

Use of Climate Scenarios Developed from Regional Climate Model Experiments
Abstract for NCAR Summer 04 Colloquium on Climate and Health

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; Lamb, 1987; 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.

Coupled atmosphere-ocean global climate models (AOGCMs) are the modeling tools traditionally used for generating climate change projections and scenarios. 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.

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 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 impacts 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.

Regional Climate Models

What is commonly referred to as nested regional climate modeling 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 gas (GHG) and aerosol forcing, as well as initial soil conditions, are also provided by the driving AOGCM.

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. 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 modeling 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). 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., Noguera 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. 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) and better than GCMs on their grid scale (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).

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 (Hay et al., 2000; Leung and Wigmosta, 1999; Wang et al., 1999; Stone et al.; 2003; Wilby et al., 1999, Pennell and Barnett, 2004); agriculture (Mearns et al., 1999, 2000, 2001, 2004; Brown et al., 1999; Thomson et al., 2001) and forest fires (Wotton et al. 1998).

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., 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.

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)

- Specifying alternative emissions futures

- Converting emissions to concentrations
- Converting concentrations to climate forcing
- Modeling the climate response to a given forcing
- Converting the model response into inputs for impact studies
- Modeling 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 modeling may be viewed as potentially part of the process of both modeling the climate response to a given forcing and converting the model response into inputs for impact studies. 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

The uncertainty that is addressed when high resolution modeling 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).

(References from this paper and a longer document may be found at:
http://ipcc-ddc.cru.uea.ac.uk/guidelines_rcm.html)

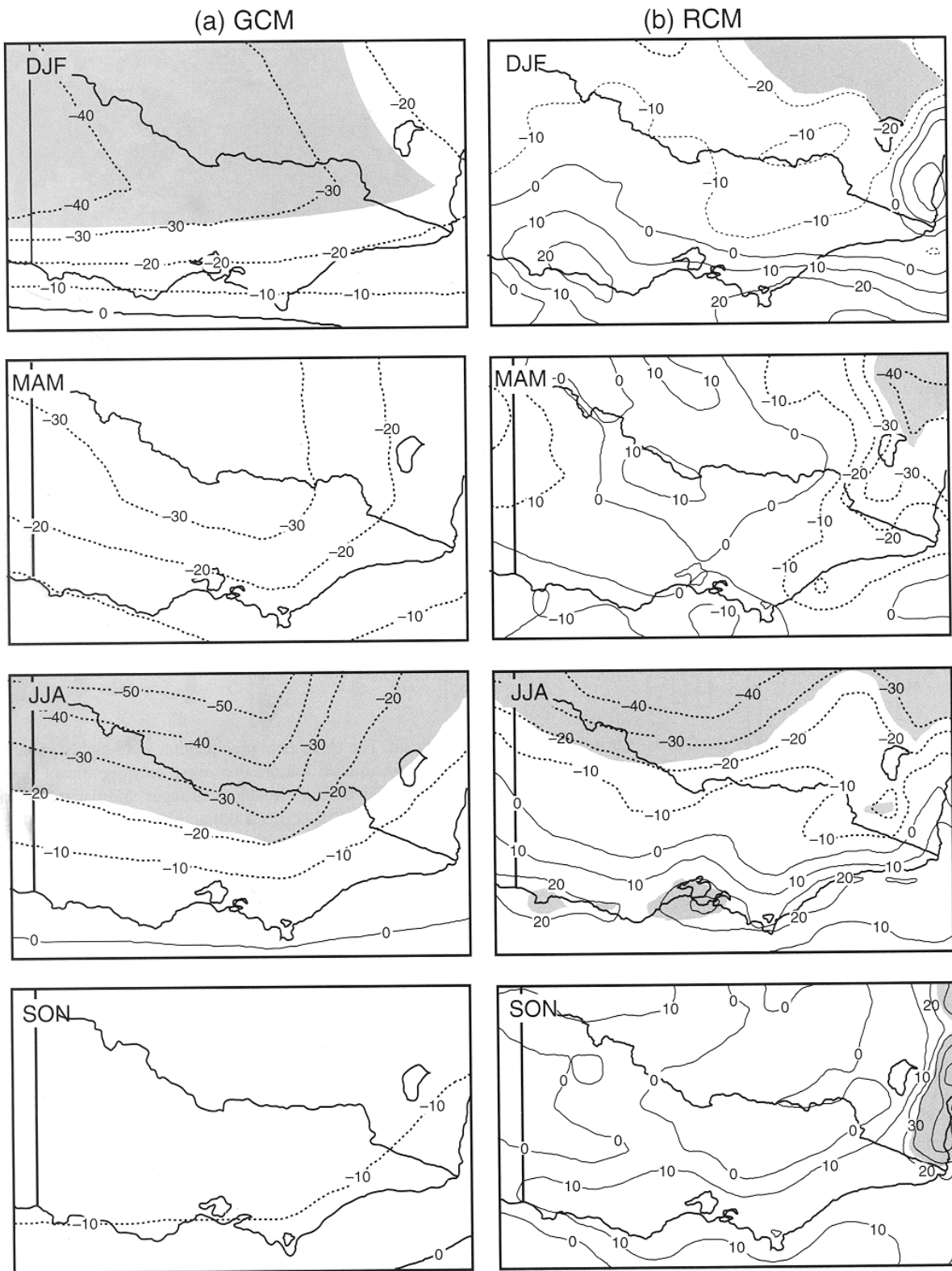


Figure 1 Percentage change in mean seasonal rainfall under $2\times\text{CO}_2$ conditions as simulated by a GCM (a) and a RCM (b) for a region around Victoria, Australia. Areas of change statistically significant at the 5% confidence level are shaded. Whetton *et al.* (2001).

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 CO₂ 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.

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.