10

Regional Climate Information – Evaluation and Projections

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Contents

Executive Summary

Introduction
This chapter assesses regional climate information from Atmosphere-Ocean General Circulation Models (AOGCMs) and techniques used to enhance regional detail. These techniques have been substantially improved since the IPCC WGI Second Assessment Report (IPCC, 1996) (hereafter SAR) and have become more widely applied. They fall into three categories: high and variable resolution Atmosphere General Circulation Models (AGCMs); regional (or nested limited area) climate models (RCMs); and empirical/statistical and statistical/dynamical methods. The techniques exhibit different strengths and weaknesses and their use depends on the needs of specific applications.

Simulations of present day climate
Coarse resolution AOGCMs simulate atmospheric general circulation features well in general. At the regional scale the models display area-average biases that are highly variable from region-to-region and among models, with sub-continental area-averaged seasonal temperature biases typically within 4°C and precipitation biases mostly between –40 and +80% of observations. In most cases, these represent an improvement compared to the AOGCM results evaluated in the SAR.

The development of high resolution/variable resolution AGCMs since the SAR shows that the models' dynamics and large-scale flow improve as resolution increases. In some cases, however, systematic errors are worsened compared with coarser resolution models although only very few results have been documented.

RCMs consistently improve the spatial detail of simulated climate compared to General Circulation Models (GCMs). RCMs driven by observed boundary conditions show area-averaged temperature biases (regional scales of 10^5 to 10^6 km^2) generally within 2°C and precipitation biases within 50% of observations. Statistical downscaling demonstrates similar performance, although greatly depending on the methodological implementation and application.

Simulation of climate change for the late decades of the 21st century

Climate means
The following conclusions are based on seasonal mean patterns at sub-continental scales emerging from current AOGCM simulations. Based on considerations of consistency of changes from two IS92a-type emission scenarios and preliminary results from two SRES emission scenarios, within the range of these four scenarios:

• It is very likely that: nearly all land areas will warm more rapidly than the global average, particularly those at high latitudes in the cold season; in Alaska, northern Canada, Greenland, northern Asia, and Tibet in winter and central Asia and Tibet in summer the warming will exceed the global mean warming in each model by more than 40% (1.3 to 6.9°C for the range of models and scenarios considered). In contrast, the warming will be less than the global mean in south and Southeast Asia in June-July-August (JJA), and in southern South America in winter.

• It is likely that: precipitation will increase over northern mid-latitude regions in winter and over northern high latitude regions and Antarctica in both summer and winter. In December-January-February (DJF), rainfall will increase in tropical Africa, show little change in Southeast Asia and decrease in central America. There will be increase or little change in JJA over South Asia. Precipitation will decrease over Australia in winter and over the Mediterranean region in summer. Change of precipitation will be largest over the high northern latitudes.

Results from regional studies indicate that at finer scales the changes can be substantially different in magnitude or sign from the large area average results. A relatively large spread exists between models, although attribution is unclear.

Climate variability and extremes
The following conclusions are based on patterns emerging from a limited number of studies with current AOGCMs, older GCMs and regionalisation studies.

• Daily to interannual variability of temperature will likely decrease in winter and increase in summer in mid-latitude Northern Hemisphere land areas.

• Daily high temperature extremes will likely increase in frequency as a function of the increase in mean temperature, but this increase is modified by changes in daily variability of temperature. There is a corresponding decrease in the frequency of daily low temperature extremes.

• There is a strong correlation between precipitation interannual variability and mean precipitation. Future increases in mean precipitation will very likely lead to increases in variability. Conversely, precipitation variability will likely decrease only in areas of reduced mean precipitation.

• For regions where daily precipitation intensities have been analysed (e.g., Europe, North America, South Asia, Sahel, southern Africa, Australia and the South Pacific) extreme precipitation intensity may increase.

• Increases in the occurrence of drought or dry spells are indicated in studies for Europe, North America and Australia.

Tropical cyclones
Despite no clear trends in the observations, a series of theoretical and model-based studies, including the use of a high resolution hurricane prediction model, suggest:

• It is likely that peak wind intensities will increase by 5 to 10% and mean and peak precipitation intensities by 20 to 30% in some regions;

• There is no direct evidence of changes in the frequency or areas of formation.

Recommendations
The material assessed identifies key priorities for future work:

GCMs:
• Continued improvement in GCMs, as their use is fundamental to deriving regional climate information.
• GCM simulations with a greater range of forcing scenarios and an increased ensemble size to assess the spread of regional predictions.
• More assessment of GCM regional attributes and climate change simulations.
• A much greater effort in the evaluation of variability (daily to interannual) and extreme events.

RCMs:
• A more systematic and wide application of RCMs to adequately assess their performance and to provide information for regional scenarios.
• Ensemble RCM simulations with a range of regional models driven by different AOGCM simulations.

• A much greater effort in the evaluation of variability (daily to interannual) and extreme events.

Empirical/statistical and statistical/dynamical methods:
• More regional observations to provide for more comprehensive statistical downscaling functions.
• Much further work to identify the important climate change predictors for statistical downscaling.
• Application of different techniques to a range of AOGCM simulations.

Tropical cyclones:
• A greater range of models and techniques for a comprehensive assessment of the future behaviour of tropical cyclones.

Cross-cutting:
• Systematic comparisons of the relative strengths and weaknesses of techniques to derive regional climate information.
• The development of high-resolution observed climatologies, especially for remote and physiographically complex regions.
• A systematic evaluation of uncertainties in regional climate information.

10.1 Introduction

This chapter is a new addition compared with previous IPCC assessment reports. It stems from the 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 the processes that determine regional climate change, which span a wide range of spatial and temporal scales, and to the difficulty in 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, of the order of 300 to 500 km, due to the centennial to millennial time-scales associated with the ocean circulation and the computing requirements that these imply. However, regional climate is often affected by forcings and circulations that occur at the sub-AOGCM horizontal grid scale (e.g., Giorgi and Mearns, 1991). Consequently, AOGCMs cannot explicitly capture the fine-scale structure that characterises climatic variables in many regions of the world and that is needed for impact assessment studies (see Chapter 13).

Therefore, a number of techniques have been developed with the goal of enhancing the regional information provided by coupled AOGCMs and providing fine-scale climate information. Here these are referred to as "regionalisation" techniques and are classified into three categories:

• high resolution and variable resolution Atmosphere GCM (AGCM) experiments;
• nested limited area (or regional) climate models (RCMs);
• empirical/statistical and statistical/dynamical methods.

Since the IPCC WGI Second Assessment Report (IPCC, 1996) (hereafter SAR), a substantial development has been achieved in all these areas of research. This chapter has two fundamental objectives. The first is to assess whether the scientific community has been able to increase the confidence that can be placed in the projection of regional climate change caused by anthropogenic forcings since the SAR. The second is to evaluate progress in regional climate research. It is not the purpose of this chapter to provide actual regional climate change information for use in impact work, although the material discussed in this chapter serves most often for the formation of climate change scenarios (see Chapter 13).

The assessment is based on all the different modelling tools that are currently available to obtain regional climate information, and includes: (a) an evaluation of the performance, strengths and weaknesses of different techniques in reproducing present day climate characteristics and in simulating processes of importance for regional climate; and (b) an evaluation of simulations of climate change at the regional scale and associated uncertainties.

Evaluation of present day climate simulations is important because, even though a good simulation of present day climate does not necessarily imply a more accurate simulation of future climate change (see also Chapter 13), confidence in the realism of a model's response to an anomalous climate forcing can be expected to be higher when the model is capable of reproducing observed climate. In addition, interpretation of the response is often facilitated by understanding the behaviour of the model in simulating the current climate. When possible, the capability of models to simulate climates different from the present, such as palaeoclimates, may also provide additional confidence in the predicted climatic changes.

The chapter is organised as follows. In the remainder of this section a summary is first presented of the conclusions reached in the SAR concerning regional climate change. This is followed by a brief discussion of the regional climate problem. Section 10.2 examines the principles behind different approaches to the generation of regional climate information. Regional attributes of coupled AOGCM simulations are discussed in Section 10.3. This discussion is important for different reasons: first, because AOGCMs are the starting point in the generation of regional climate change scenarios; second, because many climate impact assessment studies still make use of output from coupled AOGCM experiments without utilising any regionalisation tool; and third because AOGCMs provide the baseline against which to assess the added value of regionalisation techniques. Sections 10.4, 10.5 and 10.6 are devoted to the analysis of experiments using high resolution and variable resolution AGCMs, RCMs and empirical/statistical and statistical/dynamical methods, respectively. Section 10.7 analyses studies in which different regionalisation techniques have been intercompared and Section 10.8 presents a summary assessment.

10.1.1 Summary of SAR

The analysis of regional climate information in the SAR (Section 6.6 of Kattenberg *et al.*, 1996) consisted of two primary segments. In the first, results were analysed from an intercomparison of AOGCM experiments over seven large (subcontinental) regions of the world. The intercomparison included AOGCMs with and without ocean flux correction and focused on summer and winter precipitation and surface air temperature. Biases in the simulation of present day climate with respect to observations and sensitivities at time of greenhouse gas (GHG) doubling were analysed. A broad inter-model range of regionally averaged biases and sensitivities was found, with marked interregional variability. Temperature biases were mostly in the range of ±5°C, with several instances of larger biases (even in excess of 10°C). Precipitation biases were mostly in the range of ±50%, but with a few instances of biases exceeding 100%. The range of sensitivities was lower for both variables.

The second segment of the analysis focused on results from nested RCMs and statistical downscaling experiments. Both these techniques were still at the early stages of their development and application, so that only a limited set of studies was available. The primary conclusions from these studies were that (a) both RCMs and downscaling techniques showed a promising

performance in reproducing the regional detail in surface climate characteristics as forced by topography, lake, coastlines and land use distribution; and (b) high resolution surface forcings can modify the surface climate change signal at the sub-AOGCM grid scale.

Overall, the SAR placed low confidence in the simulation of regional climate change produced by available modelling tools, primarily because of three factors:

• errors in the reproduction of present day regional climate characteristics;
• wide range in the simulated regional climatic changes by different models;
• need to more comprehensively use regionalisation techniques to study the sub-AOGCM grid scale structure of the climate change signal.

Other points raised in the SAR were the need for better observational data sets for model validation at the regional scale and the need to examine higher order climate statistics.

10.1.2 The Regional Climate Problem

A definition of regional scale is difficult, as different definitions are often implied in different contexts. For example, definitions can be based on geographical, political or physiographic considerations, considerations of climate homogeneity, or considerations of model resolution. Because of this difficulty, an operational definition is adopted in this chapter based on the range of "regional scale" found in the available literature. From this perspective, regional scale is here defined as describing the range of 10^4 to 10^7 km^2. The upper end of the range (10^7 km^2) is also often referred to as sub-continental scale, and marked climatic inhomogeneity can occur within sub-continental scale regions in many areas of the globe. Circulations occurring at scales greater than 10^7 km^2 (here referred to as "planetary scales") are clearly dominated by general circulation processes and interactions. The lower end of the range (10^4 km^2) is representative of the smallest scales resolved by current regional climate models. Scales smaller than 10^4 km^2 are referred to as "local scale".

Given these definitions, the climate of a given region is determined by the interaction of forcings and circulations that occur at the planetary, regional and local spatial scales, and at a wide range of temporal scales, from sub-daily to multi-decadal. Planetary scale forcings regulate the general circulation of the global atmosphere. This in turn determines the sequence and characteristics of weather events and weather regimes that characterise the climate of a region. Embedded within the planetary scale circulation regimes, regional and local forcings and mesoscale circulations modulate the spatial and temporal structure of the regional climate signal, with an effect that can in turn influence planetary scale circulation features. Examples of regional and local scale forcings are those due to complex topography, land-use characteristics, inland bodies of water, land-ocean contrasts, atmospheric aerosols, radiatively active gases, snow, sea ice, and ocean current distribution. Moreover, climatic

variability of a region can be strongly influenced through teleconnection patterns originated by forcing anomalies in distant regions, such as in the El Niño-Southern Oscillation (ENSO) and North Atlantic Oscillation (NAO) phenomena.

The difficulty of simulating regional climate change is therefore evident. The effects of forcings and circulations at the planetary, regional and local scale need to be properly represented, along with the teleconnection effects of regional forcing anomalies. These processes are characterised by a range of temporal variability scales, and can be highly non-linear. In addition, similarly to what happens for the global Earth system, regional climate is also modulated by interactions among different components of the climate system, such as the atmosphere, hydrosphere, cryosphere, biosphere and chemosphere, which may require coupling of these components at the regional scale.

Therefore, a cross-disciplinary and multi-scale approach is necessary for a full understanding of regional climate change processes. This is based on the use of AOGCMs to simulate the global climate system response to planetary scale forcings and the variability patterns associated with broad regional forcing anomalies (see Chapter 9). The information provided by the AOGCMs can then be enhanced to account for regional and local processes via a suitable use of the regionalisation techniques discussed in this chapter.

10.2 Deriving Regional Information: Principles, Objectives and Assumptions

For some applications, the regional information provided by AOGCMs might suffice (Section 10.2.1), while in other cases regionalisation techniques are needed in order to enhance the regional information provided by coupled AOGCMs. The "added value" expected of a regionalisation technique essentially depends on the specific problem of interest. Examples in which regionalisation tools can enhance the AOGCM information include the simulation of the spatial structure of temperature and precipitation in areas of complex topography and land-use distribution, the description of regional and local atmospheric circulations (e.g., narrow jet cores, mesoscale convective systems, sea-breeze type circulations, tropical storms) and the representation of processes at high frequency temporal scales (e.g., precipitation frequency and intensity distributions, surface wind variability, monsoon front onset and transition times).

The basic principles behind the regionalisation methods identified here are discussed in Section 10.2.2, high resolution and variable resolution AGCM experiments; Section 10.2.3, RCMs; and Section 10.2.4, empirical/statistical and statistical/dynamical models. The general philosophy behind regionalisation techniques is to use input data from AOGCMs to produce more detailed regional information. By design, many of these techniques are not intended to strongly modify the planetary scale circulations produced by the forcing AOGCM. This ensures consistency with the AOGCM simulation and facilitates the interpretation of the additional detail as due to the increase in resolution. However, high and variable resolution AGCMs, as well as RCMs with sufficiently large domains, can

yield significant modification of the large-scale circulations, often leading to an improved simulation of them. This would tend to increase confidence in the simulations, but the implications of inconsistencies with the AOGCM forcing fields would need to be considered carefully in the interpretation of the climate change information.

Note that RCMs and statistical models are often referred to as "downscaling" tools of AOGCM information. The concept of "downscaling" implies that the regional climate is conditioned but not completely determined by the larger scale state. In fact, regional states associated with similar larger scale states may vary substantially (e.g., Starr, 1942; Roebber and Bosart, 1998).

10.2.1 Coupled AOGCMs

The majority of climate change impact studies have made use of climate change information provided by transient runs with coupled AOGCMs without any further regionalisation processing. The primary reason for this is the ready availability of this information, which is global in nature and is routinely stored by major laboratories. Data can easily be drawn from the full range of currently available AOGCM experiments of the various modelling centres for any region of the world and uncertainty due to inter-model (or inter-run) differences can thus be evaluated (e.g., Hulme and Brown, 1998). In addition, data can be obtained for a large range of variables down to short (sub-daily) time-scales.

From the theoretical viewpoint, the main advantage of obtaining regional climate information directly from AOGCMs is the knowledge that internal physical consistency is maintained. The feedback resulting from climate change in a particular region on planetary scale climate and the climate of other regions is allowed for through physical and dynamical processes in the model. This may be an important consideration when the simulation of regional climate or climate change is compared across regions.

The limitations of AOGCM regional information are, however, well known. By definition, coupled AOGCMs cannot provide direct information at scales smaller than their resolution (order of several hundred kilometres), neither can AOGCMs capture the detailed effects of forcings acting at sub-grid scales (unless parametrized). Biases in the climate simulation at the AOGCM resolution can thus be introduced by the absence of sub-grid scale variations in forcing. As an example, a narrow (sub-grid scale) mountain range can be responsible for rain shadow effects at the broader scale. Many important aspects of the climate of a region (e.g., climatic means in areas of complex topography or extreme weather systems such as tropical cyclones) can only be directly simulated at much finer resolution than that of current AOGCMs. Analysis relevant to these aspects is undertaken with AOGCM output, but various qualifications need to be considered in the interpretation of the results. Past analyses have indicated that even at their smallest resolvable scales, which still fall under our definition of regional, AOGCMs have substantial problems in reproducing present day climate characteristics. The minimum skilful scale of a model is of several grid lengths, since these are necessary to describe the smallest wavelengths in the model and

since numerical truncation errors are most severe for the smallest resolved spatial scales. Furthermore, non-linear interactions are poorly represented for those scales closest to the truncation of a model because of the damping by dissipation terms and because only the contribution of larger scale (and not smaller scale) eddies is accounted for (e.g., von Storch, 1995).

Advantages and disadvantages of using AOGCM information in impact studies can weigh-up differently depending on the region and variables of interest. For example, in instances for which sub-grid scale variation is weak (e.g., for mean sea level pressure) the practical advantages of using direct AOGCM data may predominate (see also Chapter 13). However, even if resolution factors limit the feasibility of using regional information from coupled AOGCMs for impact work, AOGCMs are the starting point of any regionalisation technique presently used. Therefore, it is of utmost importance that AOGCMs show good performance in simulating circulation and climatic features affecting regional climates, such as jet streams and storm tracks. Indeed, most indications are that, in this regard, the AOGCM performance is generally improving, because of both increased resolution and improvements in the representation of physical processes (see Chapter 8).

10.2.2 High Resolution and Variable Resolution AGCM Experiments

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 (e.g., Bengtsson *et. al.*, 1995; Cubasch *et al.*, 1995; Dèquè and Piedelievre, 1995).

Here the AGCM is used to provide a reinterpretation of the atmospheric response to the anomalous atmospheric forcing (from GHG and aerosols) experienced in a transient AOGCM simulation. Hence, both this forcing and its accumulated effect on the ocean surface have to be provided to the AGCM. In a typical experiment (e.g., May and Roeckner, 2001), two time slices, say 1961 to 1990 and 2071 to 2100, are selected from a transient AOGCM simulation. The simulations include prescribed time-dependent GHG and aerosol concentrations as in the corresponding periods of the AOGCM run. Also prescribed as lower boundary conditions are the time-dependent Sea Surface Temperature (SST) and sea-ice distributions simulated by the AOGCM. The AGCM simulations are initialised using atmospheric and land-surface conditions interpolated from the corresponding AOGCM fields.

Alternative experimental designs may be more appropriate. Large systematic errors in the AOGCM simulation of SST and sea ice may induce significant biases in the climatology of the AGCM. In this case, observed SSTs and sea-ice distributions could be used for the present day simulation and changes derived from the AOGCM experiment can be added to provide the

forcing for the anomaly simulation. If the AOGCM calculates the aerosol concentrations from prescribed sources then the AGCM may use the same method. This has the advantage of providing aerosol concentrations consistent with the AGCM circulations, although its global and regional effects may be different from those in the AOGCM.

The philosophy behind the use of high or variable resolution AGCM simulations is that, given the SST, sea ice, trace gas and aerosol forcing, relatively high-resolution information can be obtained globally or regionally without having to perform the whole transient simulation with high resolution models. The main theoretical advantage of this approach is that the resulting simulations are globally consistent, capturing remote responses to the impact of higher resolution. The use of higher resolution can lead to improved simulation of the general circulation in addition to providing regional detail (e.g., HIRETYCS, 1998; Stratton, 1999a).

