provide guidance on what should be considered in deciding whether to use a high resolution scenario, and describe procedures for producing high quality regional modelling experiments. Finally in part 6 we make general recommendations for use of RCM results for climate scenarios in impacts work.

Much of the background information provided in this document is drawn from two chapters of the IPCC Third Assessment Report, Working Group I volume, specifically chapter 10 on Regional Climate Information (Giorgi et al., 2001) and Chapter 13 on Climate Scenario Development (Mearns et al., 2001). The reader is encouraged to review these chapters for more in-depth discussion of some topics. Also the document *Guidelines on the Use of Scenario Data for Climate Impact and Adaptation Assessment* available on the Data Distribution Centre Web site (http://ipcc-ddc.cru.uea.ac.uk) contains general guidance on the use of scenarios, and should also be read.

2. REVIEW OF METHODS

This section presents an overall discussion of the principles, objectives and assumptions underlying the different techniques today available for deriving regional climate change information. Table 1 provides a summary of climate scenario techniques that rely on the various techniques described below. Coupled atmosphere-ocean global climate models (AOGCMs) are the modelling tools traditionally used for generating climate change projections and scenarios.

Table 1: *The role of some types of climate scenarios and an evaluation of their advantages and disadvantages according to the five criteria listed below the Table. . Note that in some applications a combination of methods may be used (e.g. regional modelling and a weather generator).*
(Modified from Mearns et al., 2001).

Scenario type or tool	Description/Use	Advantages*	Disadvantages*
Climate model based: Direct AOGCM outputs	• Starting point for most climate scenarios • Large-scale response to anthropogenic forcing	• Information derived from the most comprehensive, physically-based models (1, 2) • Long integrations (1) • Data readily available (5) • Many variables (potentially) available (3)	• Spatial information is poorly resolved (3) • Daily characteristics may be unrealistic except for very large regions (3) • Computationally expensive to derive multiple scenarios (4, 5) • Large control run biases may be a concern for use in certain regions (2)
High resolution/stretched grid (AGCM)	• Providing high resolution information at global/continental scales	• Provides highly resolved information (3) • Information is derived from physically-based models (2) • Many variables available (3) • Globally consistent and allows for feedbacks (1,2)	• Computationally expensive to derive multiple scenarios (4, 5) • Problems in maintaining viable parameterizations across scales (1,2) • High resolution is dependent on SSTs and sea ice margins from driving model (AOGCM) (2) • Dependent on (usually biased) inputs from driving AOGCM (2)
Regional models	• Providing high spatial/temporal resolution information	• Provides very highly resolved information (spatial and temporal) (3) • Information is derived from physically-based models (2) • Many variables available (3) • Better representation of some weather extremes than in GCMs (2, 4)	• Computationally expensive, and thus few multiple scenarios (4, 5) • Lack of two-way nesting may raise concern regarding completeness (2) • Dependent on (usually biased) inputs from driving AOGCM (2)
Statistical downscaling	• Providing point/high spatial resolution information	• Can generate information on high resolution grids, or non-uniform regions (3) • Potential for some techniques to address a diverse range of variables (3) • Variables are (probably) internally consistent (2) • Computationally (relatively) inexpensive (5) • Suitable for locations with limited computational resources (5) • Rapid application to multiple GCMs (4)	• Assumes constancy of empirical relationships in the future (1, 2) • Demands access to daily observational surface and/or upper air data that spans range of variability (5) • Not many variables produced for some techniques (3, 5) • Dependent on (usually biased) inputs from driving AOGCM (2)

* Numbers in parentheses under Advantages and Disadvantages indicate that they are relevant to the numbered criteria described. The five criteria are: 1) *Consistency* at regional level with global projections; 2) *Physical plausibility and realism*, such that changes in different climatic variables are mutually consistent and credible, and spatial and temporal patterns of change are realistic; 3) *Appropriateness* of information for impact assessments (i.e. resolution, time horizon, variables); 4) *Representativeness* of the potential range of future regional climate change; and 5) *Accessibility* for use in impact assessments.

However, the horizontal atmospheric resolution of present day AOGCMs is still relatively coarse, order of 300 km, and regional climate is often affected by forcings and circulations that occur at smaller scales (e.g., Giorgi and Mearns 1991). As a result, AOGCMs cannot explicitly capture the fine scale structure that characterizes climatic variables in many regions of the world and that is needed for many impact assessment studies.

Conventionally, regional “detail” in climate scenarios has been incorporated by applying changes in climate derived from the coarse scale GCM or AOGCM grid points to observation points distributed often at resolutions higher than that of the GCMs. Recently, high resolution (eg., 0.5 deg.) gridded baseline climatologies have been developed with which coarse resolution GCM results have been combined (e.g., Saarikko and Carter, 1996; Kittel et al., 1997, New et al., 1999; 2000). Such relatively simple techniques, however, cannot overcome the limitations imposed by the fundamental spatial coarseness of the simulated climate change information itself.

Therefore, different "regionalization" techniques have been developed to enhance the regional information provided by GCMs and AOGCMs and to provide fine scale climate information. These techniques can be classified into three categories:

1) High resolution and variable resolution “time-slice” Atmosphere GCM (AGCM) experiments;
2) Nested limited area (or regional) climate models (RCMs);
3) Empirical/statistical and statistical/dynamical methods.

To date, most impact studies have used climate change information provided by equilibrium GCMs or coupled AOGCM simulations without any further regionalization processing. This is primarily because of the ready availability of this information and the relatively recent development of regionalization techniques.

For some applications, the regional information provided by AOGCMs may be sufficient, for example when sub-grid scale variations are weak or when assessments are global in scale. In fact, from the theoretical view point, the main advantage of obtaining regional climate information directly from AOGCMs is the knowledge that internal physical consistency is maintained. However, by definition, coupled AOGCMs cannot provide direct information about climate at scales smaller than their resolution, neither can they capture the detailed effects of forcings acting at sub-grid scales (unless parameterized). Therefore, in cases where fine scale processes and forcings are important drivers of climate change the use of regionalization techniques is essential and recommended to the extent that it enhances the information of AOGCMs at the regional and local scale. The "added value" provided by the regionalization techniques depends on the spatial and temporal scales of interest, as well as on the variables concerned and on the climate statistics required.

Even if resolution factors limit the feasibility of using regional information from AOGCMs for impact work, AOGCMs are the starting point of any regionalization technique presently used. Therefore, it is of utmost importance that AOGCMs show a good performance in simulating large scale circulation and climatic features that affect regional climates. Indeed, improvement of AOGCMs is a necessary condition for the long term improvement of regional climate change projections.

2.1 . High Resolution and Variable Resolution Time-slice AGCM Experiments

For many applications, regional climate information is required for several decades. Over these time scales atmosphere global climate model (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 o interest (or "time-slices") within AOGCM transient simulations and modelling these with a higher resolution or variable resolution AGCM to provide additional spatial detail (e.g. Bengtsson et. al., 1995; Cubasch et al., 1995; Hudson and Jones, 2002a,b; Govindasamy et al., 2003). The external forcings necessary to run the AGCM time slices, such as sea surface temperature (SST), sea ice distribution and greenhouse gas (GHG) and aerosol concentration, are obtained from the corresponding periods in the AOGCM simulation or a combination of observed and AOGCM predicted changes. Typically, a present day (e.g. 1960-1990) and a future climate (2070-2100) time slice are simulated to calculate changes in relevant climatic variables.