In general, AGCMs will evolve their own planetary scale climatology. Therefore, in a climate change simulation they are providing a reinterpretation of the impact on the atmosphere of the sea surface and radiative forcings compared to that given by the driving AOGCM. This may lead to inconsistency with the AOGCM-derived forcing. This issue has yet to be explored but should be considered carefully when interpreting AGCM responses. It would be of less concern if a model simulation of the resolved planetary scale variables were asymptoting to a solution as resolution increased, i.e., if the solution would not change fundamentally in character with resolution but just add extra detail at the finer scales. Evidence shows that this is not the case at the current resolution of AOGCMs (Williamson, 1999).

A current weakness of high resolution AGCMs is that they generally use the same formulations as at the coarse resolution for which these have been optimised to reproduce current climate. Some processes may be represented less accurately when finer scales are resolved and so the model formulations would need to be optimised for use at higher resolution. Experience with high resolution GCMs is still limited, so that, at present, increasing the resolution of an AGCM generally both enhances and degrades different aspects of the simulations. With global variable resolution models, this issue is further complicated as the model physics parametrizations have to be designed in such a way that they can be valid, and function correctly, 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 larger scales are represented only as generated by the region of interest. Conversely, in the real atmosphere, feedbacks derive from different regions and interact with each other so that a variable resolution model, based on a single high resolution region, might give an improper description of fine-to-coarse scale feedbacks. 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 to the increase in resolution obtainable with this method. However, it has been suggested that high-resolution AGCMs could be used to obtain forcing fields for higher resolution RCMs or statistical downscaling, thus effectively providing an intermediate step between AOGCMs and regional and empirical models.

10.2.3 Regional Climate Models (RCMs)

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 (e.g., Kida *et al.*, 1991; Cocke and LaRow, 2000; von Storch *et al.*, 2000)

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.

The nested regional modelling technique essentially originated from numerical weather prediction, and the use of RCMs for climate application was pioneered by Dickinson *et al.* (1989) and Giorgi (1990). RCMs are now used in a wide range of climate applications, from palaeoclimate (Hostetler *et al.*, 1994, 2000) to anthropogenic climate change studies (Section 10.5). They can provide high resolution (up to 10 to 20 km or less) and multi-decadal simulations and are 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. More recently, RCMs have begun to couple atmospheric models with other climate process models, such as hydrology, ocean, sea-ice, chemistry/aerosol and land-biosphere models.

Two main theoretical limitations of this technique are the effects of systematic errors in the driving fields provided by global models; and lack of two-way interactions between regional and global climate (with the caveats discussed in Section 10.2.2 for variable resolution models). Practically, for a given application, consideration needs to be given to the choice of physics parametrizations, model domain size and resolution, technique for assimilation of large-scale meteorological conditions, and internal variability due to non-linear dynamics not associated with the boundary forcing (e.g., Giorgi and Mearns, 1991, 1999; Ji and Vernekar 1997). Depending on the domain size and resolution, RCM simulations can be computationally demanding, which has limited the length of many experiments to date. Finally, GCM fields are not routinely stored at high temporal frequency (6-hourly or higher), as required for RCM boundary conditions, and thus careful co-ordination between global and regional modellers is needed in order to perform RCM experiments.

10.2.4 Empirical/Statistical and Statistical/Dynamical Downscaling

Statistical downscaling is based on the view that regional climate may be thought of as being conditioned by two factors: the large-scale climatic state, and regional/local physiographic features (e.g., topography, land-sea distribution and land use; von Storch, 1995, 1999a). 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 predictors from an AOGCM simulation are fed into this statistical model to estimate the corresponding local and regional climate characteristics.

A range of statistical downscaling models, from regressions to neural networks and analogues, has been developed for regions where sufficiently good data sets are available for model calibration. In a particular type of statistical downscaling method, called statistical-dynamical downscaling (see Section 10.6.2.3), output of atmospheric mesoscale models is used in statistical relationships. Statistical downscaling techniques have their roots in synoptic climatology (*Growetterlagen*; e.g., Baur *et al.*, 1944; Lamb, 1972) and numerical weather prediction (Klein and Glahn, 1974), but they are also currently used for a wide range of climate applications, from historical reconstruction (e.g., Appenzeller *et al.*, 1998; Luterbacher *et al.*, 1999), to regional climate change problems (see Section 10.6). A number of review papers have dealt with downscaling concepts, prospects and limitations: von Storch (1995); Hewitson and Crane (1996); Wilby and Wigley (1997); Zorita and von Storch (1997); Gyalistras *et al.* (1998); Murphy (1999,2000).

One of the primary advantages of these techniques is that they are computationally inexpensive, and thus can easily be applied to output from different GCM experiments. Another advantage is that they can be used to provide local information, which can be most needed in many climate change impact applications. The applications of downscaling techniques vary widely with respect to regions, spatial and temporal scales, type of predictors and predictands, and climate statistics (see Section 10.6). In addition, empirical downscaling methods often offer a framework for testing the ability of physical models to simulate the empirically found links between large-scale and small-scale climate (Busuioc *et al.*, 1999; Murphy, 1999; Osborn *et al.*, 1999; von Storch *et al.*, 1993; Noguer, 1994).

The major theoretical weakness of statistical downscaling methods is that their basic assumption is not verifiable, i.e., that the statistical relationships developed for present day climate also hold under the different forcing conditions of possible future climates. In addition, data with which to develop relationships may not be readily available in remote regions or regions with complex topography. Another caveat is that these empirically-based techniques cannot account for possible systematic changes in regional forcing conditions or feedback processes. The possibility of tailoring the statistical model to the requested regional or local information is a distinct advantage. However, it has the drawback that a systematic assessment of the uncertainty of this type of technique, as well as a comparison with other techniques, is difficult and may need to be carried out on a case-by-case basis.

10.2.5 Sources of Uncertainty in the Generation of Regional Climate Change Information

There are several levels of uncertainty in the generation of regional climate change information. The first level, which is not dealt with in this chapter, is associated with alternative scenarios of future emissions, their conversion to atmospheric concentrations and the radiative effects of these (see Chapter 13). The second level is related to the simulation of the transient climate response by AOGCMs for a given emission scenario (see also Chapters 8 and 9). This uncertainty has a global aspect, related to the model global sensitivity to forcing, as well as a regional aspect, more tied to the model simulation of general circulation features. This uncertainty is important both, when AOGCM information is used for impact work without the intermediate step of a regionalisation tool, and when AOGCM fields are used to drive a regionalisation technique. The final level of uncertainty occurs when the AOGCM data are processed through a regionalisation method.

Sources of uncertainty in producing regional climate information are of different nature. On the modelling and statistical downscaling side, uncertainties are associated with imperfect knowledge and/or representation of physical processes, limitations due to the numerical approximation of the model's equations, simplifications and assumptions in the models and/or approaches, internal model variability, and inter-model or inter-method differences in the simulation of climate response to given forcings. It is also important to recognise that the observed regional climate is sometimes characterised by a high level of uncertainty due to measurement errors and sparseness of stations, especially in remote regions and in regions of complex topography. Finally, the internal variability of the global and regional climate system adds a further level of uncertainty in the evaluation of a climate change simulation.

Criteria to evaluate the level of confidence in a regional climate change simulation can be based on how well the models reproduce present day climate or past climates and how well the climate change simulations converge across models and methods (see Chapters 8 and 9). These criteria will be drawn upon in evaluating available simulations. We add that the emerging activity of seasonal to interannual climate forecasting, particularly at the regional scale, may give valuable insights into the capability of models to simulate climatic changes and may provide objective methodologies for evaluating the long-term prediction performance of climate models at the regional scale.

10.3 Regional Attributes of AOGCMs

10.3.1 Simulations of Current Climate

10.3.1.1 Mean climate
Although current AOGCMs simulate well the observed global pattern of surface temperature (see Chapter 8), at the regional scale substantial biases are evident. To give an overview of the regional performance of current models, results are presented of Giorgi and Francisco (2000b), who compared model and observed seasonal mean temperature and precipitation averaged

for the regions indicated in Figure 10.1. The AOGCM experiments they considered were a selection of those available through the IPCC Data Distribution Centre (DDC) and included single simulations using the CSIRO Mk2, CCSR/NIES and ECHAM/OPYC models, a three-member ensemble of CGCM1 simulations and a four-member ensemble of HadCM2 simulations (see Table 9.1 for further model details). Figure 10.2 shows the biases in regionally averaged seasonal mean surface temperature and precipitation for 1961 to 1990 using as reference the gridded analysis of New *et al.* (1999). Nearly all regional temperature biases are within the range of ±4°C. The main exceptions to this are negative biases of more than 5°C in some models over Asia in DJF. Precipitation biases are mostly between −40 and +80%, with the exception of positive biases in DJF in excess of 100% over central America (CAM), northern Africa (WAF and SAH), Alaska (ALA), and some parts of Asia (EAS, SAS, TIB and NAS). The regional biases of Figure 10.2 are, in general terms, smaller than those of a similar analysis presented in the SAR (see also Kittel *et al.*, 1998) which, for example, showed regional temperature biases as high as 10 to 15°C in some models and regions. Given that the current analysis also includes many more regions, this difference in general performance strongly suggests that simulation of surface climate at the sub-continental scale is improved in current generation AOGCMs.

Current generation AOGCM simulations in which historical changes in climate forcing over the 20th century are used enable simulated regional climatic trends to be assessed against observations. This was done by Boer *et al.* (2000a) for temperature and precipitation for the regions of southern Europe, North America, Southeast Asia, Sahel and Australia (defined as in the SAR) using the CGCM1 model. Simulated and observed regional linear temperature trends agreed for all regions, except the Sahel, when sulphate forcing was included. Little could be said about agreement in observed and model precipitation trends as these trends were weak over the period in both the model and the observations.

It should be stressed that assessments of model regional performance based on area-averaging of AOGCM output over broad regularly-shaped regions should not be assumed to apply to all areas within these regions. Many of the regions considered contain a number of distinct climate regimes, and model performance may vary considerably from regime to regime. For the purpose of assessing model performance in a particular region, more detailed analysis is appropriate.

Where studies have examined spatial patterns within regions (e.g., Joubert and Tyson, 1996; Labraga and Lopez, 1997; Lal *et al.,* 1998a), reasonable correspondence with observations was found, especially for temperature and mean sea level pressure (MSLP). Most studies focus on seasonal mean conditions, but models can be analysed to focus on simulation of specific climate features. For example, Arritt *et al.* (2000) examined circulation and precipitation patterns associated with the onset of the North American monsoon in simulations with the HadCM2 model, and found this feature to be well simulated. Some studies have identified important errors in current simulations of regional MSLP, such as the tendency for pressure to be too low over Europe and too high north and south of this area (Machenhauer *et al.*, 1998). Such errors contribute significantly to local temperature and precipitation biases both in the global climate model and in nested high-resolution RCM simulations (Risbey and Stone, 1996; Machenhauer *et al.*, 1998; Noguer *et al.*, 1998).

As would be expected, GCM simulations of current climate are often poor at the local scale (e.g., Schubert, 1998). However, in areas without complex topography, it is possible for the model results at individual grid points to compare well with observations (Osborn *et al.*, 1999).

10.3.1.2 Climate variability and extreme events
Analysis of global climate model performance in reproducing observed regional climate variability has given widely varying results depending on model and region. Interannual variability in temperature was assessed regionally, as well as globally, in a long control simulation with the HadCM2 model (Tett *et al.*, 1997). Many aspects of model variability compared well against observations, although there was a tendency for temperature variability to be too high over land. In the multi-regional study of Giorgi and Francisco (2000a), both regional temperature and precipitation interannual variability of HadCM2 were found to be generally overestimated. Similar results were obtained in the European study of Machenhauer *et al.* (1998) using the ECHAM/OPYC3 model. However, in a 200-year control simulation with the CGCM1 model (see Table 9.1), Flato *et al.* (2000) noted that simulated interannual variability in seasonal temperature and precipitation compared well with observations both globally and in five selected study regions (Sahel, North America, Australia, southern Europe and Southeast Asia).

Comparison against observations of daily precipitation variability as simulated at grid boxes in GCMs is problematic because the corresponding variability in the real world operates at much finer spatial scale (see Hennessy *et al.*, 1997). A significant development in this area has been the work of Osborn and Hulme (1997) who devised a method of calculating grid box average observed daily precipitation that corrects for biases commonly introduced by insufficient station density. Using this correction, agreement between observations and the results of the CSIRO GCM were significantly improved. In an analysis of different AGCMs over Europe, Osborn and Hulme (1998) found that the models commonly simulated precipitation in winter to be more frequent and less intense than observed. Daily temperature variability over Europe was found to be too high in winter in the Hadley Centre model (Gregory and Mitchell, 1995) and in winter and spring in the ECHAM3/LSG model (Buishand and Beersma, 1996).

Synoptic circulation variability at daily and longer time-scales operates at a spatial scale which GCMs can simulate directly and work has focused on GCM performance in this area (e.g., Katzfey and McInnes, 1996; Huth, 1997; Schubert, 1998; Wilby *et al.*, 1998a; Osborn *et al.*, 1999; Fyfe, 1999). Regions studied include North America, Europe, southern Africa, Australia and East Asia. Although in many respects model performance is good, some studies have noted synoptic variability to be less than in the observations and the more
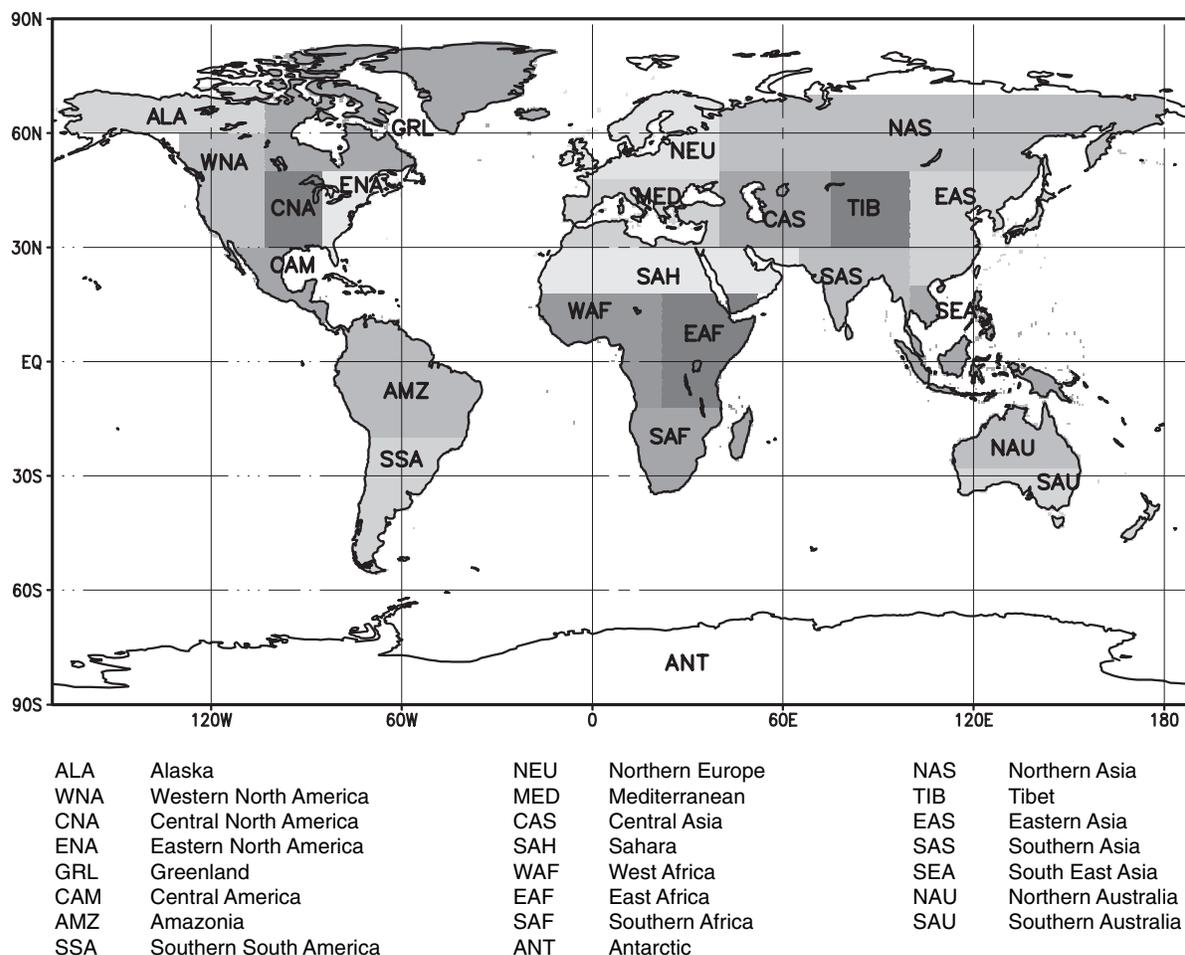
ALA	Alaska	NEU	Northern Europe	NAS	Northern Asia
WNA	Western North America	MED	Mediterranean	TIB	Tibet
CNA	Central North America	CAS	Central Asia	EAS	Eastern Asia
ENA	Eastern North America	SAH	Sahara	SAS	Southern Asia
GRL	Greenland	WAF	West Africa	SEA	South East Asia
CAM	Central America	EAF	East Africa	NAU	Northern Australia
AMZ	Amazonia	SAF	Southern Africa	SAU	Southern Australia
SSA	Southern South America	ANT	Antarctic		

Figure 10.1: Regions used for the analysis presented in Figures 10.2 to 10.5 (from Giorgi and Francisco, 2000b).

extreme deviations from the mean flow to be less intense or less frequent than observed (e.g., Osborn *et al.*, 1999).

Simulated climatic variability has also been examined as part of assessing model representation of the link between atmospheric circulation and local climate. Results have shown considerable regional differences. Osborn *et al.* (1999) examined the relationship between the circulation anomalies and grid-box average temperature and precipitation anomalies and found this to be well represented by the HadCM2 model. However, Wilby and Wigley (2000) found HadCM2 less satisfactory in reproducing the observed correlations between daily precipitation over six regions in the United States and a variety of different atmospheric predictor variables. In a similar investigation over Europe, Busuioc *et al.* (1999) found the performance of the ECHAM3 AGCM to be good in some seasons.

Widmann and Bretherton (2000) examined precipitation variability from atmospheric reanalyses as an alternative method of validating GCMs under historic flow conditions. By virtue of this approach, the atmospheric circulation is constrained to be unbiased, but the precipitation is calculated according to model physics and parametrizations. Results based on the GCM used in the reanalysis were found to be in good agreement with observations over Oregon and Washington.

10.3.2 Simulations of Climate Change

10.3.2.1 Mean climate

Giorgi and Francisco (2000b) analysed regional temperature change in five AOGCMs under a range of forcing scenarios. In all regions warming depended strongly on the forcing scenario used and inter-model differences in simulated warming were large compared to differences between ensemble members from a single model. Figure 10.3a presents some results from Giorgi and Francisco (2000b) relative to scenarios of 1%/yr increase in GHG concentration without sulphate aerosol effects. Most regional warmings for 2071 to 2100 compared to 1961 to 1990 are in the range of 2 to 8°C. Exceptions are the high northern latitudes in DJF (5 to 11°C in GRL, NAS and ALA) and central and eastern Asia in DJF (3 to 11°C in EAS, CAS and TIB). In many regions, the warming is 2 to 3°C higher in the CCC simulation than in the other models (e.g., in the African regions of WAF, EAF, SAF and SAH). Giorgi and Francisco (2000b) also considered corresponding simulations in which large increases in sulphate aerosols (consistent with IS92a emission scenarios) were included in addition to the GHG changes and found significantly reduced regional warming (the range for most regions is 1.5 to 7°C) (Figure 10.3b). Nearly all the temperature changes in
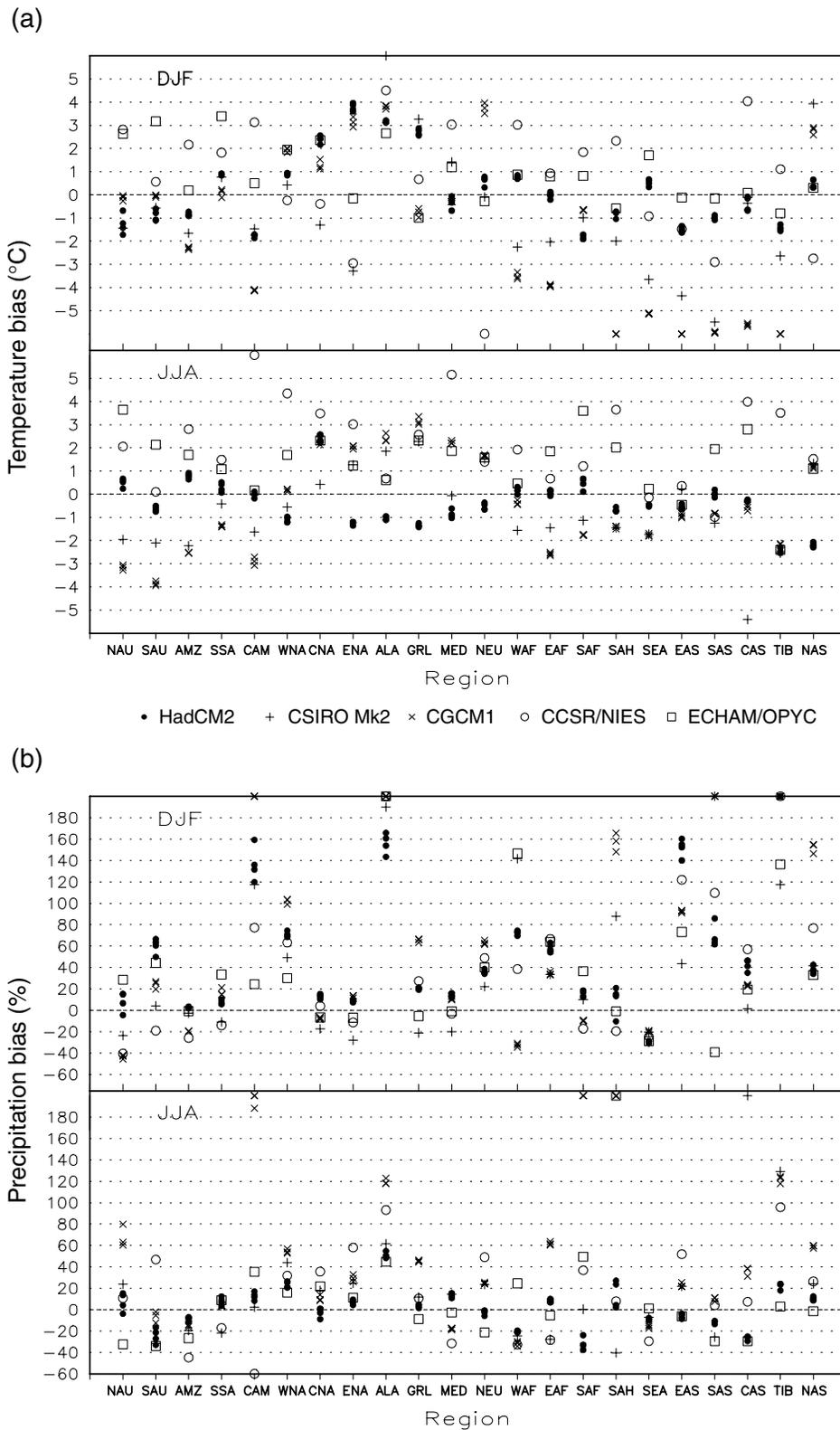
Figure 10.2: Surface temperature biases (in °C) and precipitation biases (% of observed) for 1961 to 1990 for experiments using the AOGCMs of CSIRO Mk2, CCSR/NIES, ECHAM/OPYC, CGCM1 (a three-member ensemble) and HadCM2 (a four-member ensemble) with historical forcing including sulphates (further experimental details are in Table 9.1). Regions are as indicated in Figure 10.1 and observations are from New *et al.* (1999a,b). (a) surface air temperature, (b) precipitation (from Giorgi and Francisco, 2000b).

(a)

(b)
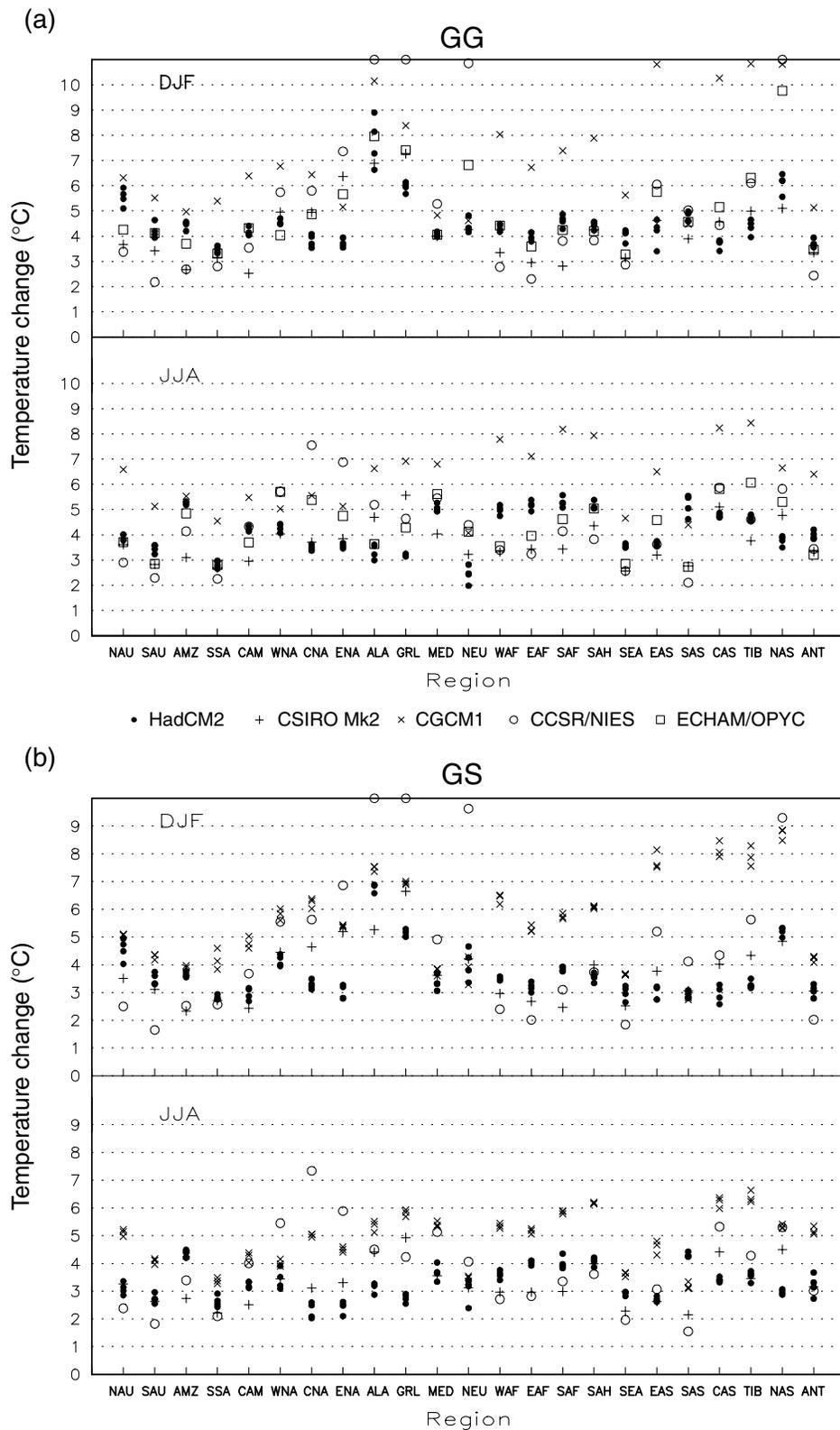
Figure 10.3: Simulated temperature changes in °C (mean for 2071 to 2100 minus mean of 1961 to 1990) under conditions of 1%/yr increasing CO_2 without and with sulphate forcing using experiments undertaken with the AOGCMs of CSIRO Mk2, CCSR/NIES, ECHAM/OPYC, CGCM1 and Hadley Centre (further experimental details are in Table 9.1). Under both forcing scenarios a four-member ensemble is included of the Hadley Centre model, and under the CO_2 plus sulphate scenario a three-member ensemble is included for the CGCM1 model. (a) increased CO_2 only (GG), (b) increased CO_2 and sulphate aerosols (GS). Global model warming values in the CO_2 increase-only experiments are 3.07°C for HadCM2 (ensemble average), 3.06°C for CSIRO Mk2, 4.91°C for CGCM1, 3.00°C for CCSR/NIES and 3.02°C for ECHAM/OPYC. Global model warming values for the experiments including sulphate forcing are 2.52°C for HadCM2 (ensemble average), 2.72°C for CSIRO Mk2, 3.80°C for CGCM1 (ensemble average) and 2.64°C for CCSR/NIES (from Giorgi and Francisco, 2000b).
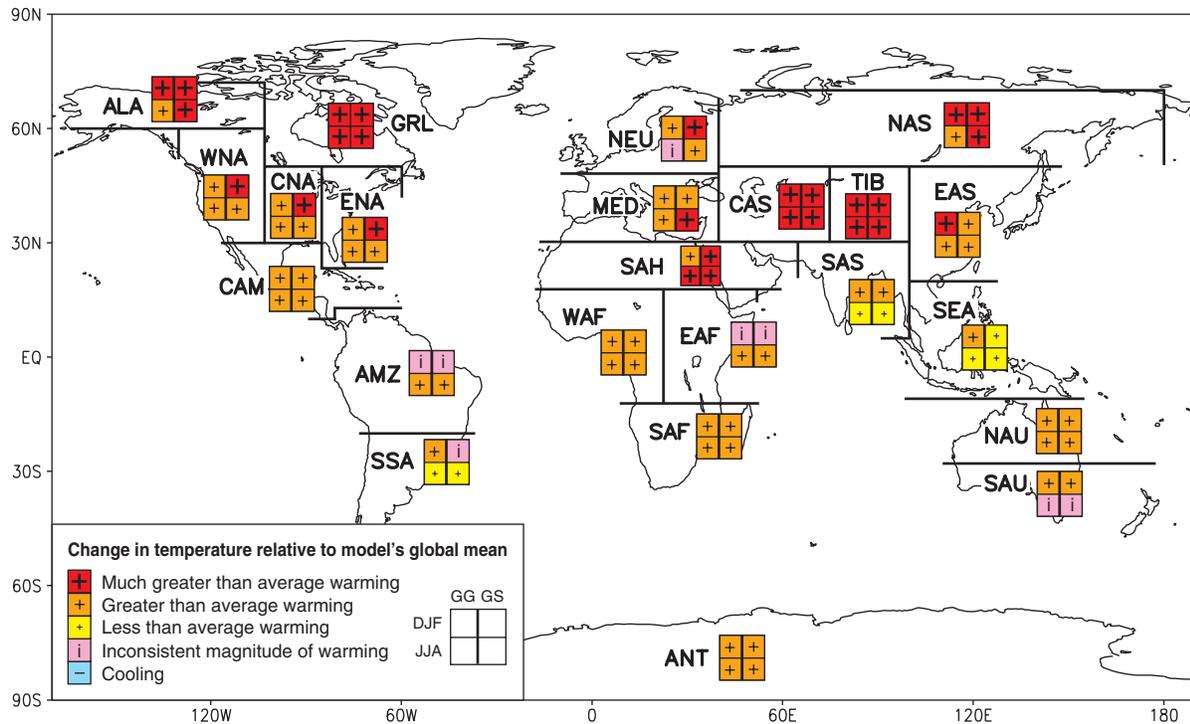
Figure 10.4: Analysis of inter-model consistency in regional warming relative to each model's global warming, based on the results presented in Figure 10.3. Regions are classified as showing either agreement on warming in excess of 40% above the global average ("Much greater than average warming"), agreement on warming greater than the global average ("Greater than average warming"), agreement on warming less than the global average ("Less than average warming"), or disagreement amongst models on the magnitude of regional relative warming ("Inconsistent magnitude of warming"). There is also a category for agreement on cooling (which is not used). GG is the greenhouse gas only case (see Figure 10.3a), and, GS, the greenhouse gas with increased sulphate case (see Figure 10.3b). In constructing the figure, ensemble results were averaged to a single case, and "agreement" was defined as having at least four of the five GG models agreeing or three of the four GS models agreeing. The global annual average warming of the models used span 3.0 to 4.9°C for GG and 2.5 to 3.8°C for GS, and therefore a regional 40% amplification represents warming ranges of 4.2 to 6.9°C for GG and 3.5 to 5.3°C for GS.

Figure10.3a were statistically significant at the 5% confidence level (Giorgi and Francisco, 2000b).

Inter-model differences in regional warming partially reflect differences in the global climate sensitivities of the models concerned. This effect may be set aside by comparing the regional warmings given in Giorgi and Francisco (2000b) with the corresponding global average warmings of the simulations used (Figure 10.4). Nearly all land areas warm more rapidly than the global average, particularly those at high latitudes in the cold season. For both the non-sulphate and sulphate cases, in the northern high latitudes, central Asia and Tibet (ALA, GRL, NAS, CAS and TIB) in DJF and in northern Canada, Greenland and central Asia and Tibet (GRL, CAS and TIB) in JJA, the warming is in excess of 40% above the global average. In both cases, warming is less than the global average in South and Southeast Asia, and southern South America (SAS, SEA and SSA) in JJA. In this analysis, differences between the non-sulphate and sulphate cases are minor. A strong contribution to the enhancement of warming over cold climate regions is given by the snow and sea ice albedo feedback mechanism (Giorgi and Francisco, 2000b). The snow albedo feedback also tends to enhance warming over high elevation regions (Fyfe and Flato, 1999).

In line with the globally averaged precipitation increase given by all models (see Chapter 9), precipitation is also simulated to increase regionally in the majority of cases. However, regions of precipitation decrease are also simulated. Precipitation reduction can be due to changes in large and synoptic scale features (e.g., changes in storm track characteristics) and/or to local feedback processes (e.g., between soil moisture and precipitation). The results of the regional analysis of Giorgi and Francisco (2000b) are presented in Figure 10.5 (as percentage changes for each model, region and forcing scenario) and are used in an analysis of inter-model consistency which is presented in Figure 10.6. In both the non-sulphate and sulphate cases for DJF, most simulations show increased precipitation for regions in the mid- to high latitudes of the Northern Hemisphere (ALA, GRL, WNA, ENA, CNA, NEU, NAS, CAS and TIB) and over Antarctica (ANT). In the tropics, models consistently show increase in Africa (EAF and WAF), increase or little change in South America (AMZ) and little change in Southeast Asia (SEA). Simulated regional precipitation decreases are common in subtropical latitudes, but only for central America (CAM) and northern Australia (NAU) are decreases indicated by most models in both cases. The pattern is broadly similar in JJA,
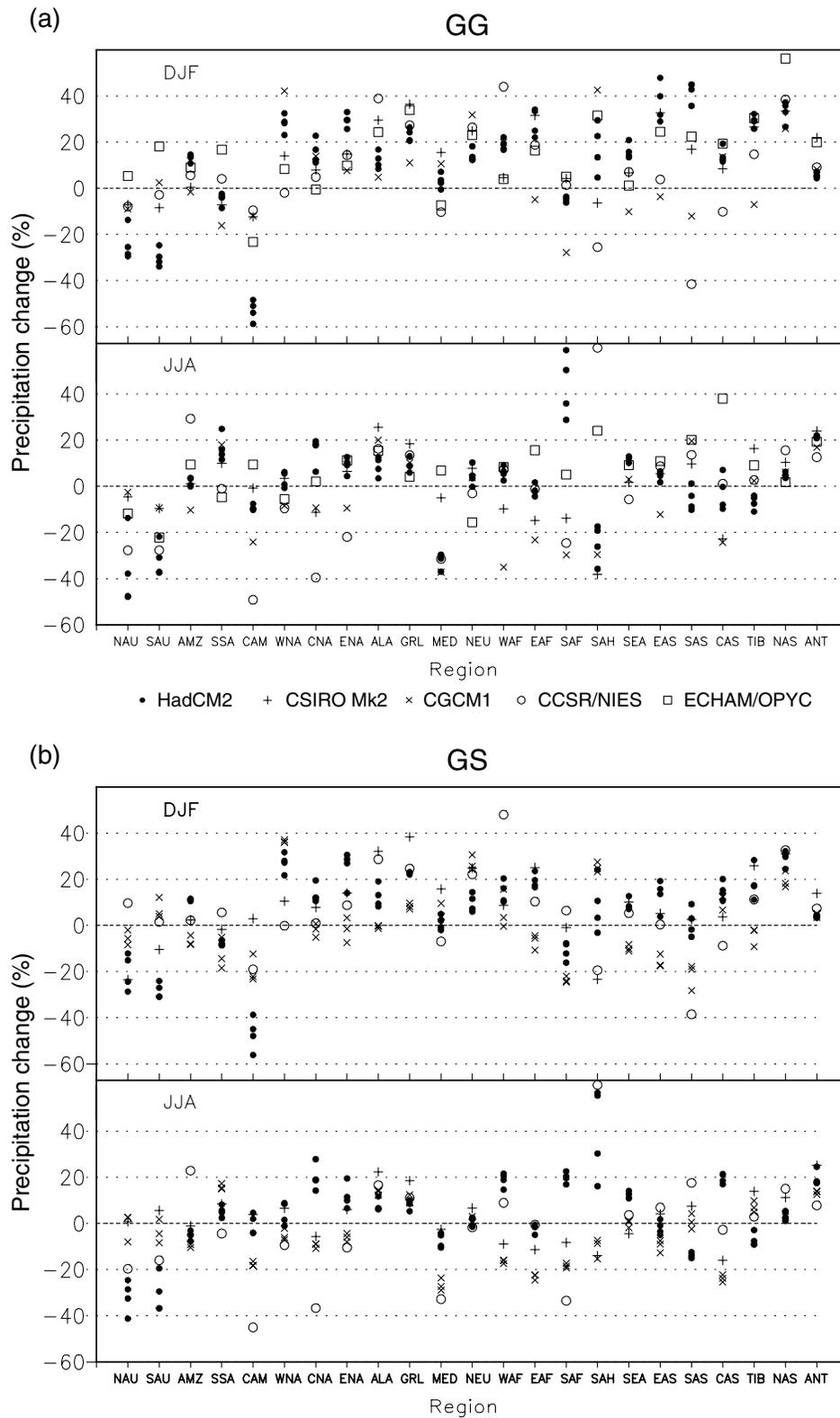
Figure 10.5: As Figure 10.3, but for percentage precipitation change (from Giorgi and Francisco, 2000b).
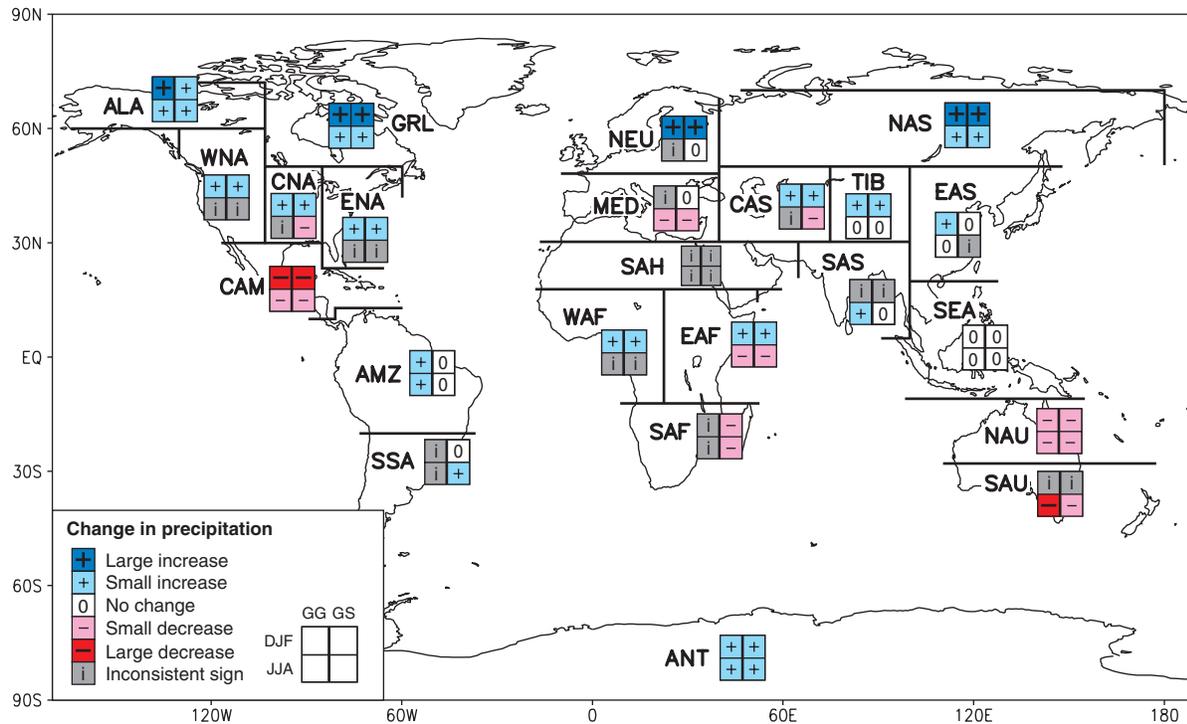
Figure 10.6: Analysis of inter-model consistency in regional precipitation change based on the results presented in Figure 10.5. Regions are classified as showing either agreement on increase with an average change of greater than 20% ("Large increase"), agreement on increase with an average change between 5 and 20% ("Small increase"), agreement on a change between –5 and +5% or agreement with an average change between –5 and 5% ("No change"), agreement on decrease with an average change between –5 and –20% ("Small decrease"), agreement on decrease with an average change of less than –20% ("Large decrease"), or disagreement ("Inconsistent sign"). GG is the greenhouse gas only case (see Figure 10.5a), and, GS, the greenhouse gas with increased sulphate case (see Figure 10.5b). In constructing the figure, ensemble results were averaged to a single case, and "agreement" was defined as having at least of four the five GG models agreeing or three of the four GS models agreeing.