The approach is based on two major assumptions. The first is that the large scale circulation patterns in the coarse and high resolution GCMs are not markedly different from each other, otherwise the consistency between the high resolution AGCM climate and the coarse resolution forcing would be questionable. Thus it is important to consider the degree of convergence of model climatology at the standard and high resolutions. The other assumption is that the state of the atmosphere may be considered as being in equilibrium with its lower boundary conditions provided by the slower-evolving ocean and sea ice components.The main theoretical advantage of this approach is that the resulting simulations are globally consistent, capturing remote responses to the impact of higher resolution. Also, the performance of the atmospheric component of an AOGCM is somewhat constrained to provide a stable coupled system (e.g. ensuring a top of atmosphere radiation balance and accurate fluxes at the air-sea interface). Using an AGCM alone somewhat loosens this constraint allowing more of a focus on the large-scale atmospheric and land-surface performance of the model . A practical weakness of high resolution models is that they generally use the same formulations as at the coarse resolution at which they have been optimized, so that some model formulations may need to be "re-tuned" for use at higher resolution. With global variable resolution models this issue is further complicated as the model physics parameterizations need to be valid and function properly over the range of resolutions covered by the model.

Another issue concerning the use of variable resolution models is that feedback effects from fine scales to large scales are represented only as generated by the region of interest, while in the real atmosphere feedbacks derive from different regions and interact with each other. In addition, a sufficient minimal resolution must be retained outside the high resolution area of interest in order to prevent a degradation of the simulation of the whole global system.

Use of high resolution and variable resolution global models is computationally very demanding, which poses limits on the increase in resolution obtainable with this method. This and the advantage of better atmospheric large-scale and land surface simulation suggest the use of high resolution AGCMs to obtain forcing fields for higher resolution regional model experiments (Hudson and Jones, 2002a,b) or statistical downscaling, thus effectively providing an intermediate step between AOGCMs and regional and empirical models.

2.2 Regional Climate Models

What is commonly referred to as nested regional climate modelling technique consists of using output from global model simulations to provide initial conditions and time-dependent lateral meteorological boundary conditions to drive high-resolution RCM simulations for selected time periods of the global model run (e.g. Dickinson et al. 1989; Giorgi 1990). Sea surface temperature (SST), sea ice, greenhouse gase (GHG) and aerosol forcing, as well as initial soil conditions, are also provided by the driving AOGCM. Some variations of this technique include forcing of the large scale component of the solution throughout the entire RCM domain (e.g. Kida et al., 1991; Zorita and von Storch, 1999)

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 underlying this one-way nesting approach is that the GCM is used to simulate the response of the global circulation to large scale forcings and the RCM is used 1) to account for sub-GCM grid scale forcings (e.g. complex topographical features and land cover inhomogeneity) in a physically-based way, and 2) to enhance the simulation of atmospheric circulations and climatic variables at fine spatial scales. The nested regional modelling technique essentially originated from numerical weather prediction, but is by now extensively used in a wide range of climate applications, ranging from paleoclimate to anthropogenic climate change studies. Over the last decade, regional climate models have proven to be flexible tools, capable of reaching high resolution (down to 10-20 km or less) and multi-decadal simulation times and capable of describing climate feedback mechanisms acting at the regional scale. A number of widely used limited area modelling systems have been adapted to, or developed for, climate application.

The main theoretical limitations of this technique are the effects of systematic errors in the driving large scale fields provided by global models (which is common to all downscaling methodologies using AOGCM output) and the lack of two-way interactions between regional and global climate. In addition, for each application careful consideration needs to be given to some aspects of model configuration, such as physics parameterizations, model domain size and resolution, and the technique for assimilation of large scale meteorological forcing(e.g. Giorgi and Mearns 1991, 1999). Recent studies have also shown that regional models exhibit internal variability due to non-linear internal dynamics not associated with the boundary forcing, which adds another factor of uncertainty in regional climate change simulations (Ji and Vernekar, 1997; Giorgi and Bi 2000, Christensen et al., 2001).

From the practical viewpoint, depending on the domain size and resolution, RCM simulations can be computationally demanding (though comparable to the costs of AOGCMs). An additional consideration is that in order to run an RCM experiment, high frequency (e.g. 6-hourly) time dependent GCM fields are needed. These are not routinely stored because of the implied mass-storage requirements, so that careful coordination between global and regional modelers is needed to design nested RCM experiments.

There have now been numerous control (current climate) simulations of RCMs driven by GCM boundary conditions. Errors introduced by the GCM large scale representation are transmitted to the RCM (e.g., Noguer et al., 1998). Typical regional biases of seasonal surface temperature and precipitation are usually within the range of 2 deg. C and 50 to 60% of observations, respectively (e.g. Jones et al., 1995, Giorgi and Marinucci, 1996, and Jones et al., 1999 for Europe; Giorgi et al., 1998, Pan et al., 2001, Leung et al., 2004 for the continental U.S.;