although with some features shifting northwards. Only the high-latitude regions (ANT, ALA, GRL and NAS) show consistent increase. There is disagreement on the direction of change in a number of regions in the northern mid-latitudes and the sub-tropics, although consistent decrease is evident in the Mediterranean Basin (MED) and central American (CAM) regions. Some regions along the Inter-Tropical Convergence Zone (ITCZ) show consistent increase or little change (AMZ , SEA and SAS), but eastern Africa (EAF) shows a consistent decrease. In the Southern Hemisphere, only Australia (SAU and NAU) shows a consistent pattern of change in both cases (decrease). When the non-sulphate and sulphate cases are contrasted, more frequent simulated precipitation decrease may be noted in parts of North America, Africa and Asia for the case with increased sulphate aerosols (see results in Figure 10.6 for SAF, CNA, CAS and EAS).

The magnitude of regional precipitation change varies considerably amongst models, with the typical range being around 0 to 50% where the direction of change is strongly indicated and around –30 to +30% where it is not. Larger ranges occur in some regions (e.g., –30 to +60% in southern Africa in JJA for GHG only forcing), but this occurs mainly in regions of low seasonal precipitation where the implied range in absolute terms would not be large. Changes are consistently

large (greater than 20% averaged across models) in both the sulphate and non-sulphate cases in northern high latitude regions (GRL, NEU and NAS, positive change) in DJF and central America (CAM, negative change) in DJF. The number of precipitation changes statistically significant at the 5% confidence level varied widely across regions and seasons.

A number of new transient AOGCM simulations for the SRES A2 and B2 scenarios have recently become available and a preliminary analysis was conducted by the lead authors. This follows the procedure similar to that described in this section in relation to Figures 10.3 to 10.6. The results are presented in Box 10.1.

The analysis described above is for broad area-averages only and the results described should not be assumed to apply to all areas within these regions. More focused regional studies have examined within-region spatial patterns of change (Joubert and Tyson, 1996; Machenhauer *et al.*, 1996, 1998; Pittock *et al.*, 1995; Whetton *et al.*, 1996b; Carril *et al.*, 1997; Labraga and Lopez, 1997). Such studies can reveal important features which are consistent amongst models but are not apparent in area-average regional results. For example, Labraga and Lopez (1997) noted a tendency for simulated rainfall to decrease in northern Amazonia and to increase in southern parts of this region. Jones R.N. *et al.* (2000) noted a

Figure 10.7: For the European region, simulated change in annual precipitation, averaged by latitude and normalised to % change per °C of global warming. Results are given for twenty-three enhanced GHG simulations (forced by CO_2 change only) produced between the years 1983 and 1998. The earlier experiments are those used in the SCENGEN climate scenario generator (Hulme *et al.*, 1995) and include some mixed-layer $1\times$ and $2\times CO_2$ equilibrium experiments; the later ones are the AOGCM experiments available through the DDC. From Hulme *et al.* (2000).

predominance of rainfall increase in the central equatorial Pacific (northern Polynesia), but in the areas to the west and south-west the direction of rainfall change was not clearly indicated.

To illustrate further inter-model variations in simulated regional precipitation change, results obtained in model inter-comparison studies for the Australian, Indian, North American and European regions are examined. All of these regions have been extensively studied over the years using equilibrium $2\times CO_2$ experiments (such as those featured in IPCC, 1990), first generation transient coupled AOGCMs (as in the SAR), and more recent AOGCMs available in the DDC (Table 9.1).

This comparison also enables an assessment of how the regional precipitation projections have changed as the models evolved.

In the Australian region, the pattern of simulated precipitation change in winter (JJA) has remained broadly similar across these three groups of experiments and consists of rainfall decrease in sub-tropical latitudes and rainfall increase south of 35 to 40°S (Whetton *et al.*, 1996a, 2001). However, as the latitude of the boundary between these two zones varied between models, southernmost parts of Australia lay in the zone where the direction of precipitation change was inconsistent amongst models. In summer (DJF) the equilibrium $2\times CO_2$ experiments showed a

Box 10.1: Regional climate change in AOGCMs which use SRES emission scenarios

Introduction

This box summarises results on regional climate change obtained from a set of nine AOGCM simulations undertaken using SRES preliminary marker emission scenarios A2 and B2. The models are CGCM2, CSIRO Mk2, CSM 1.3, ECHAM4/OPYC, GFDL_R30_c, HadCM3, MRI2, CCSR/NIES2, DOE PCM, (numbered 7, 10, 12, 15, 18, 23, 27, 31 and 30 in Chapter 9, Table 9.1). The results are based on data for 2071 to 2100 and 1961 to 1990 that have been directly analysed and assessed by the lead authors. These results should be treated as preliminary only.

Analysis

Regional changes in precipitation and temperature were calculated using the same methodology as that of Giorgi and Francisco (2000b) (see Figures 10.1, 10.3 and 10.5). The results were then assessed for inter-model consistency using the same method as that used in Figures 10.4 and 10.6 for the earlier set of simulations. The results for temperature are in Box10.1, Figure1 and for precipitation in Box10.2, Figure2.

    The SRES results may be compared with the earlier results summarised in Figures 10.4 and 10.6 (which will be referred to here as the IS92a results). However, it should be noted that these two sets of results differ in the set of models used (both in the model versions and in the total number of simulations), and in the scenarios contrasted in each case (for IS92a it is GHG-only versus GHG+sulphate and for SRES it is A2 versus B2). Also, due to differences in the number of models, thresholds for agreement are not the same in each case (although they have been chosen to be as nearly equivalent as possible).
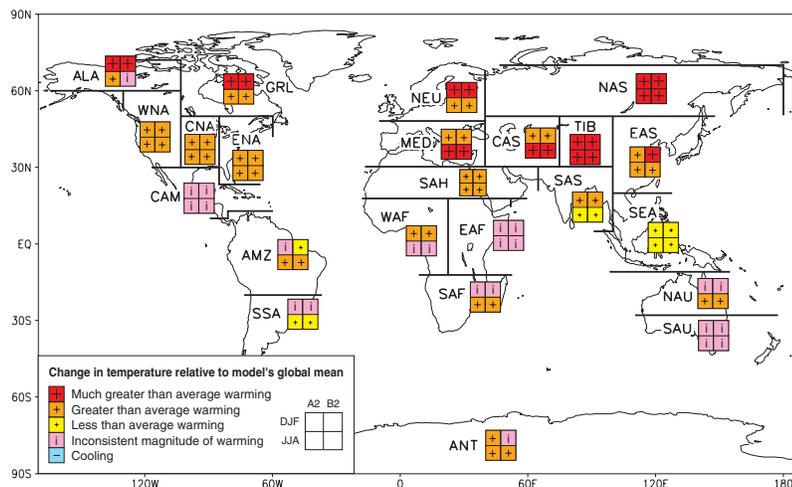
Box 10.1, Figure 1: Analysis of inter-model consistency in regional relative warming (warming relative to each model's global warming). Regions are classified as showing either agreement on warming in excess of 40% above the global average ('Much greater than average warming'), agreement on warming greater than the global average ('Greater than average warming'), agreement on warming less than the global average ('Less than average warming'), or disagreement amongst models on the magnitude of regional relative warming ('Inconsistent magnitude of warming'). There is also a category for agreement on cooling (which never occurs). A consistent result from at least seven of the nine models is deemed necessary for agreement. The global annual average warming (DJF and JJA combined) of the models used span 1.2 to 4.5°C for A2 and 0.9 to 3.4°C for B2, and therefore a regional 40% amplification represents warming ranges of 1.7 to 6.3°C for A2 and 1.3 to 4.7°C for B2.

Results

SRES

- Under both SRES cases, most land areas warm more rapidly than the global average. The warming is in excess of 40% above the global average in all high northern latitude regions and Tibet (ALA, GRL, NEU, NAS and TIB) in DJF, and in the Mediterranean basin, central and northern Asia and Tibet (MED, CAS, NAS, and TIB) in JJA. Only in South Asia and southern South America (SAS and SSA) in JJA and southeast Asia (SEA) in both seasons do the models consistently show warming less than the global average.
- For precipitation, consistent increase is evident in both SRES scenarios over high latitude regions (ALA, GRL, NAS and ANT) in both seasons, northern mid-latitude regions and tropical Africa (WNA, ENA, NEU, CAS, TIB, WAF and EAF) in DJF, and South Asia, East Asia and Tibet (SAS, EAS and TIB) in JJA. Consistent precipitation decrease is present over Central America (CAM) in DJF and over Australia and southern Africa (NAU, SAU and SAF) in JJA.
- Differences between the A2 and B2 results are minor and are mainly evident for precipitation. In the B2 scenario there are fewer regions showing consistently large precipitation changes, and there is a slight increase in the frequency of regions showing "inconsistent" and "no change" results. As the climate forcing is smaller in the B2 case and the climate response correspondingly weaker, some differences of this nature are to be expected.

SRES versus IS92a

- In broad terms, the temperature results from SRES are similar to the IS92a results. In each of the two SRES and IS92a cases, warming is in excess of 40% above the global average in Alaska, northern Canada, Greenland, northern Asia, and Tibet (ALA, GRL, NAS and TIB) in DJF and in central Asia and Tibet (CAS and TIB) in JJA. All four cases also show warming less than the global average in South and Southeast Asia, and southern South America (SAS, SEA and SSA) in JJA.

- The main difference in the results is that there are substantially more instances for the SRES cases where there is disagreement on the magnitude of the relative regional warming. This difference is mainly evident in tropical and Southern Hemisphere regions.

- The precipitation results from SRES are also broadly similar to the corresponding IS92a results. There are many regions where the direction of precipitation change (although not necessarily the magnitude of this change) is consistent across all four cases. In DJF this is true for increase in northern mid- to high latitude regions, Antarctica and tropical Africa (ALA, GRL, WNA, ENA, NEU, NAS, TIB, CAS, WAF, EAF and ANT) and decrease in Central America (CAM). In JJA it is true for increase in high latitude regions (ALA, GRL, NAS and ANT) and for decrease in southern and northern Australia (SAU and NAU). Little change in Southeast Asia in DJF and little change or increase over South Asia in JJA are also consistent results.

- Although there are no cases where the SRES and IS92a results indicate precipitation changes of opposite direction, there are some notable differences. In the Sahara and in East Asia (SAH and EAS) in JJA, the results for both SRES scenarios show consistent increase whereas this was not true in either of the IS92a cases. On the other hand, in central North America and northern Australia (CNA and NAU) in DJF, and in East Africa (EAF) in JJA, the results for both SRES scenarios show model disagreement whereas the IS92a scenarios showed a consistent direction of change (increase in CNA, and decrease in EAF and NAU). It is also notable that the consistent decrease in JJA precipitation over the Mediterranean basin (MED) seen for both IS92a cases is present for SRES only for the A2 scenario (for which the decrease is large).
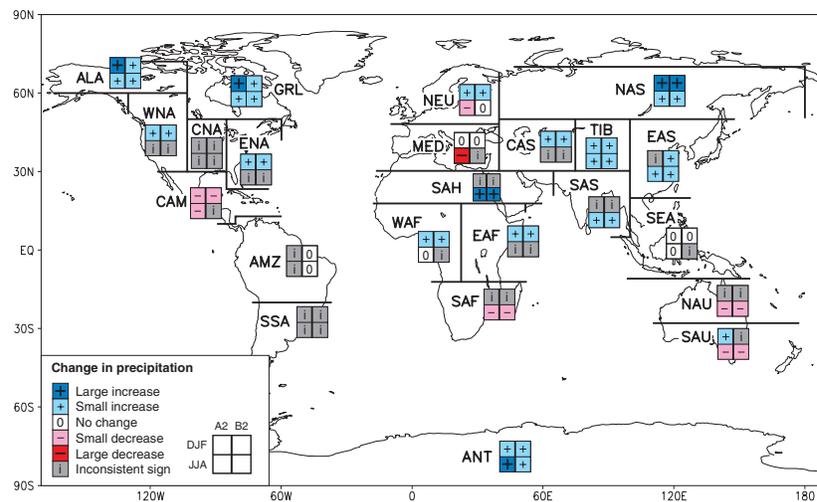
Box 10.1, Figure 2: Analysis of inter-model consistency in regional precipitation change. Regions are classified as showing either agreement on increase with an average change of greater than 20% ('Large increase'), agreement on increase with an average change between 5 and 20% ('Small increase'), agreement on a change between −5 and +5% or agreement with an average change between −5 and 5% ('No change'), agreement on decrease with an average change between −5 and −20% ('Small decrease'), agreement on decrease with an average change of less than −20% ('Large decrease'), or disagreement ('Inconsistent sign'). A consistent result from at least seven of the nine models is deemed necessary for agreement.

Uncertainty

The above comparisons concern the quantification of two different sources of uncertainty represented in the cascade of uncertainty described in Chapter 13, Section 13.5.1 (Figure 13.2). These include uncertainties in future emissions (IS92a GG and GS; SRES A2 and B2), and uncertainties in modelling the response of the climate system to a given forcing (samples of up to nine AOGCMs). Agreement across the different scenarios and climate models suggests, relatively speaking, less uncertainty about the nature of regional climate change than where there is disagreement. For example, the agreement for northern latitude winter precipitation extends across all emission scenarios and all models, whereas there is considerable disagreement (greater uncertainty) for tropical areas in JJA. Note that these measures of uncertainty are qualitative and applied on a relatively coarse spatial scale. It should also be noted that the range of uncertainty covered by the four emissions scenarios does not encompass the entire envelope of uncertainty of emissions (see Chapter 9, Section 9.2.2.4, and Chapter 13, Section 13.5.1). The range of models (representing the uncertainties in modelling the response to a given forcing) is somewhat more complete than in earlier analyses, but also limited.

strong tendency for precipitation to increase, particularly in the north-west of the continent. This tendency was replaced in the first coupled AOGCMs by one of little change or precipitation decrease, which has remained when the most recent coupled models are considered. Whetton *et al.* (1996a) partly attributed the contrast in the regional precipitation response of the two types of experiments to contrasts in their hemispheric patterns of warming.

Lal *et al.* (1998b) surveyed the results for the Indian subcontinent of seventeen climate change experiments including both equilibrium $2 \times CO_2$ and transient AOGCM simulations with and without sulphate aerosol forcing. In the simulations forced only by GHG increases, most models show wet season (JJA) rainfall increases over the region of less than 5% per degree of global warming. A minority of experiments show rainfall decreases. The experiments which included scenarios of increasing sulphate forcing all showed reduced rainfall increases, or stronger rainfall decreases, than their corresponding GHG-only experiments.

For the central plains of North America, IPCC (1990) noted a good deal of similarity in the response of equilibrium $2 \times CO_2$ experiments, with precipitation decreases prevailing in the summer and increases in the winter of less than 10%. In the second group of experiments (nine transient runs with AOGCMs) a wider range of responses was found (in the SAR). In winter, changes in precipitation ranged from about −12 to +20% for the time of CO_2 doubling, and most of the models (six out of nine) exhibited increases. In summer, the range of change was narrower, within ±10%, but there was no clear majority response towards increases or decreases. Doherty and Mearns (1999) found that the CGCM1 and HadCM2 models simulated opposite changes in precipitation in both seasons over North America. While overall there is a tendency for more decreases to be simulated in the summer and more increases in the winter, there does not seem to be a reduction in the uncertainty for this region through the progression of climate models.

Many studies have considered GCM-simulated patterns of climate change in the European region (e.g., Barrow *et al.*, 1996; Hulme and Brown, 1998; Osborn and Hulme, 1998; Räisänen, 1998; Benestad *et al.* 1999; Osborn *et al.*, 1999). Hulme *et al.* (2000) provide an overview of simulated changes in the region by considering the results of twenty-three climate change simulations (forced by GHG change only) produced between the years 1983 and 1998 and including mixed-layer $1 \times$ and $2 \times CO_2$ equilibrium experiments as well as transient experiments. Figure 10.7 shows their results for simulated change in annual precipitation, averaged by latitude and normalised to percentage change per degree of global warming. It may be seen that the consensus amongst current models for drying in southern Europe and wetter conditions in northern Europe represents a continuation of a pattern established amongst the earlier simulations. The effect of model development has primarily been to intensify this pattern of response.

Variations across simulations in the regional enhanced GHG results of AOGCMs, which are particularly evident for precipitation, represent a major uncertainty in any assessment of regional climate change. Such variation may arise due to differences in forcing, systematic model-to-model differences in the regional

response to a given forcing or differences due to natural decadal to inter-decadal scale variability in the models. Giorgi and Francisco (2000a,b) analysed AOGCM simulations including different models, forcing scenarios and ensembles of simulations, and found that the greatest source of uncertainty in regional climate change simulation was due to inter-model differences, with intra-ensemble and inter-scenario differences being less important (see Figures 10.3 and 10.5). However, it should be noted that Giorgi and Francisco (2000a,b) used long (thirty year) means and large (sub-continental scale) regions and that the uncertainty due to simulated natural variability would be larger when shorter averaging periods, or smaller regions, are used. The results of Hulme *et al.* (1999) also suggest that low-frequency natural climatic variability is important at the sub-regional scale in Europe and can mask the enhanced GHG signal.

Regional changes in the mean pattern of atmospheric circulation have been noted in various studies, although typically the changes are not marked (e.g., Huth, 1997; Schubert, 1998). Indeed, the work of Conway (1998) and Wilby *et al.* (1998b) suggests that the contribution of changes in synoptic circulation to regional climate change may be relatively small compared to that of sub-synoptic processes.

10.3.2.2 Climate variability and extreme events

Gregory and Mitchell (1995) identified in an equilibrium $2 \times CO_2$ simulation with the Hadley Centre model a tendency for daily temperature variability over Europe to increase in JJA and to decrease in DJF. Subsequent work on temperature variability at daily to monthly and seasonal time-scales has tended to confirm this pattern, as found by Buishand and Beersma (1996) over Europe, Beersma and Buishand (1999) over southern Europe, northern Europe and central North America and Boer *et al.* (2000b) throughout the northern mid-latitudes. This tendency can also be seen in the results of Giorgi and Francisco (2000a) for a set of transient HadCM2 simulations over different regions of the globe.

Daily high temperature extremes are likely to increase in frequency as a function of the increase in mean temperature, but this increase is modified by changes in daily variability of temperature. There is a corresponding decrease in the frequency of daily low temperature extremes. Kharin and Zwiers (2000) and Zwiers and Kharin (1997) found that in all regions of the globe the CGCM1 model simulated substantial increases in the magnitude of extreme daily maximum and minimum temperatures, with an average frequency of occurrence of once per twenty years. Delworth *et al.* (1999) considered simulated changes of a 'heat index' (a measure which combines the effect temperature and moisture) in the GFDL R15a model. Their results indicated that seasonally warm and humid areas such as the south-eastern United States, India, Southeast Asia and northern Australia can experience increases in the heat index substantially greater than that expected due to warming alone.

There is a strong correlation between precipitation inter-annual variability and mean precipitation. Increases in mean precipitation are likely to be associated with increases in variability, and precipitation variability is likely to decrease in areas of reduced mean precipitation. In general, where simulated

changes in regional precipitation variability have been examined, increases are more commonly noted. Giorgi and Francisco (2000a) found a tendency for regional interannual variability of seasonal mean precipitation to increase in HadCM2 simulations in many of the regions they considered. Increases in interannual variability also predominated in the CGCM1 simulation (Boer *et al.*, 2000b) although there were areas of decrease, particularly in areas where mean rainfall decreased. Beersma and Buishand (1999) mostly found increases in monthly precipitation variance over southern Europe, northern Europe and central North America. A number of studies have reported a tendency for interannual rainfall variability to increase over South Asia (SAR; Lal *et al.*, 2000). McGuffie *et al.* (1999) identified a tendency for increased daily rainfall variability in two models over the Sahel, North America, South Asia, southern Europe and Australia. It should also be noted that in many regions interannual climatic variability is strongly related to ENSO, and thus will be affected by changes in ENSO behaviour (see Chapter 9).

The tendency for increased rainfall variability in enhanced GHG simulations is reflected in a tendency for increases in the intensity and frequency of extreme heavy rainfall events. Such increases have been documented in regionally focused studies for Europe, North America, South Asia, the Sahel, southern Africa, Australia and the South Pacific (Hennessy *et al.*, 1997; Bhaskaran and Mitchell, 1998; McGuffie et al 1999; Jones, R.N. *et al.*, 2000) as well as in the global studies of Kharin and Zwiers (2000) and Zwiers and Kharin (1998). For example, Hennessy *et al.* (1997) found that under $2\times CO_2$ conditions the one-year return period events in Europe, Australia, India and the USA increased in intensity by 10 to 25% in two models.

Changes in the occurrence of dry spells or droughts have been assessed for some regions using recent model results. Joubert *et al.* (1996) examined drought occurrence over southern Africa in an equilibrium $2\times CO_2$ CSIRO simulation and noted areas of both substantial increase and decrease. Gregory *et al.* (1997) looked at drought occurrence over Europe and North America in a transient simulation using both rainfall-based and soil moisture-based measures of drought. In all cases, marked increases were obtained. This was attributed primarily to a reduction in the number of rainfall events rather than a reduction in mean rainfall. Marked increases in the frequency and intensity of drought were found also by Kothavala (1997) over Australia using the Palmer drought severity index.

Fewer studies have considered changes in variability and extremes of synoptic circulation under enhanced GHG conditions. Huth (1997) noted little change in synoptic circulation variability under equilibrium $2\times CO_2$ conditions over North America and Europe. Katzfey and McInnes (1996) found that the intense cut-off lows off the Australian east coast became less common under equilibrium $2\times CO_2$ conditions in the CSIRO model, although they had limited confidence in this result.

10.3.3 Summary and Recommendations

Analysis of transient simulations with AOGCMs indicates that average climatic features are generally well simulated at the planetary and continental scale. At the regional scale, area-average

biases in the simulation of present day climate are highly variable from region to region and across models. Seasonal temperature biases are typically within the range of ±4°C but exceed ±5°C in some regions, particularly in DJF. Precipitation biases are mostly between −40 and +80%, but exceed 100% in some regions. These regional biases are, in general terms, smaller than those of a similar analysis presented in the SAR. When it has been assessed, many aspects of model variability have compared well against observations, although significant model-dependent biases have been noted. Model performance was poorer at the finer scales, particularly in areas of strong topographical variation. This highlights the need for finer resolution regionalisation techniques.

Simulated changes in mean climatic conditions for the last decades of the 21st century (compared to present day climate) vary substantially among models and among regions. All land regions undergo warming in all seasons, with the warming being generally more pronounced over cold climate regions and seasons. Average precipitation increases over most regions, especially in the cold season, due to an intensified hydrological cycle. However, some exceptions occur in which most models concur in simulating decreases in precipitation. The magnitude of regional precipitation change varies considerably among models with the typical range being around 0 to 50%, where the direction of change is strongly indicated, and around −30 to +30% where it is not. There is strong tendency for models to simulate regional increases in precipitation variability with associated increases in the frequency of extreme rainfall events. Increased interannual precipitation variability is also commonly simulated and, in some regions, increases in drought or dry-spell occurrence have been noted. Daily to inter-annual variability of temperature is simulated to decrease in winter and increase in summer in mid-latitude Northern Hemisphere land areas.

10.4 GCMs with Variable and Increased Horizontal Resolution

This section deals with the relatively new idea of deriving regional climate information from AGCMs with variable and increased horizontal resolution. Although the basic methodology is suggested in the work of Bengtsson *et al.* (1995), where a high resolution GCM was used to simulate changes in tropical cyclones in a warmer climate, it is only in the last few years that such models have been used more widely to predict regional aspects of climate change. Even so, only a limited number of experiments have been conducted to date (see Table 10.1) and hence what follows is not a definitive evaluation of the technique but an initial exploration of its potential.

10.4.1 Simulations of Current Climate

Analysis of current climate simulations has considered both deviations from the observed climate and effects of changes in resolution on the model's climatology. Most studies have considered just the mean climate and some measures of variability, either globally or for a particular region of interest. The only extreme behaviour studied in any detail was the simulation of tropical cyclones. Even for mean climate, no comprehensive assessment

Table 10.1: *Enhanced and variable resolution GCM control and anomaly simulations. Resolution is given as either the spectral truncation or grid-point spacing depending on the model's formulation (and with a range for variable resolution models). The equivalent grid-point resolution of spectral truncation T42 is 2.8°32.8° (scaling linearly).*

Institution	Model	Horizontal Resolution	Control Forcing	Anomaly Forcing	Region of interest
MPI	ECHAM3	T42	ECHAM/LSG	ECHAM/LSG	Euro/Global
MPI	ECHAM3/4	T106	Obs	ECHAM/OPYC	Euro/Global
UKMO	HadAM2b	0.83°×1.25°	Obs		Global
UKMO	HadAM3a	0.83°×1.25°	Obs	HadCM3	Euro/Global
MRI	JMA	T106	Obs	MRI/GFDL/+2ºC	Tropics
CNRM	ARPEGE	T213–T21, T106	Obs/HadCM2	HadCM2	Euro/Global
LGGE	LMDZ	100 to 700km	Obs	CLIMAP	Polar regions

of the surface climatology of variable or high resolution models has been attempted. Europe has been the most common area of study to date, although southern Asia and the polar regions have also received attention

10.4.1.1 Mean climate

The mean circulation is generally well simulated by AGCMs, though relatively large regional-scale biases can still be present. Many features of the large-scale climate of AGCMs are retained at higher resolution (Dèquè and Piedelievre, 1995; Stendel and Roeckner, 1998; May, 1999; Stratton, 1999a). A common change is a poleward shift of the extra-tropical storm track regions. It has been suggested that this is linked to a general deepening of cyclones, noted as a common feature in high-resolution atmospheric models (Machenhauer *et al.*, 1996; Stratton 1999a). More intense activity is also seen at higher resolution in the tropics. For example, a stronger Hadley circulation was observed in ECHAM4 and HadAM3a that worsened agreement with observations (Stendel and Roeckner, 1998; Stratton, 1999b).

The repositioning of the storm tracks generally improves the simulations in the Northern Hemisphere, as it reduces a positive polar surface pressure bias which is present in the models at standard resolution. In the case of HadAM3a, this leads to substantial improvements in Northern Hemisphere low level flow in winter (Figure 10.8). In the Southern Hemisphere, the impact on the circumpolar flow is not consistently positive across models (Figure 10.8; Krinner *et al.*, 1997). In ECHAM4 and HadAM3a, increased resolution has little impact on the negative surface pressure bias over the tropics but improves the low-level South Asian monsoon flow (Lal *et al.*, 1997; Stratton, 1999b).

The existence of these common responses to increased resolution suggests that they result from improved representation of the resolved variables. In contrast, an increase in the intensity of subtropical anticyclones observed in ECHAM4 results from a tropospheric warming promoted by excessive cirrus clouds attributed to a scale-dependent response in the relevant parametrization (Stendel and Roeckner, 1998).

The aim of increasing resolution in AGCMs is generally to improve the simulation of surface climatology compared to coarser resolution models (Cubash *et al.*, 1995). Early experience shows a much more mixed response. ECHAM3 at T42 improved the seasonal cycle of surface temperature in seven regions, compared to the driving AOGCM, but overall surface temperature was too high (by 2 to 5ºC). Increasing the resolution to T106 did not improve winter temperatures and, in summer, the spatial patterns were better but the regional biases worse (Cubasch *et al.*, 1996). For precipitation, spatial patterns were improved in summer but degraded in winter. The summer warming was due to excessive insolation from reduced cloud cover and overly transparent clear skies (Wild *et al.*, 1995). Improved physics in ECHAM4 reduced some of the radiation errors but the precipitation and temperature biases remained (Wild et al, 1996; Stendel and Roeckner, 1998). In simulations of European climate with ARPEGE (Dèquè and Piedelievre, 1995) and HadAM2b/3a (Jones, 1999; Stratton, 1999a), improved flow at higher resolution generally led to better surface temperatures and precipitation. However, over southeastern Europe, precipitation biases increased in both models, as did the warm temperature bias in HadAM3a.

The increased summer temperatures in Europe in HadAM3a were caused by reduced cloud cover at higher resolution (Jones 1999) and warming and drying, in summer, was seen over all extratropical continents (Stratton, 1999b). This clearly demonstrates a potential drawback of increasing the resolution of a model without comprehensively retuning the physics. Krinner *et al.* (1997) showed that, to obtain a reasonable simulation of the surface climatology of the Antarctic with the LMD variable resolution AGCM, many modifications to the model physics were required. The model was then able to simulate surface temperatures to within 2 to 4ºC of observations and to provide a good simulation of the ice mass balance (snow accumulation), with both aspects being better than at standard resolution.

10.4.1.2 Climate variability and extreme events

Enhanced resolution improves many aspects of the AGCMs' intra-seasonal variability of circulation at low and intermediate frequencies (Stendel and Roeckner, 1998). However, in some cases values underestimated at standard resolution are overestimated at enhanced resolution (Dèquè and Piedelievre, 1995; Stratton, 1999a,b). Martin (1999) found little sensitivity to resolution in either the interannual or intra-seasonal variability of circulation and precipitation of the South Asian monsoon in HadAM3a. Extreme events have not been studied, with the exception of tropical cyclones. This subject cuts across various sections and chapters and thus is dealt with in Box 10.2.

DJF mean sea level pressure (hPa)
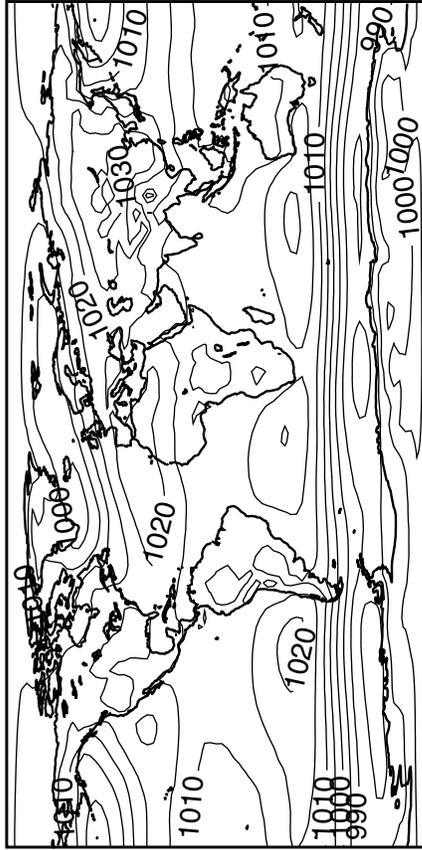
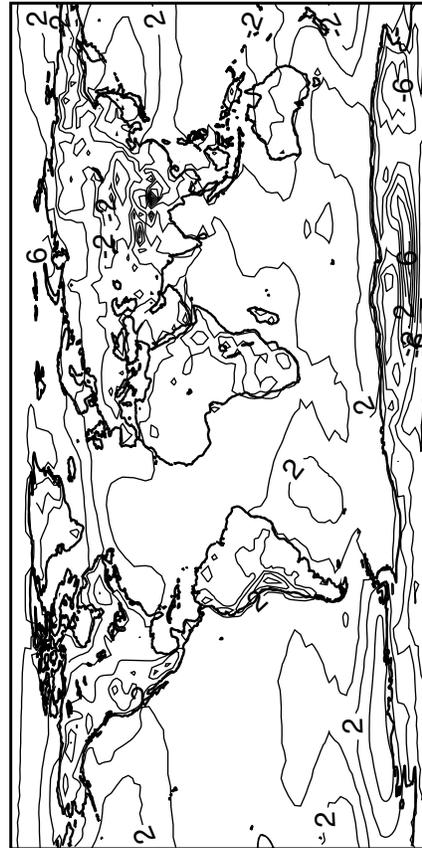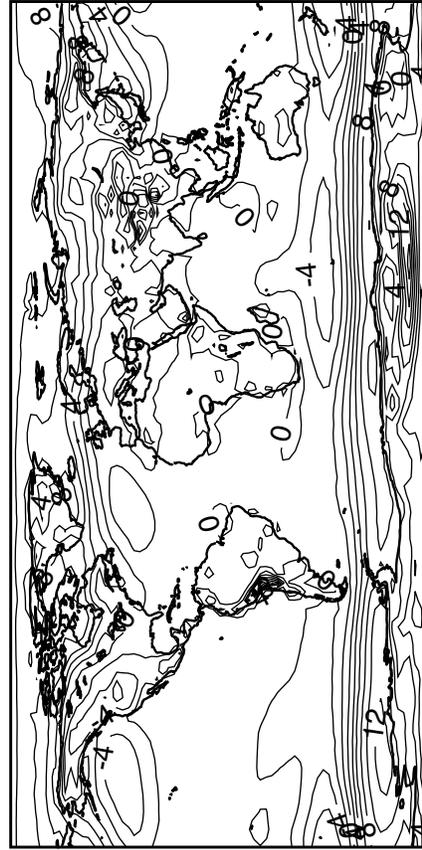
Figure 10.8: Mean sea level pressure for DJF in: (a) HadAM3a at high resolution (100 km), (b) ECMWF reanalysis (ERA), (c) HadAM3a high resolution minus ERA, (d) HadAM3a at standard resolution (300 km) minus ERA. Adapted from Stratton (1999b).

Box 10.2: Tropical cyclones in current and future climates

Simulating a climatology of tropical cyclones

Tropical cyclones can have devastating human and economic impacts (e.g., Pielke and Landsea, 1998) and therefore accurate estimates of future changes in their frequency, intensity and location would be of great value. However, because of their relatively small extent (in global modelling terms) and intense nature, detailed simulation of tropical cyclones for this purpose is difficult. Atmospheric GCMs can simulate tropical cyclone-like disturbances which increase in realism at higher resolution though the intense central core is not resolved (e.g., Bengtsson *et al.*, 1995; McDonald, 1999). Further increases of resolution, by the use of RCMs, provide greater realism (e.g., Walsh and Watterson, 1997) with a very high resolution regional hurricane prediction model giving a reasonable simulation of the magnitude and location of maximum surface wind intensities for the north-west Pacific basin (Knutson *et al.*, 1998). GCMs generally provide realistic simulation of the location and frequency of tropical cyclones (e.g., Tsutsui and Kasahara, 1996; Yoshimura *et al.*, 1999). See also Chapter 8 for more details on tropical cyclones in GCMs.

Tropical cyclones in a warmer climate

Much effort has gone into obtaining and analysing good statistics on tropical cyclones in the recent past. The main conclusion is that there is large decadal variability in the frequency and no significant trend during the last century. One study looking at the century time-scale has shown an increase in the frequency of North Atlantic cyclones from 1851 to 1890 and 1951 to 1990 (Fernandez-Partagas and Diaz, 1996). See Chapter 2 for more details on observed tropical cyclones.

    Most assessments of changes in tropical cyclone behaviour in a future climate have been derived from GCM or RCM studies of the climate response to anthropogenically-derived atmospheric forcings (e.g., Bengtsson *et al.*, 1996, 1997; Walsh and Katzfey, 2000). Recently, more focused approaches have been used: nesting a hurricane prediction model in a GCM climate change simulation (Knutson *et al.*, 1998); inserting idealised tropical cyclones into an RCM climate change simulation (Walsh and Ryan, 2000).