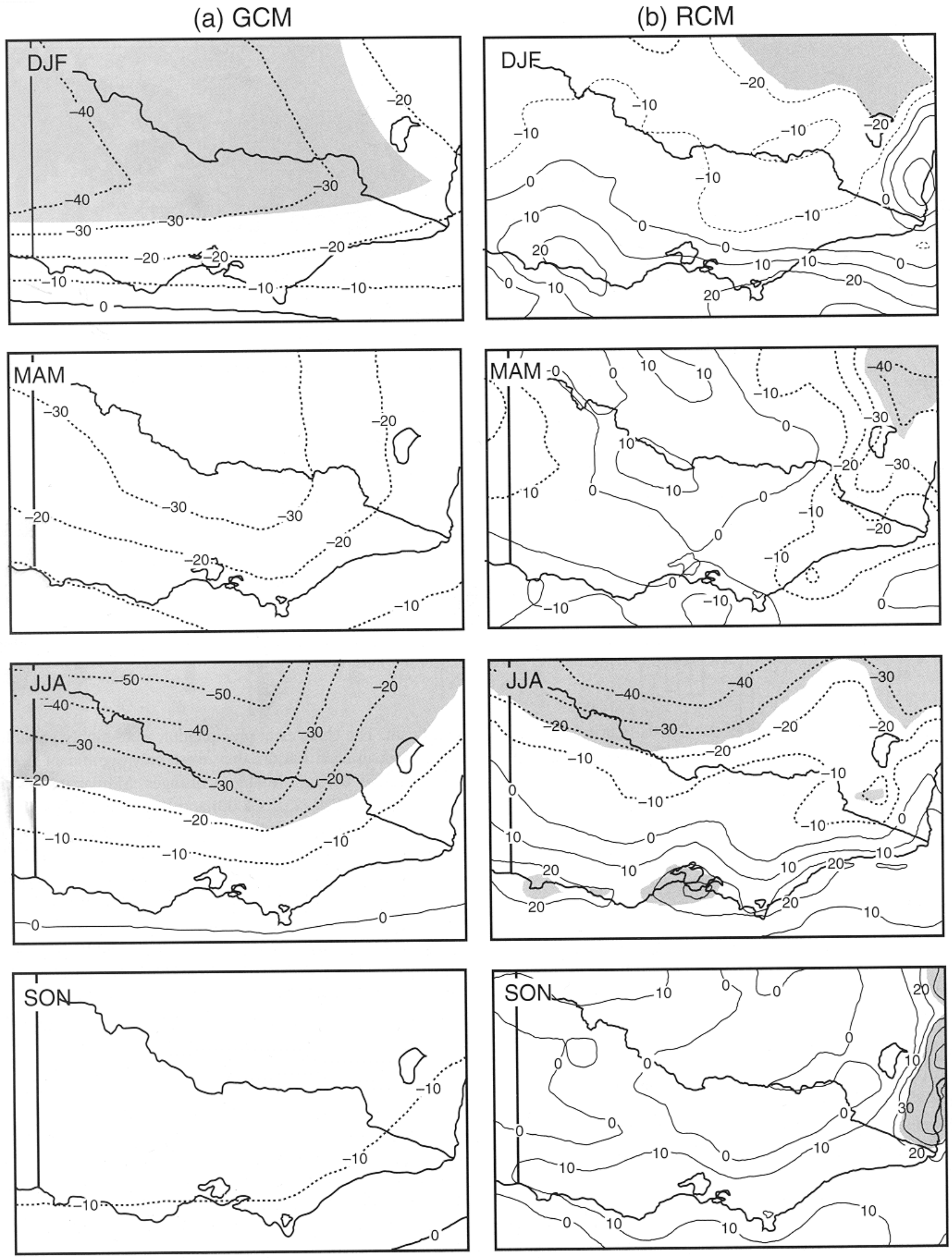
McGregor et al., 1998 for southeast Asia; and Hudson and Jones, 2002a for southern Africa). While the regional biases of the RCM are not necessarily lower than those of the driving GCM, the spatial patterns of climate produced by the RCMs are usually in better agreement with observations compared to those of the GCMs. There is also evidence that RCMs reproduce precipitation extremes well at scales not accessible to GCMs (e.g. Frei et al., 2003, Huntingford et al., 2002, Christensen and Christensen, 2003) and better than GCMs on their gridscale (Durman et al., 2001).

In climate change experiments, RCMs indicate that, while the large-scale patterns of surface climate change in the nested and driving simulated changes are usually similar, the mesoscale details of the simulated changes can sometimes be different (Machenhauer et al., 1998; Pan et al., 2001). For example significantly different patterns of changes in temperature and rainfall were found in a regional climate change simulation of Victoria, Australia (Whetton et al., 2001). Winter rainfall increased in the RCM, but decreased in the driving GCM (Figure 1). Other examples of climate change simulations are described in Giorgi et al., 2001 (IPCC Chapter 10).

2.3 Empirical/statistical and Statistical/dynamical Downscaling

Statistical downscaling is based on the view that regional climate is conditioned by two factors: the large scale climatic state, and regional/local physiographic features (e.g. topography, land-sea distribution and landuse; von Storch, 1995). From this viewpoint, regional or local climate information is derived by first determining a statistical model which relates large-scale climate variables (or "predictors") to regional and local variables (or "predictands"). Then the large-scale output of an AOGCM simulation is fed into this statistical model to estimate the corresponding local and regional climate characteristics.

Figure 1. Percentage change in mean seasonal rainfall under $2xCO_2$ conditions as simulated by a GCM (a) and a RCM (b) for a region around Victoria, Australia. Areas of change statistically significant at the 5% confidence level are shaded. Whetton *et al.* (2001).



A range of statistical downscaling models, from regressions to neural networks and analogues, have been developed for regions where sufficiently good datasets are available for model calibration. In a particular type of statistical downscaling method, called statistical-dynamical downscaling, use is made of atmospheric mesoscale models to develop the statistical models. Statistical downscaling techniques have their roots in synoptic climatology and numerical weather prediction, but they are currently used for a wide range of climate applications, from historical reconstruction to regional climate change problems.

A number of review papers have dealt with downscaling concepts, prospects and limitations: Hewitson and Crane (1996, 2004), Wilby and Wigley (1998), Gyalistras et al. (1998), Murphy (1999, 2000), Zorita and von Storch (1999).

One of the primary advantages of these techniques is that they are computationally inexpensive, and thus can be easily applied to output from different GCM experiments. Another advantage is that they can be used to provide specific local information (e.g., points, catchments), which can be most needed in many climate change impact studies. The applications of downscaling techniques vary widely with respect to regions, spatial and temporal scales, type of predictors and predictands, and climate statistics.

The major theoretical weakness of statistical downscaling methods is that their basic assumption is often not verifiable, i.e. that the statistical relationships developed for present day climate also hold under the different forcing conditions of possible future climates. Indeed, there are indications that this is not always the case (e.g., winter precipitation over Northern Europe (Murphy, 1999, 2000)). Another caveat is that these empirically based techniques cannot account for possible systematic changes in regional forcing conditions or feedback processes. Guidance material specifically concerned with statistical downscaling is being prepared in a separate document.

3. Applying RCM-based Scenarios to Impacts

While results from regional model experiments of climate change have been available for about ten years, and regional climate modelers claim use in impacts assessments as one of their important applications, it is only quite recently that scenarios developed using these techniques have actually been applied in a variety of impacts assessments such as of temperature extremes (Hennessy et al., 1998; Mearns, 1999); water resources (Hassell et al., 1998; Hay et al., 2000; Leung and Wigmosta, 1999; Wang et al., 1999; Stone et al., 2001, 2003; Wilby et al., 1999, Pennell and Barnett, 2004); agriculture (Mearns et al., 1998, 1999, 2000, 2001; Brown et al., 1999; Thomson et al., 2001) and forest fires (Wotton et al. 1998). Prior to the past few years, these techniques were mainly used in pilot studies focused on increasing the temporal resolution and spatial scale (e.g., Mearns et al., 1997; Semenov and Barrow, 1997).

One of the most important aspects of this work is determining whether the high resolution scenarios actually lead to significantly different calculations of impacts compared to the coarser resolution GCM from which the high resolution scenario was partially derived. This aspect is related to the issue of uncertainty in climate scenarios, an issue not explicitly addressed by all of the studies cited above. In many articles the authors adopted the high resolution (RCM) scenarios without comments regarding the use of high resolution versus low resolution information.

We provide here a few examples of some recent applications in which the uncertainty of spatial scale is explicitly explored. Application of high resolution scenarios produced from a regional model (Giorgi et al., 1998) over the central Plains of the United States produced changes in simulated crop yields that were significantly different from the changes calculated from a coarser resolution GCM scenario (Mearns et al., 1998; 1999, 2001). For simulated corn in Iowa, for example, the large scale (GCM) scenario resulted in a statistically significant decrease in yield, but the high resolution scenario produced an insignificant increase. Guereña et al. (2001) for the Iberian peninsula used GCM and RCM based scenarios, but they did not find significant contrasts in the resulting changes in irrigated crop yields calculated from the two scenarios. Stone et al. (2003) found significant differences in changes in water yield when using fine and coarse climate scenarios for the Missouri River Basin. Wood et al. (2004) used climate scenarios developed from results of both an RCM (Leung et al., 2004) and the NCAR-DOE Parallel (global) Climate Model (PCM) run using a transient emission scenario and found that a hydrological model produced different results based on the scenario resolution. Other recent studies are described in more detail in Box 1.