    In an early use of a high-resolution AGCM, a T106 ECHAM3 experiment simulated a decrease in tropical cyclones in the Northern Hemisphere and a reduction of 50% in the Southern Hemisphere (Bengtsson *et al.*, 1996, 1997). However, the different hemispheric responses raised questions about the model's ability to properly represent tropical cyclones and methodological concerns about the experimental design were raised (Landsea, 1997). In a similar experiment, the JMA model also simulated fewer tropical cyclone-like vortices in both hemispheres (Yoshimura *et al.*, 1999). Other GCM studies have shown consistent basin-dependent changes in tropical cyclone formation under $2 \times CO_2$ conditions (Royer *et al.*, 1998; Tsutsui *et al.*, 1999). Frequencies increased in the north-west Pacific, decreased in the North Atlantic, and changed little in the south-west Pacific. A high resolution HadAM3a simulation reproduced the latter changes, giving changes in timing in the north-west Pacific and increases in frequency in the north-east Pacific and the north Indian basin (McDonald, 1999). Some GCM studies show increases in tropical storm intensity in a warmer climate (Krishnamurti *et al.*, 1998) though these results can probably not be extrapolated to tropical cyclones as the horizontal resolution of these models is insufficient to resolve the cyclone eye. The likely mean response of tropical Pacific sea surface warming having an El Niño-like structure suggests that the pattern of tropical cyclone frequency may become more like that observed in El Niño years (see Chapter 9).

    An indication of the likely changes in maximum intensity of cyclones will be better provided by models able to simulate realistic tropical cyclone intensities. A sample of GCM-generated tropical cyclone cases nested in a hurricane prediction model gave increases in maximum intensity (of wind speed) of 5 to 11% in strong cyclones over the north-west Pacific for a 2.2°C SST warming (Knutson and Tuleya, 1999). The RCM study of idealised tropical cyclones (in the South Pacific) showed a small, but not statistically significant, increase in maximum intensity (Walsh and Ryan, 2000). These results are supported by the theory of the maximum potential intensity (MPI) of hurricanes (Emanuel, 1987). A calculation using the MPI framework of Holland (1997) suggested increases of 10 to 20% for a $2 \times CO_2$ climate (Henderson-Sellers *et al.*, 1998). This study also acknowledges physical omissions that would reduce this estimate though Emanuel (2000) suggests there is a linear relationship betweeen MPI and the wind speed of real events. Published modelling studies to date neglect the possible feedback of sea surface cooling induced by the cyclone. However, a recently submitted study using a hurricane model with ocean coupling indicates that the increased maximum intensity by CO_2 warming would still occur even when the sea surface cooling feedback is included (Knutson *et al.*, 2000).

    The extreme precipitation associated with tropical cyclones can also be very damaging. The very high resolution studies discussed above suggest that increases in the intensity of tropical cyclones will be accompanied by increases in mean and maximum precipitation rates. In the cases studied, precipitation in the vicinity of the storm centre increased by 20% whereas peak rates increased by 30%. Part of these increases may be due to the increased moisture-holding capacity of a warmer atmosphere but nevertheless point to substantially increasing destructive capacity of tropical cyclones in a warmer climate.

In conclusion, there is some evidence that regional frequencies of tropical cyclones may change but none that their locations will change. There is also evidence that the peak intensity may increase by 5% to 10% and precipitation rates may increase by 20% to 30%. There is a need for much more work in this area to provide more robust results.

10.4.2 Simulations of Climate Change

10.4.2.1 Mean climate

Climate change simulations using ECHAM3 at T42 and T106 resolutions predicted substantially different responses for southern Europe (Cubash *et al.*, 1996). For example, surface temperature response of less than +2°C in summer at T42 increased by over 4°C for much of the region at T106 and winter precipitation increased more at T106 than at T42. An important factor in generating the different responses was the substantial difference in the control simulations. Wild *et al.* (1997) showed a large positive summer surface temperature bias in the T106 control derived from a positive feedback between excessive surface insolation and summer dryness. This mechanism provided a large increase in the insolation, and thus the surface temperature, in the anomaly experiment. As this process was handled poorly in the control simulation, little confidence can be placed in the warming amplification simulated at T106.

A variable grid AGCM climate change experiment using the ARPEGE model and sea surface forcing from HadCM2 predicted moderate warmings over Europe, 1.5°C (northern) to 2.5°C (southern) in winter and 1°C to 3.5°C in summer (Dèquè *et al.*, 1998). In contrast, HadCM2 predicted greater warming and a larger north-south gradient in winter (Figure 10.9). These differences result mainly from the ARPEGE large-scale flow being too zonal and too strong over mainland Europe, which enhances the moderating influence of the SSTs. The precipitation responses are more similar, especially in summer, when both models predict a decrease over most of Europe, maximum –30% in the south. Differences in the control simulations suggest that little confidence should be placed in this result.

In a similar experiment, HadAM3a at 1.25°×0.83° resolution used observed sea surface forcing and anomalies from a HadCM3 GHG simulation and produced a response at the largest scales in the annual mean similar to the AOGCM (Johns, 1999). However, regionally or seasonally, many differences were evident in the two models, notably in land sea contrasts, monsoon precipitation and some circulation features. Over Europe, large-scale responses in surface temperature and precipitation were similar except for a larger winter surface warming in northern Europe in HadCM3. This was due to a greater melting back of Arctic sea ice which was too extensive in the HadCM3 control (Jones, 1999). In a 30-year ECHAM4 T106 experiment driven by ECHAM4/OPYC simulations for 1970 to 1999 and 2060 to 2089, the simulations of future climate were more similar to each other than those for the present day (May, 1999). This implies that the differences in the control simulations would determine a proportion of the difference in the responses. In these cases better control simulations at high resolution increase the confidence in their responses.

10.4.2.2 Climate variability and extreme events

Due to the limited number and length of simulations and a lack of comprehensive analyses, this subject has been almost completely ignored. The only response in variability or extremes that has received any attention is that of tropical cyclones (Box 10.2).

10.4.3 Summary and Recommendations

Since the SAR, several variable and high-resolution GCMs have been used to provide high-resolution simulations of climate change. Clearly the technique is still in its infancy with only a few modelling studies carried out and for only a limited number of regions. Also, there is little in-depth analysis of the performance of the models and only preliminary conclusions can be drawn.

Many aspects of the models' dynamics and large-scale flow are improved at higher resolution, though this is not uniformly so geographically or across models. Some models also demonstrate improvements in their surface climatologies at higher resolution. However, substantial underlying errors are often still present in high-resolution versions of current AGCMs. In addition, the direct use of high-resolution versions of current AGCMs, without some allowance of the dependence of models physical parametrizations on resolution, leads to some deterioration in the performance of the models.

Regional responses currently appear more sensitive to the AGCM than the SST forcing used. This result is partially due to some of the model responses being dependent on their control simulations and systematic errors within them. These factors and the small number of studies carried out imply that little confidence can be attached to any of the regional projections provided by high and variable resolution AGCM simulations. The improvements seen with this technique are encouraging, but more effort should be put in analysing, and possibly improving the performance of current models at high resolution. This is particularly important in view of the fact that future AOGCMs will likely use models approaching the resolution considered here in the next 5 to 10 years.

10.5 Regional Climate Models

Since the SAR, much insight has been provided into fundamental issues concerning the nested regional modelling technique.

Multi-year to multi-decadal simulations must be used for climate change studies to provide meaningful climate statistics, to identify significant systematic model errors and climate changes relative to internal model and observed climate variability, and to allow the atmospheric model to equilibrate with the land surface conditions (e.g., Jones *et al.*, 1997; Machenhauer *et al.*, 1998; Christensen 1999; McGregor *et al.*, 1999; Kato *et al.*, 2001).

The choice of an appropriate domain is not trivial. The influence of the boundary forcing can reduce as region size increases (Jones *et al.*, 1995; Jacob and Podzun, 1997) and may be dominated by the internal model physics for certain variables and seasons (Noguer *et al.*, 1998). This can lead to the RCM solution significantly departing from the driving data, which can make the interpretation of down-scaled regional climate changes more difficult (Jones *et al.*, 1997). The domain size has to be large enough so that relevant local forcings and effects of enhanced resolution are not damped or contaminated by the application of the boundary conditions (Warner *et al.*, 1997). The exact location of the lateral boundaries can influence the sensitivity to internal parameters (Seth and Giorgi, 1998) or may
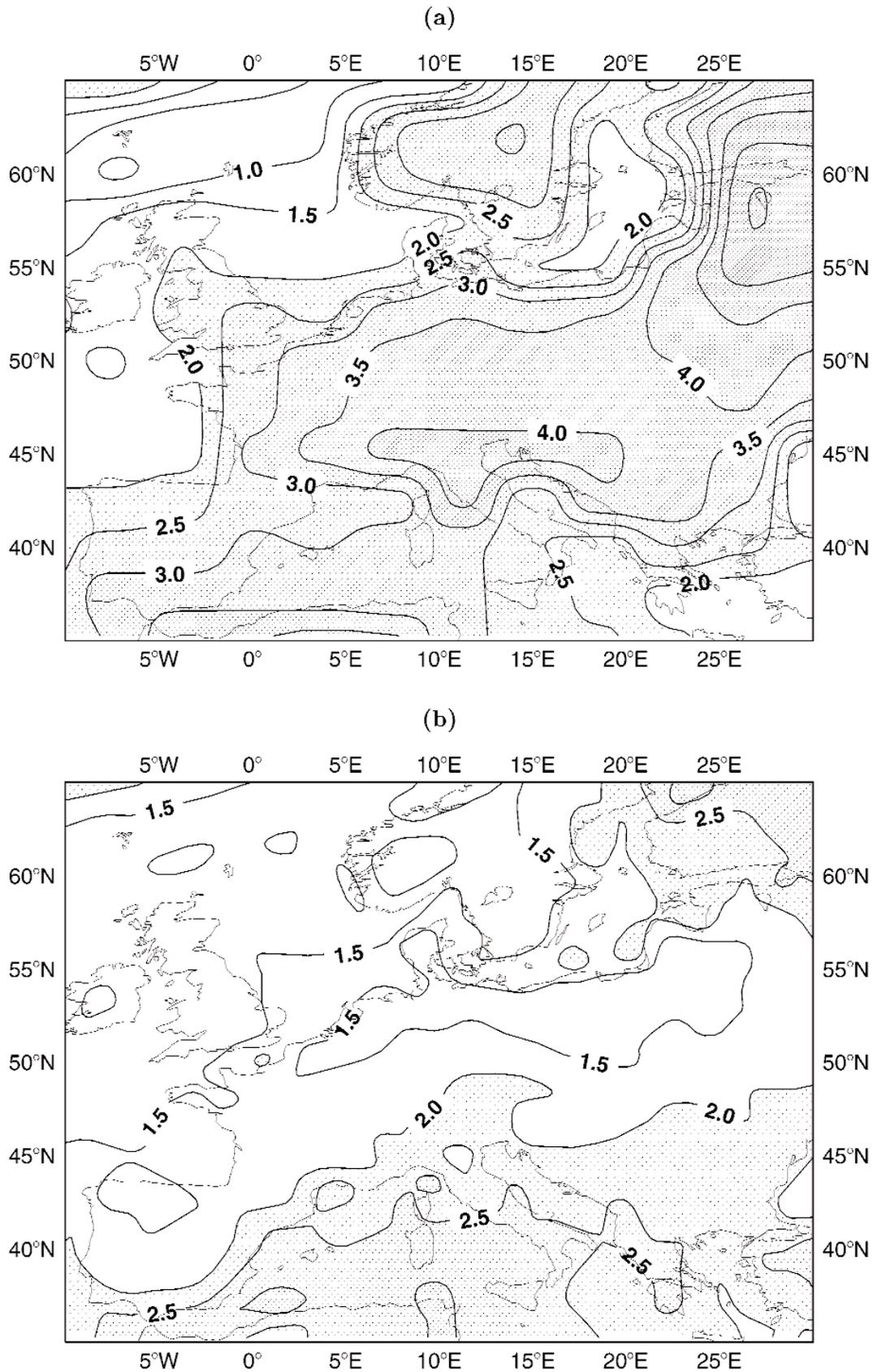
(a)

(b)

Figure 10.9: Winter surface air temperature change (°C) over Europe at the time of CO_2 doubling in (a) a transient climate change experiment with the AOGCM HadCM2 and (b) the stretched grid AGCM ARPEGE driven by SSTs and sea-ice from the HadCM2 integration. From Dèquè *et al.* (1998).

have no significant impact (Bhaskaran *et al.*, 1996). Finally, location of boundaries over areas with significant topography may lead to inconsistencies and noise generation (e.g., Hong and Juang, 1998).

Surface forcing due to land, ocean and sea ice greatly affects regional climate simulation (e.g., Giorgi *et al.*, 1996; Seth and Giorgi, 1998; Wei and Fu, 1998; Christensen, 1999; Pan *et al.*, 1999; Pielke *et al.*, 1999; Rinke and Dethloff, 1999; Chase *et al.*, 2000; Maslanik *et al.*, 2000, Rummukainen *et al.*, 2000). In particular, RCM experiments do not start with equilibrium conditions and therefore the initialisation of surface variables, such as soil moisture and temperature, is important. For example, to reach equilibrium it can require a few seasons for the rooting zone (about 1 m depth) and years for the deep soils (Christensen, 1999).

The choice of RCM resolution can modulate the effects of physical forcings and parametrizations (Giorgi and Marinucci, 1996a; Laprise *et al.*, 1998). The description of the hydrologic cycle generally improves with increasing resolution due to the better topographical representation (Christensen *et al.*, 1998; Leung and Ghan, 1998). Resolving more of the spectrum of atmospheric motions at high resolution improves the representation of cyclonic systems and vertical velocities, but can sometimes worsen aspects of the model climatology (Machenhauer *et al.*, 1998; Kato *et al.*, 1999). Different resolutions may be required to capture relevant forcings in different sub-regions, which can be achieved via multiple one-way nesting (Christensen *et al.*, 1998; McGregor *et al.*, 1999), two-way nesting (Liston *et al.*, 1999) or smoothly varying horizontal grids (Qian and Giorgi, 1999). Only limited studies of the effects of changing vertical resolution have been published (Kato *et al.*, 1999).

RCM model physics configurations are derived either from a pre-existing (and well tested) limited area model system with modifications suitable for climate application (Pielke *et al.*, 1992; Giorgi *et al.*, 1993b,c; Leung and Ghan, 1995, 1998; Copeland *et al.*, 1996; Miller and Kim, 1997; Liston and Pielke 2000; Rummukainen *et al.*, 2000) or are implemented directly from a GCM (McGregor and Walsh, 1993; Jones *et al.*, 1995; Christensen *et al.*, 1996; Laprise *et al.*, 1998). In the first approach, each set of parametrizations is developed and optimised for the respective model resolutions. However, this makes interpreting differences between nested model and driving GCM more difficult, as these will not result only from changes in resolution. Also, the different model physics schemes may result in inconsistencies near the boundaries (Machenhauer *et al.*, 1998; Rummukainen *et al.*, 2000). The second approach maximises compatibility between the models. However, physics schemes developed for coarse resolution GCMs may not be adequate for the high resolutions used in nested regional models and may, at least, require recalibration (Giorgi and Marinucci, 1996a; Laprise *et al.*, 1998; see also Section 10.4). Overall, both strategies have shown performance of similar quality (e.g., IPCC, 1996), and either one may be preferable (Giorgi and Mearns, 1999). In the context of climate change simulations, if there is no resolution dependence, the second approach may be preferable to maximise consistency between RCM and GCM responses to the radiative forcing.

Ocean RCMs have been developed during the last decades for a broad variety of applications. To date, the specific use of these models, in a context similar to the use of nested atmospheric RCMs for climate change studies, is very limited (Kauker, 1998). Although the performance of ocean RCMs has yet to be assessed, it is known that a very high resolution, few tens of kilometres or less, is needed for accurate ocean simulations.

The construction of coupled RCMs is a very recent development. They comprise atmospheric RCMs coupled to other models of climate system components, such as lake, ocean/sea ice, chemistry/aerosol, and land biosphere/hydrology models (Hostetler *et al.*, 1994; Lynch *et al.*, 1995, 1997a,b, 1998; Leung *et al.*, 1996; Bailey *et al.*, 1997; Kim *et al.*, 1998; Qian and Giorgi 1999; Small *et al.*, 1999a,b; Bailey and Lynch, 2000a,b; Mabuchi *et al.*, 2000; Maslanik *et al.*, 2000; Rummukainen *et al.*, 2000; Tsvetsinskaya *et al.*, 2000; Weisse *et al.*, 2000). This promises the development of coupled "regional climate system models".

10.5.1 Simulations of Current Climate

Simulations of current climate conditions serve to evaluate the performance of RCMs. Since the SAR, a vast number of such simulations have been conducted (McGregor, 1997; Appendices 10.1 to 10.3). These fall into two categories, RCMs driven by observed (or "perfect") boundary conditions and RCMs driven by GCM boundary conditions. Observed boundary conditions are derived from Numerical Weather Prediction (NWP) analyses (e.g., European Centre for Medium Range Weather Forecast (ECMWF) reanalysis, Gibson *et al.* 1997; or National Center for Environmental Prediction (NCEP) reanalysis, Kalnay *et al.*, 1996). Over most regions they give accurate representation of the large-scale flow and tropospheric temperature structure (Gibson *et al.*, 1997), although errors are still present due to poor data coverage and to observational uncertainty. The analyses may be used to drive RCM simulations for short periods, for comparison with individual episodes, or over long periods to allow statistical evaluation of the model climatology. Comparison with climatologies is the only available evaluation tool for RCMs driven by GCM fields, with the caveats applied to GCM validation concerning the influence of sample size and decadal variability (see Sections 10.2, 10.3, and 10.4). Despite these, relatively short simulations (several years) can identify major systematic RCM biases if they yield departures from observations significantly greater than the observed natural variability (Machenhauer *et al.*, 1996, 1998; Christensen *et al.*, 1997; Jones *et al.*, 1999).

Often a serious problem in RCM evaluation is the lack of good quality high-resolution observed data. In many regions, observations are extremely sparse or not readily available. In addition, only little work has been carried out on how to use point measurements to evaluate the grid-box mean values from a climate model, especially when using sparse station networks or stations in complex topographical terrain (e.g., Osborn and Hulme, 1997). Most of the observational data available at typical RCM resolution (order of 50 km) is for precipitation and daily minimum and maximum temperature. While these fields have been shown to be useful for evaluating model performance, they

are also the end product of a series of complex processes, so that the evaluation of individual model dynamical and physical processes is necessarily limited. Additional fields need to be examined in model evaluation to broaden the perspective on model performance and to help delineate sources of model error. Examples are the surface energy and water fluxes.

Despite these problems, the situation is steadily improving in terms of grid-cell climatologies (Daly *et al.*, 1994; New *et al.*, 1999, 2000; Widman and Bretherton, 2000), with various groups developing high-resolution regional climatologies (e.g., Christensen *et al.*, 1998; Frei and Schär, 1998). In addition, regional programs such as the Global Energy and Water Cycle Experiment (GEWEX) Continental-Scale International Program (GCIP) have been designed with the purpose of developing sets of observation databases at the regional scale for model evaluation (GCIP, 1998).

10.5.1.1 Mean climate: Simulations using analyses of observations
Ideally, experiments using analyses of observations to drive the RCMs should precede any attempt to simulate climate change. The model behaviour, with realistic forcing, should be as close as possible to that of the real atmosphere and experiments driven by analyses of observations can reveal systematic model biases primarily due to the internal model dynamics and physics.

A list of published RCM simulations driven by analyses of observations is given in Appendix 10.1. Many of these studies present regional differences (or biases) of seasonally or monthly-averaged surface air temperature and precipitation from observed values. They indicate that current RCMs can reproduce average observations over regions of size 10^5 to 10^6 km^2 with errors generally below 2°C and within 5 to 50% of observed precipitation, respectively (Giorgi and Shields, 1999; Small *et al.*, 1999a,b; van Lipzig, 1999; Pan *et al.*, 2000). Uncertainties in the analysis fields, used to drive the models, and, in the observed station data sets, should be considered in the interpretation of these biases.

Various RCM intercomparison studies have been carried out to identify different or common model strengths and weaknesses, over Europe by Christensen *et al.* (1997), over the USA by Takle *et al.* (1999), and over East Asia by Leung *et al.* (1999a). For Europe a wide range of performance was reported, with the better models exhibiting a good simulation of surface air temperature (sub-regional monthly bias in the range ±2°C), except over south-eastern Europe during summer. For the USA, a major finding was that the model ability to simulate precipitation episodes varied depending on the scale of the relevant dynamical forcing. Organised synoptic-scale precipitation systems were well simulated deterministically, while episodes of mesoscale and convective precipitation were represented in a more stochastic sense, with less degree of agreement with the observed events and among models. Over East Asia, a major factor in determining the model performance was found to be the simulation of cloud radiative processes.

10.5.1.2 Mean climate: Simulations using GCM boundary conditions
Since the SAR, evaluation of RCMs driven by GCM simulations of current climate has gained much attention (Appendix 10.2), as

this is the context in which many RCMs are used (e.g., for climate change experiments). Errors introduced by the GCM representation of large-scale circulations are transmitted to the RCM as, for example, clearly shown by Noguer *et al.* (1998). However, since the SAR, regional biases of seasonal surface air temperature and precipitation have been reduced and are mostly within 2°C, and 50 to 60% of observations (with exceptions in all seasons), respectively (Giorgi and Marinucci, 1996b; Noguer *et al.*, 1998; Jones *et al.*, 1999 for Europe; Giorgi *et al.*, 1998 for the continental USA; McGregor *et al.*, 1998 for Southeast Asia; Kato *et al.*, 2001 for East Asia). The reduction of biases is due to both better large-scale boundary condition fields and improved aspects of internal physics and dynamics in the RCMs.

The regionally averaged biases in the nested RCMs are not necessarily smaller than those in the driving GCMs. However, all the experiments mentioned above, along with those of Leung *et al.* (1999a,b), Laprise *et al.* (1998), Christensen *et al.* (1998) and Machenhauer *et al.* (1998) clearly show that the spatial patterns produced by the nested RCMs are in better agreement with observations because of the better representation of high-resolution topographical forcings and improved land/sea contrasts. For example, in simulations over Europe and central USA, Giorgi and Marinucci (1996a) and Giorgi *et al.* (1998) find correlation coefficients between simulated and observed seasonally averaged precipitation in the range of +0.53 to +0.87 in a nested RCM and –0.69 to +0.85 in the corresponding driving GCM.

The role of the high-resolution forcing was clearly demonstrated in the study of Noguer *et al.* (1998), which showed that the skill in simulating the mesoscale component of the climate signal (Giorgi *et al.*, 1994; Jones *et al.*, 1995) was little sensitive to the quality of the driving data (Noguer *et al.*, 1998). On the other hand, interactions between the large-scale driving data and high resolution RCM forcings can have negative effects. In simulations over the European region of Machenauer *et al.* (1998), the increased shelter due to the better-resolved mountains in the RCMs caused an intensification of the GCM-simulated excessively dry and warm summer conditions over south-eastern Europe.

Horizontal resolution is especially important for the simulation of the hydrologic cycle. Christensen *et al.* (1998) showed that only at a very high resolution do the mountain chains in Norway and Sweden become sufficiently well resolved to yield a realistic simulation of the surface hydrology (Figure 10.10). An alternative strategy is to utilise a sub-grid scale scheme capable of resolving complex topographical features (Leung *et al.*, 1999a).

10.5.1.3 Climate variability and extreme events
A number of studies have investigated the interannual variability in RCM simulations driven by analyses of observations over different regions (e.g., Lüthi *et al.*, 1996 for Europe; Giorgi *et al.*, 1996 and Giorgi and Shields 1999 for the continental USA; Sun *et al.*, 1999 for East Africa; Small *et al.*, 1999a for central Asia; Rinke *et al.*, 1999 for the Arctic; van Lipzig, 1999 for Antarctica). These show that RCMs can reproduce well interannual anomalies of precipitation and surface air temperature, both in sign and magnitude, over sub-regions varying in size from a few hundred kilometres to about 1,000 km (Figure 10.11).
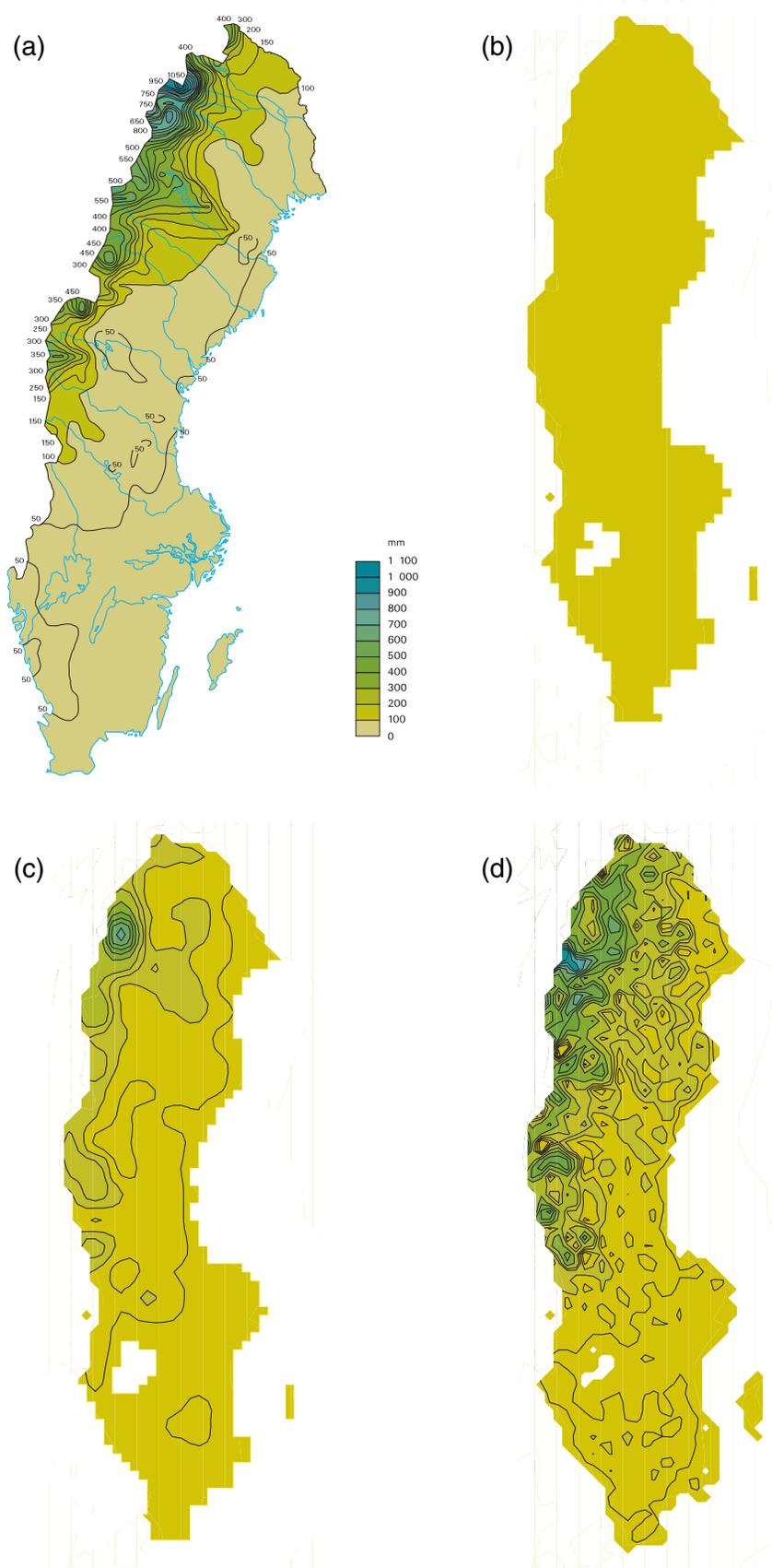
Figure 10.10: Summer (JJA) runoff for Sweden. (a) calculated with a calibrated hydrological model, using daily meteorological station observations and stream gauging stations (Raab and Vedin, 1995); (b) GCM simulation; (c) 55 km RCM simulation; (d) 18 km resolution RCM. Units are mm (from Christensen *et al.*, 1998).
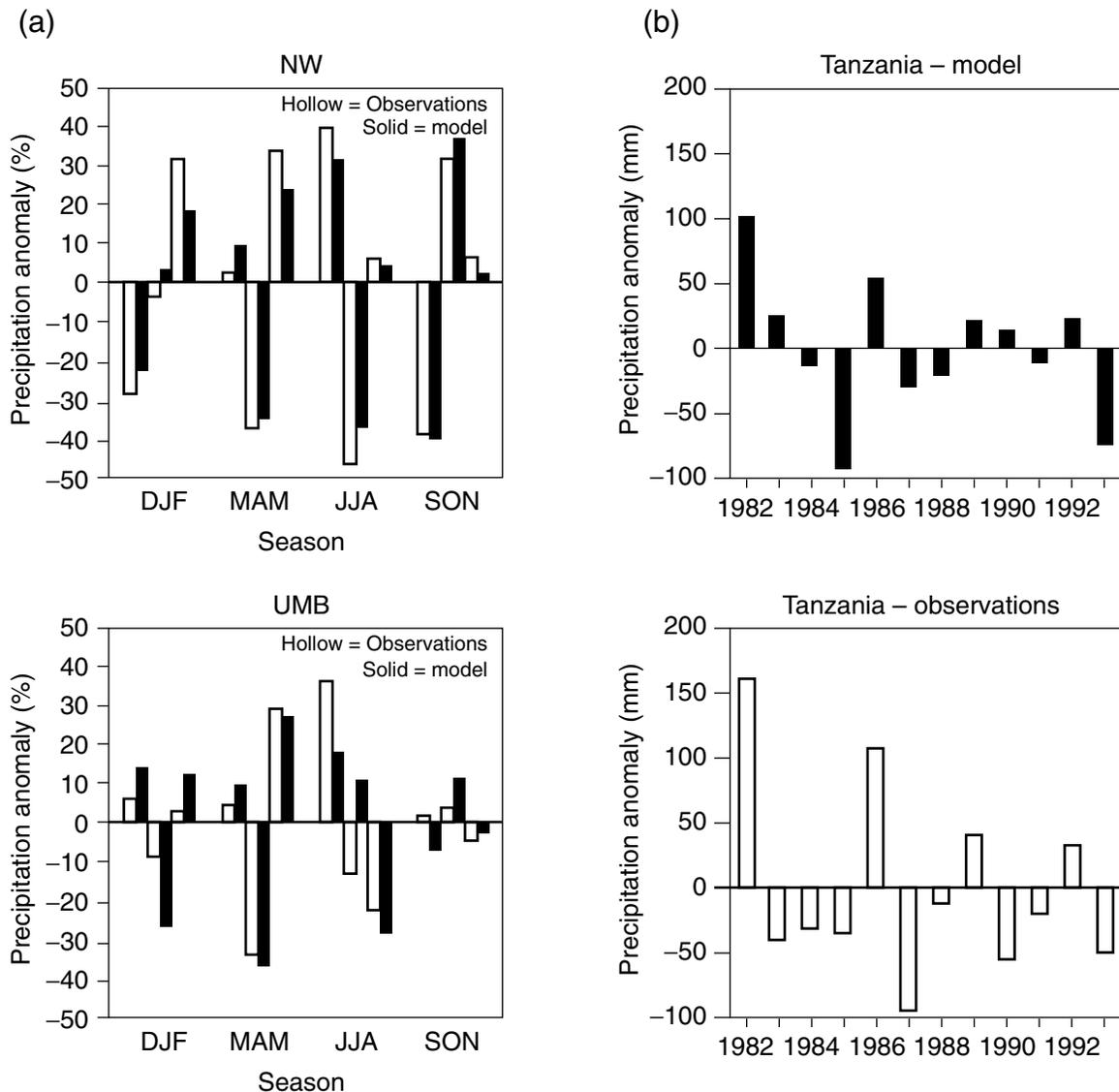
(a)

(b)

Figure 10.11: Examples of seasonal precipitation anomalies simulated with RCMs driven by analyses of observations over different regions. In all cases the anomalies are calculated as the difference between the precipitation of an individual season and the average for the seasonal value for the entire simulation. (a) (top) Northwestern USA (NW), and (bottom) Upper Mississippi Basin (UMB) for a three year simulation (1993 to 1996) over the continental USA. The three pairs of observed (hollow bars) and simulated (solid bars) anomalies for each season are grouped in sequential order from 1993 to 1996. Units are percentage of the three-year seasonal average (from Giorgi and Shields, 1999, Figure 9). (b) Precipitation anomalies for twelve short-rains periods over Tanzania for the October-December season: (top) model simulation, and (bottom) observations. Units are mm. (From Sun *et al.*, 1999).

At the intra-seasonal scale, the timing and positioning of regional climatological features such as the East Asia rain belt and the Baiu front can be reproduced with a high degree of realism with an RCM (Fu *et al.*, 1998). A good simulation of the intra-seasonal evolution of precipitation during the short rain season of East Africa has also been documented (Sun *et al.*, 1999). However, at shorter time-scales, Dai *et al.* (1999) found that, despite a good simulation of average precipitation, significant problems were exhibited by an RCM simulation of the observed diurnal cycle of precipitation over different regions of the USA.

Only a few examples are available of analysis of variability in RCMs driven by GCMs. At the intra-seasonal scale, Bhaskaran

et al. (1998) showed that the leading mode of sub-seasonal variability of the South Asia monsoon, a 30 to 50 day oscillation of circulation and precipitation anomalies, was more realistically captured by an RCM than the driving GCM. Hassell and Jones (1999) then showed that a nested RCM captured observed precipitation anomalies in the active break phases of the South Asia monsoon (5 to 10 periods of anomalous circulations and precipitation) that were absent from the driving GCM (Figure 10.12).

At the daily time-scale, some studies have shown that nested RCMs tend to simulate too many light precipitation events compared with station data (Christensen *et al.* 1998; Kato *et al.*, 2001). However, RCMs produce more realistic statistics of heavy precipitation events than the driving GCMs, sometimes capturing
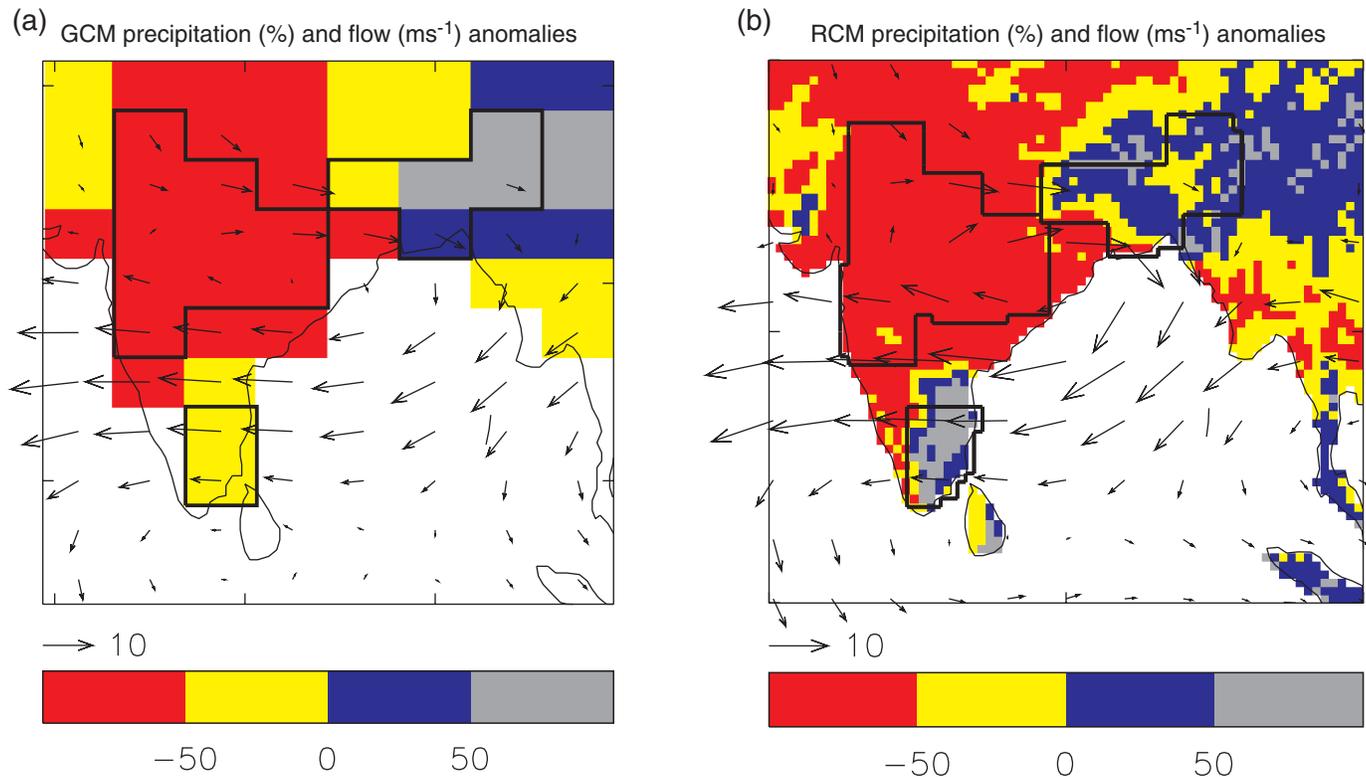
Figure 10.12: Relative characteristics of break and active precipitation composites of the Indian monsoon as simulated by (a) GCM and (b) RCM. Each field is the difference in the break and active composite precipitation as a percentage of the full mean. Overlaid are the 850 hPa wind anomalies (break composite minus active composite, units ms^{-1}). Regions marked where observed ratios are <−50% (central India) and >+50% (Tamil Nadu and north-eastern India) according to Hamilton (1977). From Hassel and Jones (1999).

extreme events entirely absent in the GCMs (Christensen *et al.*, 1998; Jones, 1999). Part of this is due to the inherent disaggregation of grid-box mean values resulting from the RCM's higher horizontal resolution. However, in one study, even when aggregated to the GCM grid scale, the RCM was closer to observations than the driving GCM (Durman *et al.*, 2001).

10.5.2 Simulations of Climate Change

Since the SAR, several multi-year RCM simulations of anthropogenic climate change, either from equilibrium experiments or for time slices of transient simulations, have become available (Appendix 10.3).

10.5.2.1 Mean climate

An important issue when analysing RCM simulations of climate change is the significance of the modelled responses. To date RCM simulations have been mostly aimed at evaluating models and processes rather than producing projections and, as such, they have been relatively short (10 years or less). At short timescales, natural climate variability may mask all but the largest responses. For example, in an analysis of 10-year RCM simulations over Europe, Machenhauer *et al.* (1998) concluded that generally only the full area averaged seasonal mean surface temperature responses were statistically significant, and in only a few cases were sub-domain deviations from the mean response

significant. The changes in precipitation were highly variable in space, and, in each season, they were only significant in those few sub-areas having the largest changes. Similar results were documented by Pan *et al.* (2000) and Kato *et al.* (2001) for the USA and East Asia, respectively. Hence, 30-year samples may be required to confidently assess the mesoscale response of a RCM (Jones *et al.*, 1997). Partly to improve signal to noise definition, a transient RCM simulation of 140 years duration was recently conducted (Hennessy *et al.*, 1998; McGregor *et al.*, 1999).