Box 1. Selected New Studies Using RCMs and AGCMs or AOGCMs

1) Arnell, Hudson, and Jones (2003): Climate change scenarios from a regional model: Estimating change in runoff in southern Africa.

This paper analyzes a number of different means of constructing climate change scenarios, based on the A2 SRES emissions scenario, using the HadRM3H RCM at 50 km resolution, driven by a global version of the RCM, HadAM3H at 1.9x1.25 deg. which itself was driven by sea-surface temperature and sea-ice change from the AOGCM HadCM3 at 3.75 x 2.5 deg. The scenarios included changes in mean climate from these models as well as cases where change in interannual variability of climate are included. The scenarios are applied to a macro-scale hydrological model, which calculates the components of the water balance; in particular runoff is the hydrological variable of interest. In general, the HadAM3H and the HadRM3H results were similar to each other as would be expected from the experimental design. They created greater decreases in runoff across the central parts of southern Africa, than did the HadCM3. This demonstrates that for some applications over large regions information at the scale of HadAM3H may be sufficient.

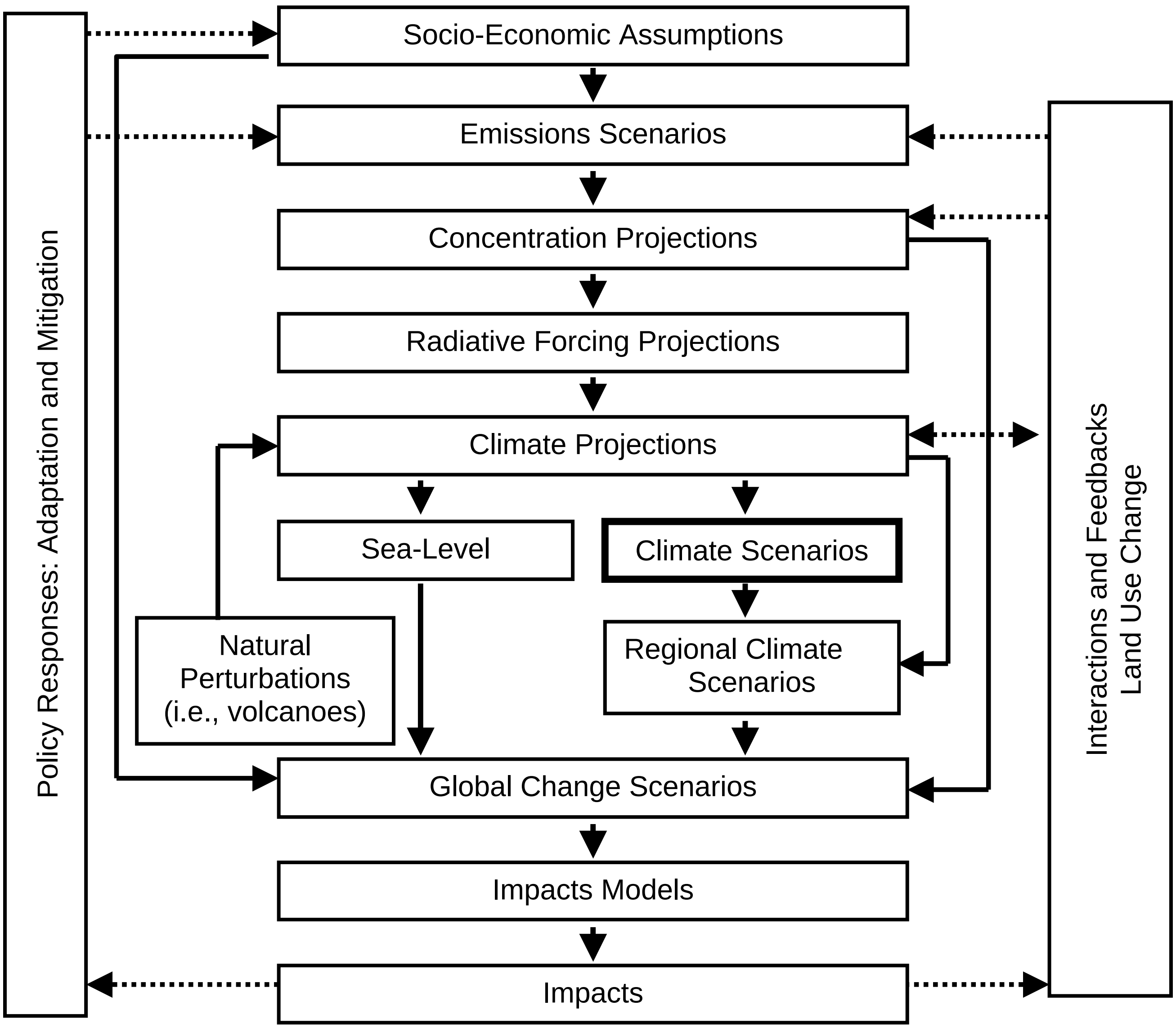
2) Mearns (2003) and papers described therein (*Climatic Change*, Special Issue on Issues in the Impacts of Climatic Variability and Change on Agriculture: Applications to the Southeastern United States.) And Mearns et al. (2003) : The uncertainty of spatial scale in integrated assessment: An example of agriculture in the United States.

The collection of papers in the special issue describes a study of the effect of spatial scale of climate scenarios on an integrated assessment of agriculture in the southeastern US, which was extended to the entire US for the agricultural economic analysis. Using control and doubled CO_2 runs of the CSIRO Mk 2 GCM and those of the regional model RegCM2, the researchers produced coarse and fine scale climate scenarios over the southeastern U.S. The scenarios were applied to crop models simulating corn, cotton, rice, soybeans, sorghum, and wheat yields. For all crops except wheat, significant differences in the change in crop yield with climate change were calculated based on the scale of the scenario at various levels of spatial aggregation. In general, the fine scale scenario produced larger decreases in yield. Economic results (Adams et al., 2003), which required creating scenarios for the rest of the U.S., indicated that there was an order of magnitude difference in total economic welfare based on the scenario scale.

4. Putting High Resolution Information in the Context of Other Uncertainties

Climate change impact assessment recognizes that there are a number of sources of uncertainty in such studies which contribute to uncertainty in the final assessment. These uncertainties form a series, or cascade, extending through each of the following areas, (after Mearns et al., 2001) (see Figure 2 - the cascade of uncertainty):

Figure 2: Cascade of Uncertainty (Adapted from Mearns et al., 2001.)



· Specifying alternative emissions futures

· Converting emissions to concentrations

· Converting concentrations to climate forcing

· Modelling the climate response to a given forcing

· Converting the model response into inputs for impact studies

· Modelling impacts

At each step, and at each sub-component of each step, alternative approaches or estimates are available which then have the potential to yield a range of valid results as inputs for the next step. High resolution modelling may be viewed as potentially part of the process of both modelling the climate response to a given forcing and converting the model response into inputs for impact studies (see Figure 2). Its objective is to take coarse resolution climate change results and produce climate change information at a spatial scale closer to that required for the impact application. Obtaining such high resolution results introduces its own uncertainty, as different regional models (or statistical downscaling methods) can yield different results even when conditioned by the same GCM (Machenauer et al.,1998; Pan et al., 2001; Murphy, 1999, 2000).

Managing the cascade of uncertainty in impact studies presents difficulties because only a small subset of the potential pathways through the cascade would have been explicitly modeled. However there are techniques which enable a representative range of climates to be considered (see Mearns et al., 2001) and emerging techniques involving probabilistic methods which assist in managing the large ranges of possible climate change which can emerge from the cascade (Jones, 2000; Mearns et al., 2001; Wigley and Raper, 2001, Giorgi and Mearns, 2003).

If the relative importance of the various sources of uncertainty are measured in terms of their effect on the final range of possible impacts, then their importance will likely vary from one impact study to another. For example, because models disagree more on the details of regional precipitation change than temperature change (Giorgi et al., 2001), the main uncertainty in the response of a temperature-driven impact might be the rate of global warming, whereas for precipitation-driven impact the main uncertainty may be model to model differences in the regional climate change. As an example of the latter, Jones and Page (2001) in a study of changes in water resources in southeastern Australia found that two thirds of the total uncertainty range in the impacts was due to global model-to-model differences in rainfall change per degree of global warming, and that the uncertainty in global warming itself contributed only 25% of the range. Finally it may be noted that , depending on the research question being addressed in an impact study, portions of the uncertainty cascade may not be relevant.

The uncertainty that is addressed when high resolution modelling is introduced into a study needs to be weighed up against the effect of the other uncertainties. For example, it would be a mistake to put considerable resources into preparing high resolution information if other uncertainties, potentially more relevant to the results, are left unaddressed.

Research so far has identified uncertainty in the emissions scenarios and uncertainty in the climate model responses to external forcing as two central parts of the cascade (Visser et al., 2000; Wigley and Raper, 2001). To date, there has not been sufficient research to evaluate the relative importance of spatial scale in the cascade. However, ongoing programs such as PRUDENCE (Prediction of Regional Scenarios and Uncertainties for Defining European Climate Change Risks and Effects) consider multiple uncertainties including spatial scale (Christensen et al., 2002) (see Box 2).

Box 2. PRUDENCE - Managing Multiple Sources of Uncertainty Including Scale
http://www.dmi.dk/f+u/klima/prudence/

Scientific Objectives:

1. To address deficiencies of spatial scale of climate scenarios;
2. To quantify uncertainties in predictions of future climate using an array of climate models and impacts models;
3. To interpret the results in relation to European policies for adapting to or mitigating climate change

More than 8 different RCMs have been run at 50 km resolution driven by time slice experiments of several AGCMS, which are based on AOGCM simulations for 2070-2100 for the A2 and B2 SRES scenarios. AOGCM forcings are from: A2 and B2 SRES scenarios with HadCM3, A2 scenario with ECHAM4 and the B2 scenario with ARPEGE .

Experiments (current and future climate) with the HadCM3, HadAM3H, ECHAM4 and eleven different RCMs have been completed.

A complete set of impacts studies are also planned, including those for storm surges, ecosystems, agriculture, and Mediterranean agriculture and hydrology.

5. GUIDELINES

5.1 What We Know about the Added Value of Regional Modelling -- What Can One Gain from Using RCMs?

The issue of "added value" of regionalization techniques is a difficult and much debated one. This is because it essentially depends on, and thus needs to be carefully formulated for, the specific scientific problem of interest. AOGCMs generate information at the large scale but, due to their resolution limitations, in many circumstances they are not expected to provide accurate regional and local climate detail. A fundamental question is, therefore, whether it is possible to use regionalization techniques to add information about processes at the unresolved scales and their interaction with the climate system taking as input the large scale information from AOGCMs. The use of a regionalization tool for climate change simulation is thus advisable to the extent that it produces additional information compared to the AOGCM.

One of the reasons for developing regionalization techniques is to capture the effect of fine scale forcings in areas characterized by fine spatial variability of features such as topography and land surface conditions. In fact, in many regions topography and land use affect the spatial distribution of climate variables and generate (or modulate) atmospheric circulations at scales that are not explicitly described by AOGCMs. A regionalization method is thus needed to capture these effects, and research has shown for example that the simulation of the spatial patterns of precipitation and temperature over complex terrain is generally improved with the increasing resolution obtained with regionalization techniques (Giorgi et al., 2001).

The increased spatial resolution of regionalization tools also allows an improved description of regional and local atmospheric circulations. Examples are synoptic and frontal extratropical systems, narrow jet cores, cyclogenetic processes, gravity waves, mesoscale convective systems, sea-breeze type circulations and extreme weather systems (e.g. tropical storms). Sub-grid scale processes that are parameterized in AOGCMs, such as cloud and precipitation formation, can also benefit from increased spatial resolution.

Because spatial and temporal scales in atmospheric phenomena are often related, regionalization techniques can also be expected to improve the AOGCM information at high frequency temporal scales, such as daily or sub-daily. This is despite the fact that AOGCMs do provide high resolution temporal information. Therefore, for example, regionalization models can be used to improve the simulation of quantities such as daily precipitation frequency and intensity distributions, surface wind speed variability, storm inter-arrival times, monsoon front onset and transition times.

From a philosophical point of view, regionalization techniques are not intended to strongly modify the large scale circulations produced by the forcing AOGCMs. This would result in inconsistencies between large scale forcing fields and high resolution simulated fields. The effects and implications of these inconsistencies would be difficult to evaluate. In practice, however, the high resolution forcing described by some regionalization methods, such as high resolution and variable resolution AGCMs and RCMs with sufficiently large domains, can yield significant modification of the large scale flows (e.g. storm tracks), possibly leading to an improved simulation of them. This has the important by-product of providing valuable information for the future development of higher resolution AOGCMs.

5.2 When to Use High Resolution Information -- the Different Factors to Consider

In this section we attempt to provide readers with information on what to consider when trying to decide to use high resolution information from RCMs or not. It is difficult to make extremely specific recommendations because so much depends on the details of the proposed study. However, we do provide a framework for thinking about this question. Box 3 presents a simple decision tree to aid the researcher in deciding when to use high resolution information.

For a given region and impact system, the need for high resolution climate scenario information may vary depending upon the particular question being addressed. With regard to this, it is useful to divide studies into two types: research-oriented and policy advice-oriented. The primary objectives of a research-oriented study will be to attempt to advance the knowledge of potential climate impacts in an impact system and/or of the most appropriate methods that may be used for assessing impacts in that system. Such studies may only address one question amongst a number of key questions surrounding a topic, and in doing so will often set aside a number of key elements of the uncertainty cascade. Where such studies address questions primarily associated with climate scenarios, the need for high resolution may be very strong. It is essential for questions such as 'Does using high resolution significantly affect the impact results?', and very strong for questions such as 'Does including changes in variability affect the impact result?' where it is likely that the conclusions may be significantly affected by the resolution of the scenario used. On the other hand, where the research focus is primarily on aspects of the impact system, there may be cases where use of high resolution inputs is not seen as important. Examples might be when different impact models are being compared, or where system sensitivity is being explored (and arbitrarily incrementing the input observed climate database may be sufficient).

Box 3. An Approach to Considering the Relevance of High Resolution Regional Modelling for a Climate Change Impact Study.

This is for guidance only. This proposed decision process is simplified and neglects some issues that may be relevant in some studies. References to the main text are to sections relevant to the question being posed.

1. *Is the climate scenario or scenarios particularly relevant to the objectives of the study?*
In some research-oriented studies in impact methods, the climate scenarios may not be particularly important. For example an arbitrary warming may be sufficient, and it would be wasteful to expend resources on detailed scenarios. However, this is not the case in policy-oriented studies, and most research-oriented studies. See section 5.2.1 for relevant discussion.

No – High resolution modelling not required - STOP

Yes – Go to 2.

2. Is the study posing a research question for which high resolution scenarios are essential?

The most obvious example of this is where the effect of high resolution on the impact results is being tested. See section 5.2.1 for further relevant discussion.

Yes – High resolution modelling is highly relevant, although statistical downscaling may be a valid alternative.

No – Go to 3.

3. Are the simulated changes in the key variables relevant to the study likely to be strongly affected by heterogeneous land surface in the regions of interest?

Consider in particular the possibility of qualitatively different changes, which are quite possible for rainfall in areas of strongly heterogeneous topography. Quantitative differences (such as the intensity of local warming) may not be significant in the context of other uncertainties. In a multi-regional study, heterogeneous land surface effects would have to be evident in most regions. See section 4.2.3 for further relevant discussion.

Yes – Go to 5.

No – Go to 4.

4. Are changes in variability and extremes required for input and are likely to be significantly more realistic at high resolution, or only available at high resolution?

See section 5.2.4 for further relevant discussion.

Box 3, continued

Yes – Go to 5.

No – Course resolution GCM-based scenarios are likely to be adequate.

5. Although high resolution modelling-based scenarios are likely to be more realistic, are course resolution GCM-based scenarios nevertheless still plausible?

Judgement is required. In areas of strong topographical control with simulated changes in atmospheric circulation, a bland pattern of change (similar change everywhere) is arguable implausible. Also if the study requires climate inputs for multiple sites (i.e. a spatially-oriented impact study) the argument for having climate inputs which are more realistic spatially is stronger. Finally, if the study requires information unobtainable at course resolution (such as tropical cyclone changes) course resolution results are implausible. See sections 5.2.3 and 5.2. 4.

Yes – Go to 6.

No – High resolution modelling is likely to be essential, although in some cases statistical downscaling may be a valid alternative.

6. Although high-resolution modelling-based scenarios are likely to be more realistic, do they extend significantly the range of plausible changes in climate based on a range of course resolution GCMs?

Where the results from a group of plausible GCMs already give a broad range of change in, say, rainfall change, it is less likely that high resolution modelling will significantly extend the range of uncertainty. See section 3 and Sections 5.2.5 and 5.2.6.

Yes – High resolution modelling-based scenarios are likely to be very valuable, and consideration should be given to preparing them, even if this requires a significant proportion of the project's resources.

No – GCM-based scenarios are likely to be adequate, although high-resolution scenarios may be considered if their production does not require a significant proportion of the projects resources.

5.2.1. Different goals/purpose of study

Policy-oriented research can address various questions, but will usually be aimed at providing advice on the range of possible climate change impacts on a system so that possible adaptations may be planned. Because the output of such research is linked to decision-making (clients will be mainly government and industry), it is very important that the climate scenarios be plausible and that key uncertainties be represented in the output. In such cases, use of high resolution may be considered essential if coarse resolution scenarios are a priori implausible (e.g., due to topographic effects or the inability to resolve extreme events.), or may be considered not important if coarse resolution scenarios are plausible and the uncertainty in outcome associated with resolution is considered small relative to other uncertainties.

5.2.2. Spatial Context of Study

Obviously the spatial scale of the study relates to whether it would be desirable to use high resolution information. We here divide Impacts Studies into four categories, based largely on their spatial scale: 1) global integrated assessments; 2) national or continental scale assessments; 3) regional (subcontinental/smaller nation) impacts assessment; and 4) local impacts assessment.

Global integrated assessments. This is the type of study least likely to require or desire high resolution climate scenarios from any source. Since they are global in extent, any climate scenario must be global in extent to be useful. In this regard, scenarios from time slice experiments would be the most likely to serve. These assessments tend to focus on uncertainties based on emissions and climate sensitivity.

Large national or continental scale assessments. Examples of such programs and experiments include the PRUDENCE program in Europe (Christensen et al., 2002, and Box 2), the OURANOS program in Canada (http://www.ouranos.ca), and the various runs produced over the continental US (e.g., Giorgi et al. 1998; Pan et al., 2001), and double nested runs over Australia (Whetton et al., 2001). Regional climate model results have been produced at this scale for impacts purposes. These continents have complex topography, irregular coasts, etc. They tend to use RCM results produced on the order of 50km scale. But is the regional detail necessary for this scale of study? National studies of this scale have often been performed using results from GCMs and AOGCMs. Here the issue might only be decided in concert with the other factors listed here.

Regional, small nation. These would most obviously need high resolution information, given that some nations are not even represented at the scale of GCMs or occupy only a few GCM grid boxes. An example of such a context is the UK Climate Impacts Program (UKCIP), which uses regional model results to form scenarios for impacts use (Hulme et al., 2002). An important geo-political issue may be the importance of national representation in climate models in the context of international negotiations (i.e., it may matter if a country is or is not on the map). Examples of regional studies requiring high resolution information include Switzerland, island states such as Jamaica, and Belgium. For some studies there may be a need to go to very high resolutions e.g., mountain hydrology studies, which may benefit from double nesting (e.g. Scandinavia, Christensen et al., 1998).

Local, site specific. High resolution regional modelling will obviously be desirable for this scale, but here may be a situation where statistical downscaling would be most convenient and appropriate to use. Another possibility is a combined approach where regional modelling experiments are statistically downscaled.

5.2.3. Different Physiographic Contexts

The contexts of relevance to high resolution information include: regions with: small irregular land masses and complex coastlines; areas of complex topography, areas with heterogeneous landscapes, and areas where resolving synoptic and meso-scale features of the atmosphere is critical to reproducing important features of the climate.

Areas with small, irregular land masses most likely must have high resolution, e.g., the Caribbean, archipelagos, Indonesia, Madagascar, the Mediterranean. The different thermal characteristics of land and ocean clearly indicate GCM results for ocean points are not adequate for representing small land masses. However, there have not been sufficient experiments that clearly indicate the degree to which scenarios that explicitly represent small land masses differ from those that do not. We also do not know if there is a minimum size, i.e., are some islands so small that there is very little land/sea contrast effect.. For such small islands statistical downscaling may be the best solution.

Examples of regions with complex topography include the Rocky Mountains, the Alps, Victoria, Australia, Afghanistan, and parts of eastern Africa.

Regions where it is important to resolve synoptic scale features include the Great Plains of US, which has a very steep precipitations gradient, and for which it is important to resolve the low level jet (Anderson et al., 2003). Moreover, a scale of only a few kilometers could be necessary to resolve mesoscale convective systems.

Areas with heterogeneous land surfaces include the southeastern US, the Sahael, and inland Australia. :

There essentially is no area where we would absolutely say that high resolution, say the difference between 300 km and 50 km, is not necessary at this point, obviously given a particular context, resource, and study goal. More experiments testing the importance of these different high resolution features are necessary before we can clearly determine where high resolution is likely not necessary.

5.2.4. Type of climate information required - (e.g. extremes)

The particular climate change information required for an impact assessment may influence the decision as to whether a high resolution modelling product is used. Some climate variables, and some aspects of a given climate variable, are more sensitive to model resolution than others. With regard to current climate realism, surface variables such as surface temperature or rainfall are more likely to be significantly improved by the use of high resolution than free atmosphere variables such as 500 hPa height. Also, because for most variables temporal variability is closely linked to spatial variability, short-term (i.e., daily) variability and extremes are more likely to be more realistically simulated at high resolution. For example, it may be the case that a coarse resolution simulation provides an acceptably realistic mean rainfall for a location, but that high resolution is needed (but not necessarily sufficient) for a realistic simulation of extreme rainfall (Huntingford et al., 2002). However, it should be noted that some climatic variability is less likely to be improved by high resolution modelling, such as interannual climate variability associated with large scale circulation systems such as El Nino-Southern Oscillation.

Apart from current climate realism, another consideration is the likely impact of resolution on the simulated enhanced greenhouse changes. For some variables in some circumstances, resolution can have an impact in qualitative terms. For example, the simulated direction of rainfall change has been shown on occasions to differ in sign, in a systematic way, between coarse and fine resolution simulations (Whetton et al., 2001). Thus, the argument for using high resolution is likely to be stronger for a study where precipitation change is the key input than, say, one where temperature change is the key input.

5.2.5 Computer resources required

Running a new high resolution simulation appropriate for use in a regional impact study is resource intensive. All projects have limitations in the resources they have available, in terms of each of finance, time, computers, skill base of the research team, etc. This means that in cases where the use of high resolution is desirable but not essential, it may be reasonable to not use it. This factor is not a consideration if an appropriate high resolution is already available for use as part of the outcome of another project.

Examples of computer resources required include: On a Pentium III 1 Ghz PC a domain of about 90x110x14 grid points and 50 km grid point spacing runs at about 10 hours per simulated month (1 processor), or about 8 days per simulated year. Another example, on a Pentium IV 2 GHz PC, a domain of 100x110x19 points, took 3 months for 30 years (or 3 days per year). A further example is a domain with 129x80x18 grid points at a 55 km resolution and a 180 second time step on a Pentium IV 2.4 GHz PC took 9 hours for a one month simulation. With the rapid increase in computing power available on PCs, for example, longer mulit-year simulations are becoming more common (e.g., 20 to 30 years) and are desirable particularly for policy relevant research.

5.2.6. Weighing up the factors in the context of a given study and some examples of studies

Here we consider the importance of weighing the various factors (purpose, physiography, variables, etc.) in the context of a particular regional study and limited resources. The guiding principle is to maximize the relevance of the scenarios used to the research or policy question being addressed while staying within resource limitations. Use of high resolution will then emerge as a priority in some cases.

For a particular study, it may then be, in the judgment of the researchers, more relevant to devote resources to preparing multiple GCM-based scenarios or to using alternative impact models, rather than to preparing high resolution climate scenarios. For example, where current GCMs provide scenarios of regional rainfall change which can differ in sign, running a regional model to provide an additional high resolution scenario may expend a large amount of resources, but have little effect on the range of plausible impact results. On the other hand, in regions where topographic effects are likely to be very strong, it may be reasonable to reject all of the GCM results as implausible and to proceed to prepare scenarios based on high resolution modelling.

Examples of studies that would need high resolution information.

1) Study of US Great Plains. Research question: How might climate change by the end of the 21st century affect the steep precipitation gradient of the region and thereby influence the spatial extent of management practices (e.g. continuous and summer fallow wheat cropping). For other types of research questions in the eastern portion of the Great Plains, the need for high resolution may be less compelling.

2) Climate change impacts assessment of the Caribbean region. Any research question concerning the impacts of climate change in this region would require the use of high resolution information. However, there have not yet been any RCM experiments that clearly demonstrate the difference high resolution makes in results for impacts studies here.

3) Impacts studies in Colombia. The topographic complexity of the northern Andes, which cover most of the country, produces a diversity of climate and ecosystems that is highly relevant to all impacts.

5.3. Creating High Quality Scenarios

While it is assumed that impacts researchers will not be themselves producing RCM experiments, it is important, for background, that they understand what is required in producing the best possible climate scenarios using RCMs. This section describes the procedures and how to manipulate the output of RCM experiments to create inputs for impacts models.

5.3.1. Necessary RCM procedures

The use of nested RCMs to produce regional climate change scenarios generally requires substantial modelling experience, since a nested RCM simulation depends on many factors that need to be carefully considered. In other words, RCMs cannot be treated as black boxes and the results from RCM simulations need to be carefully evaluated. A general discussion of issues pertaining to the use of RCMs can be found in Giorgi and Mearns (1991, 1999), McGregor (1997), Giorgi et al. (2001) and references cited therein, Leung et al. (2003), and Hewitson and Crane (2004).

A foremost requirement for the use of RCMs in climate change applications is that they adequately reproduce the regional characteristics of present day climate, and that model errors in describing the climate of a region be identified and possibly minimized. This can be achieved by running the RCM using boundary conditions from analyses of observations for given historical periods. The results from these experiments, which are usually referred to as "perfect boundary condition (PBC)" experiments, can then be compared with actual observations for the simulation period.

Errors in an RCM simulation can derive either from the lateral boundary forcing fields or from the model configuration (e.g. domain and resolution) and internal physics. Since the fields used to drive the RCM in PBC experiments are of the best possible quality, these experiments allow the identification of model errors primarily due to the model configuration and internal physics.

In general the selection of model domain and resolution is an important issue. Ideally, the model domain should be large enough to allow the RCM to develop its mesoscale circulation features and to include all areas where forcings and processes are important for the climate of a region. It is also advisable to place the region of interest as far away from the lateral boundaries as possible in order to minimize the influence of possible spurious boundary effects. Similarly, the model resolution should be sufficient to capture the high resolution forcings and circulations of relevance for the region. On the other hand, the computational resources needed to run an RCM increase linearly with domain size and at least quadratically with resolution (more if the timestep has to be reduced proportionally). Therefore a compromise needs to be reached between available computing resources and representation of relevant forcings and processes. PBC experiments can provide valuable information towards an optimal achievement of this compromise.

Because of these issues it is highly recommended that PBC experiments be carried out and analyzed prior to RCM nesting within a GCM. For a proper evaluation of the model climatology, the PBC experiments should be as long as possible, certainly multi-year and preferably multi-decadal in length.

The second step after an RCM has been validated and its configuration optimized is to assess the RCM performance when nested within the driving GCM. This can be achieved by running the nested RCM for present day climate conditions ("control" experiments) and comparing the results with observed climatologies. In this regard, it is important that the RCM simulation be as long as possible in order to yield more meaningful statistics. RCM simulations of present day climate and their comparison with PBC simulations allow the identification of errors primarily deriving from the GCM boundary conditions (Pan et al., 2001). It is important to identify, quantify and understand the errors in nested control runs because these can help in the interpretation of the climate change simulations.

The analysis of the PBC and control run should involve a range of variables (e.g. temperature, precipitation, atmospheric circulations, sea level pressure, cloudiness, surface energy and water budget) and a range of scales, from local to regional spatially, and from sub-daily and daily to seasonal and interannual/interdecadal temporally.

Another important function of nested control simulations is that of aiding in the identification of the added value of the RCM simulations compared to the forcing GCM simulation. In other words, these experiments provide information on how the high resolution nested RCM enhances the low resolution driving GCM fields. This aspect of the climate change experiment is important for the assessment of the RCM-produced climate change signal in relation to the GCM-produced signal, since the GCM and RCM signals are often different at the regional or sub-regional scale.

After the PBC and control simulations have been completed and analyzed, climate change simulations can be carried out. Similarly to the control experiments, the climate change experiments should be of length sufficient to yield robust statistics, minimally 5-10 years, but preferably 20-30 years. Relatively short runs can provide some information on first order effects, but they limit the breadth of statistical analysis. A range of variables should be analyzed in the climate change simulations, including not only those of interest for the particular impact application but also those that would provide an overall view of changes in the climatology of the model. This analysis in conjunction with a similar analysis of the control run, can help separate signal from noise in the changed climate (discussed in the next paragraph).

Since the climate change signal can be affected by errors in the control simulation, attention should be paid to the identification of true physical signals from spurious signals resulting from biases in the control run. An example of such an analysis for western Africa, can be found in Jenkins (2003). In addition, since the climate change signal response may be different in the forcing GCM and nested RCM, it is important to identify the causes and the statistical significance of these differences, and in particular to assess whether they are due to identifiable physical processes. In other words, it is critical to distinguish physical signals from model-produced noise. Such analyses should be undertaken in cooperation with climate modelers and climatologists.

In general, RCM users should be aware that a number of RCM systems are today available which are portable, usable on different computing platforms, and applicable to any region of the world (e.g., Noguer et al., 2003; Giorgi et al., 2003). Intercomparison experiments such as PIRCS (Project to Intercompare Regional Climate Simulations, Takle et al., 1999) show that there is no single RCM that consistently outperforms the others and that different models may simulate better different aspects of regional climates. Since different RCMs generally give varying responses to the same boundary forcing, ideally, the use of more than one RCM would be recommended. This however is often not practical, and various considerations, some of them not strictly scientific, can enter the choice of a given RCM. Among them are model availability, flexibility and user friendliness, consulting support, portability and computing efficiency. Some RCMs may be more or less suitable for given scales, for example some models (e.g. those that use the hydrostatic approximation) may not be suitable for resolutions finer than about 10 km.

Often, fields from more than one GCM may be available for RCM nesting. Ideally, use of more than one GCM would provide a measure of the uncertainty related to the response of different GCMs to the climate forcings. On the other hand, use of more than one GCM is not always practical from the point of view of available resources. The choice of the forcing GCM is thus important and can be based on different considerations. A critical one is the performance of the GCM in reproducing present day large scale circulation features over the region of interest. Since errors in the GCM driving fields affect the RCM simulation, it is highly recommended to select the GCM that shows the best performance in this respect. Another consideration is that of compatibility between forcing GCM and nested RCM physics. Driving GCM and nested RCM may have either the same or different physics schemes (each tailored to the respective model resolution). Overall, these modelling strategies have different advantages and limitations (e.g Giorgi et al. 2001) and have shown performance of similar quality. Depending on the particular experiment set up and model environment, either one may be preferable (i.e., the same or different physics in the two models).

Finally, if very high resolution is needed over specific sub-regions of the domain, this can be achieved in different ways. Some RCMs have capability of running interactive 2-way high resolution sub-nests within their domain. Alternatively, double (or multiple) one-way nesting can be used. This consists of using the fields obtained from the RCM simulation to drive at the lateral boundaries a higher resolution simulation over the sub-region of interest with the same (or a different) RCM. Another possibility is statistically downscaling the RCM results to obtain higher resolution.

5.3.2. Combining RCM output with observed data sets

In developing climate scenarios, the common procedure has been to combine changes in climate (perturbed climate versus control climate) with observed climate data, because the errors in the climate models are too large to allow for direct use of the control runs in impacts models. This is still generally true in the case of RCM results. However, as the resolution of the climate runs increases, it becomes more difficult to obtain observed data at the desired resolution. Therefore, the issue of direct use of RCM output has been raised. Thomson et al. (2001), for example, used direct RCM output in a crop model because no observed data were available at the needed resolution. However, they did not explicitly account for the error this usage produced in the crop model results. Arnell et al. (2003) (see Box 1) used both direct RCM output and combined it with observations and found that using the control run output directly produced hydrologic impacts quite different from those obtained when using observed climate data. Jha et al. (2003) used RCM output directly in a hydrological study of the upper Mississippi basin. Essentially, when possible, observed data should still be used. If the desired resolution is not available, then, careful evaluation of the error introduced by using direct output should be made, and this error considered in any inferences made from the study results (see the general Scenario

Guidance material available on the DDC web site for more information on use of observed data sets).

6. SUMMARY RECOMMENDATIONS

1. Carefully consider the purpose of the study and evaluate what the role of higher resolution information would be in that context.
   One should attempt to maximize the relevance of the scenarios used to the research/policy question being addressed while staying within resource limitations. For some projects this will require the development of high resolution scenarios, but other projects may benefit more from using the resources required for high resolution modelling in other ways. For a given project considerable judgment is required in making this decision. This guide has described the relevant issues that need to be considered to assist impacts researchers in making carefully considered choices. The key issue may often be the need to represent uncertainty in spatial scale amongst a range of uncertainties which may need to be allowed for in the study.

2. If regional/time slice/variable resolution modelling is to be used, work with experienced climate/regional modelers.

3. Emphasis of analysis should still be on the scale dependence of the scenarios and impacts when this makes sense, i.e., compare impacts using driving GCM scenarios and with high resolution RCM scenarios except where there really isn't any sensible corresponding coarse scenario. This is particularly true for research-oriented studies.

4. Keep the uncertainty associated with spatial scale in perspective given other uncertainties affecting climate projections. These particularly include the uncertainty on the regional scale of different GCMs and AOGCMs. Also remember that different regional models can respond differently. There is uncertainty in the responses of regional models.

5. Take advantage of existing RCM output. Many experiments (at least with $2xCO_2$) have been performed over many regions (see Appendix). Many of them can be used for certain

types of impacts investigations, such as sensitivity analyses exploring the effect of altering spatial scale.

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