Despite the limitations in simulation length, most RCM experiments clearly indicate that, while the large-scale patterns of surface climate change in the nested and driving models are similar, the mesoscale details of the simulated changes can be quite different. For example, significantly different patterns of temperature and rainfall changes were found in a regional climate change simulation for Australia (Whetton *et al.*, 2001). This was most clearly seen in mountainous areas (Figure 10.13). Winter rainfall in southern Victoria increased in the RCM simulation, but decreased in the driving GCM. High resolution topographical modification of the regional precipitation change signal in nested RCM simulations has been documented in other studies (Jones *et al.*, 1997; Giorgi *et al.*, 1998; Machenhauer *et al.*, 1998; Kato *et al.*, 2001).

The response in an RCM can also be modified by changes in regional feedbacks. In a 20 year nested climate change experiment for the Indian monsoon region, Hassell and Jones (1999)

(a) GCM   (b) RCM

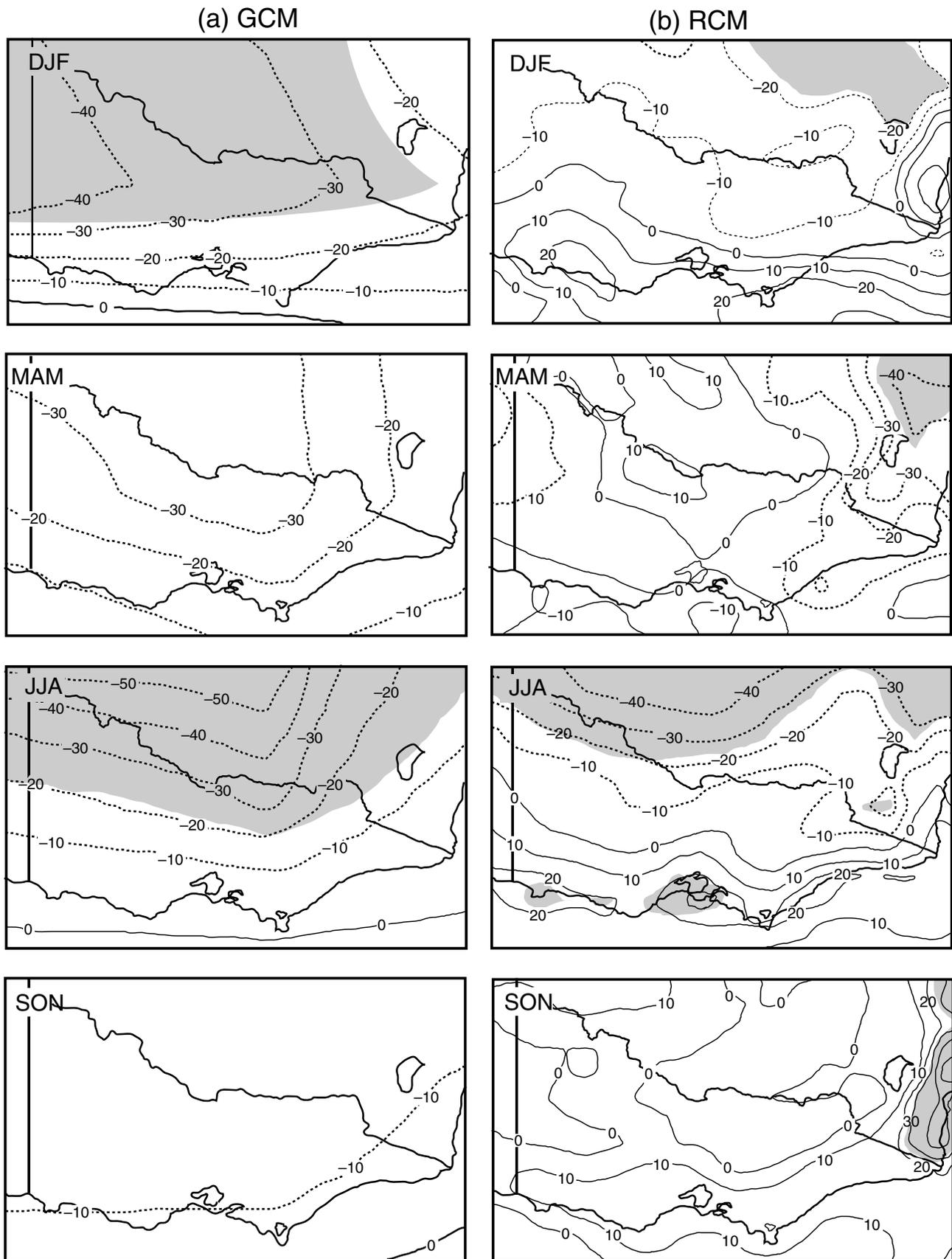**Figure 10.13:** Percentage change in mean seasonal rainfall under $2 \times CO_2$ conditions as simulated by a GCM (a) and a RCM (b) for a region around Victoria, Australia. Areas of change statistically significant at the 5% confidence level are shaded. Whetton *et al.* (2001).
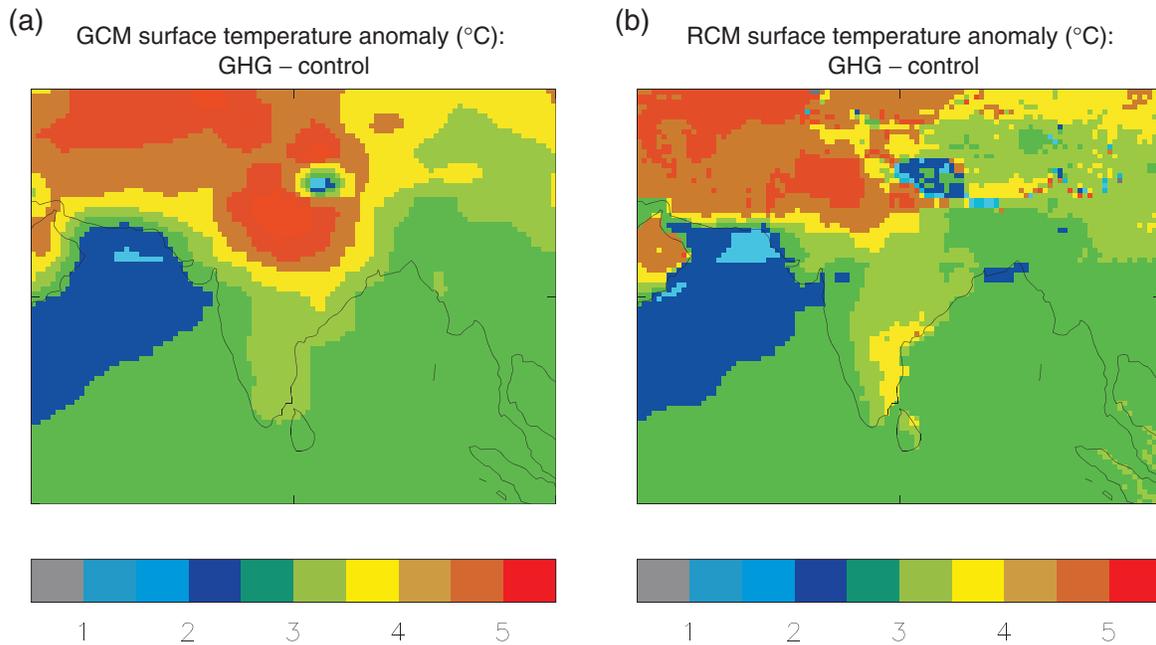
Figure 10.14: Simulated surface air temperature anomaly (°C) for JJA, Indian monsoon region. GHG (2040 to 2060) minus control 20 year average for (a) GCM and (b) RCM. From Hassel and Jones (1999).

showed that a maximum anomaly of 5°C seen in central northern India in the GCM simulation was reduced and moved to the north-west in the nested RCM, with a secondary maximum appearing to the south-east (Figure 10.14). The shift of the main maximum was attributed to deficiencies in the GCM control climate that promoted excessive drying of the soil in North-west India. The secondary maximum was attributed to a complex response involving the RCM's better representation of the flow patterns in southern India resulting from an improved representation of the Western Ghats mountains. In this instance, it was argued that the improved realism of the RCM's control simulation increases confidence in its response.

The high resolution representation of mountainous areas in an RCM has made it possible to show that the simulated surface air temperature change signal due to $2\times CO_2$ concentration could have a marked elevation dependency, resulting in more pronounced warming at high elevations than low elevations as shown in Figure 10.15 (Giorgi *et al.*, 1997). This is primarily caused by a depletion of the snow pack in enhanced GHG conditions and the associated snow albedo feedback mechanism, and it is consistent with observed temperature trends for anomalous warm winters over the alpine region. A similar elevation modulation of the climate change signal has been confirmed in later studies utilising both RCMs and GCMs (e.g., Leung and Ghan, 1999b; Fyfe and Flato, 1999).

The impact of land-use changes on regional climate has been addressed in RCM simulations (e.g., Wei and Fu, 1998; Pan *et al.*, 1999; Pielke *et al.*, 1999; Chase *et al.*, 2000). Land-use changes due to human activities could induce climate modifications, at the regional and local scale, of magnitude similar to the observed climatic changes during the last century (Pielke *et al.*, 1999; Chase *et al.*, 2000). The issue of regional climate modification by

land-use change has been little explored within the context of the global change debate and, because of its potential importance, is in need of further examination.

10.5.2.2 Climate variability and extreme events
Changes in climate variability between control and $2\times CO_2$ simulations with a nested RCM for the Great Plains of the USA have been reported (Mearns, 1999; Mearns *et al.*, 1999). There is indication of significant decreases in daily temperature variability in winter and increases in temperature variability in summer. These changes are very similar to those of the driving GCM, while changes in variability of precipitation are quite different in the nested and driving models, particularly in summer, with increases being more pronounced in the RCM. Similar results have been documented over the Iberian Peninsula (Gallardo *et al.*, 1999).

Different studies have analysed changes in the frequency of heavy precipitation events in enhanced GHG climate conditions over the European region (Schär *et al.,* 1996; Frei *et al.*, 1998; Durman *et al.*, 2001). They all indicate an increase of up to several tens of percentage points in the frequency of occurrence of precipitation events exceeding 30 mm/day, with these increases being less than those simulated by the driving GCMs (see also Jones *et al.*, 1997). In a transient RCM simulation for 1961 to 2100 over south-eastern Australia, substantial increases were found in the frequency of extreme daily rainfall and days of extreme high maximum temperature (Hennessy *et al.*, 1998), In this long simulation, changes in the frequency of long-duration extreme events (such as droughts) were identified. Finally, increases in the number of typhoons reaching mainland China and in the number of heavy rain days were reported for enhanced GHG conditions in RCM simulations over East Asia (Gao *et al.*, 2001).
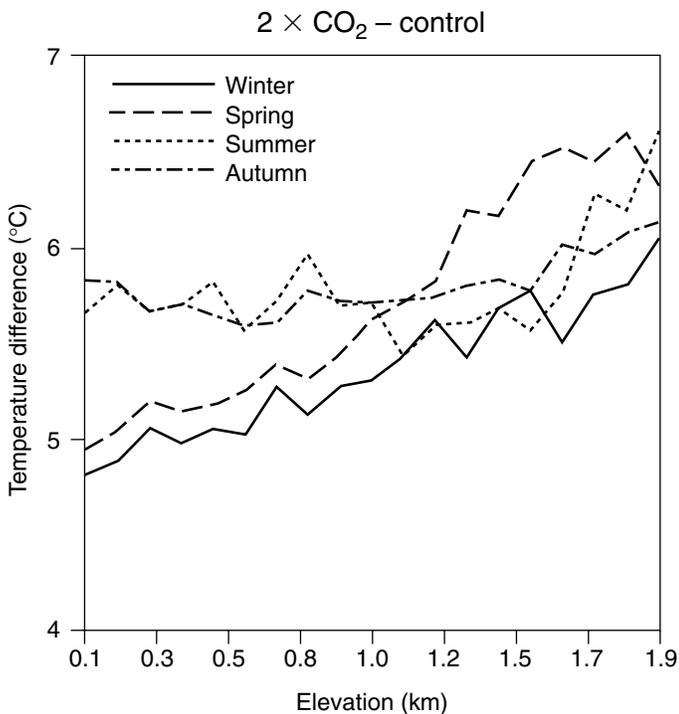
$2 \times CO_2$ – control

Figure 10.15: Difference between $2 \times CO_2$ and control run surface air temperature as a function of elevation over the Alpine sub-region for the four seasons. Units are °C. From Giorgi *et al.* (1997).

10.5.3 Summary and Recommendations

Since the SAR, significant improvements have been achieved in the areas of development and understanding of the nested regional climate modelling technique. These include many new RCM systems, multiple nesting, coupling with different components of the climate system and research into the effects of domain size, resolution, boundary forcing and internal model variability. As a result, a number of RCM systems are currently available with the capability of high-resolution, multi-decadal simulations in a variety of regional settings. Nested RCMs have shown marked improvements in their ability to reproduce present day average climate, with some of this improvement due to better quality driving fields provided by GCMs. Seasonal temperature and precipitation biases in state-of-the-art RCMs are generally less than 1 to 2°C and a few percent to 50 to 60 % of observed precipitation, respectively, over regions of size 10^5 to 10^6 km². However, it is imperative for the effective use of RCMs in climate change work that the quality of GCM large-scale driving fields continues to improve. Research aiming at reducing systematic errors in both GCMs and RCMs should be carried out. With significantly improved model systems the evidence, so far, indicates that improved regional climate change simulations can be produced in the near future.

The analysis of RCM simulations has extended beyond simple averages to include higher-order climate statistics, and has indicated that RCMs can effectively reproduce interannual variability when driven by good quality forcing fields. However, more anlysis and improvements are needed of the model performance in simulating climate variability at short time-scales (daily to sub-daily).

A serious problem concerning RCM evaluation is a general lack of good quality high-resolution observed data. In many areas, observations are extremely sparse due to complex geography or remoteness of settings. In addition, only a little work has been carried out on how to use point measurements to evaluate the grid-box mean values from a climate model, especially when using sparse station networks. This limits the ability to assess model skill in complex terrain and remote regions. It is essential for the advancement of regional climate understanding and modelling, that more research aiming at improving the quality of data for model evaluation is performed.

Overall, the evidence is strong that regional models consistently improve the spatial detail of simulated climate compared to GCMs because of their better representation of sub-GCM grid scale forcings, especially in regard to the surface hydrologic budget. This is not necessarily the case for region-averaged climate. The increased resolution of RCMs also allows the simulation of a broader spectrum of weather events, in particular concerning higher order climate statistics such as daily precipitation intensity distributions. Analysis of some RCM experiments indicate that this is in the direction of increased agreement with observations.

Several RCM studies have been important for understanding climate change processes, such as the elevation signature of the climate change signal or the effect of climate change at the river catchment level. However, a consistent set of RCM simulations of climate change for different regions which can be used as climate change scenarios for impact work is still not available. Most RCM climate change simulations have been sensitivity and process studies aimed at specific goals. The need is there to co-ordinate RCM simulation efforts and to extend studies to more regions so that ensemble simulations with different models and scenarios can be developed to provide useful information for impact assessments. This will need to be achieved under the auspices of international or large national programmes. Within this context, an important issue is to provide RCM simulations of increasing length to minimise limitations due to sampling problems.

10.6 Empirical/Statistical and Statistical/Dynamical Methods

10.6.1 Introduction

As with the dynamical downscaling of RCMs, the methods described in this section rely on the concept that regional climates are largely a function of the large-scale atmospheric state. In empirical downscaling the cross-scale relationship is expressed as a stochastic and/or deterministic function between a set of large-scale atmospheric variables (predictors) and local/regional climate variables (predictands). Predictor and predictand can be the same variables on different spatial scales (e.g., Bürger, 1997; Wilks, 1999b; Widmann and Bretherton, 2000), but more commonly are different.

When using downscaling for assessing regional climate change, three implicit assumptions are made:

- The predictors are variables of relevance to the local climate variable being derived, and are realistically modelled by the GCM. Tropospheric quantities such as temperature or geopotential height are more skilfully represented than derived variables such as precipitation at the regional or grid scale (e.g., Osborn and Hulme, 1997; Trigo and Palutikof, 1999). Furthermore, there is no theoretical level of spatial aggregation at which GCMs can be considered skilful, though there is evidence that this is several grid lengths (Widmann and Bretherton, 2000).

- The transfer function is valid under altered climatic conditions (see Section 10.6.2.2). This cannot be proven in advance, as it would require the observational record to span all possible future realisations of the predictors. However, it could be evaluated with nested AOGCM/RCM simulations of present and future climate, using the simulation of present climate to determine the downscaling function and testing the function against the future time slice.

- The predictors fully represent the climate change signal. Most downscaling approaches to date have relied entirely on circulation-based predictors and, therefore, can only capture this component of the climate change. More recently other important predictors, e.g., atmospheric humidity, have been considered (e.g., Charles *et al.*, 1999b; Hewitson, 1999).

A diverse range of downscaling methods has been developed, but, in principle, these models are based on three techniques:

- Weather generators, which are random number generators of realistic looking sequences of local climate variables, and may be conditioned upon the large-scale atmospheric state (Section 10.6.2.1);

- Transfer functions, where a direct quantitative relationship is derived through, for example, regression (Section 10.6.2.2);

- Weather typing schemes based on the more traditional synoptic climatology concept (including analogues and phase space partitioning) and which relate a particular atmospheric state to a set of local climate variables (Section 10.6.2.3).

Each of these approaches has relative strengths and weaknesses in representing the range of temporal variance of the local climate predictand. Consequently, the above approaches are often used in conjunction with one another in order to compensate for the relative deficiencies in one method.

Most downscaling applications have dealt with temperature and precipitation. However, a diverse array of studies exists in which other variables have been investigated. Appendix 10.4 provides a non-exhaustive list of past studies indicating predictands, geographical domain, and technique category. In light of the diversity in the literature, we concentrate on references to applications since 1995 and based on recent global climate change projections.

10.6.2 Methodological Options

10.6.2.1 Weather generators

Weather generators are statistical models of observed sequences of weather variables (Wilks and Wilby, 1999). Most of them focus on the daily time-scale, as required by many impact models, but sub-daily models are also available (e.g., Katz and Parlange, 1995). Various types of daily weather generators are available, based on the approach to modelling daily precipitation occurrence, and usually these rely on stochastic processes. Two of the more common are the Markov chain approach (e.g., Richardson, 1981; Hughes *et al.*, 1993, Lettenmaier, 1995; Hughes *et al.*, 1999; Bellone *et al.*, 2000) and the spell length approach (Roldan and Woolhiser, 1982; Racksko *et al.*, 1991; Wilks, 1999a). The adequacy of the stochastic models analysed in these studies varied with the climate characteristics of the locations. For example, Wilks (1999a) found the first-order Markov model to be adequate for the central and eastern USA, but that spell length models performed better in the western USA. An alternative approach would include stochastic mechanisms of storm arrivals able to produce the clustering found in observed sequences (e.g., Smith and Karr, 1985; Foufoula-Georgiou and Lettenmeier, 1986; Gupta and Waymrie, 1991; Cowpertwait and O'Connel, 1997; O'Connell, 1999).

In addition to statistical models of precipitation frequency and intensity, weather generators usually produce time-series of other variables, most commonly maximum and minimum temperature, and solar radiation. Others also include additional variables such as relative humidity and wind speed (Wallis and Griffiths, 1997; Parlange and Katz, 2000.) The most common means of including variables other than precipitation is to condition them on the occurrence of precipitation (Richardson, 1981), most often via a multiple variable first-order autoregressive process (Perica and Foufoula-Georgiou, 1996a,b; Wilks, 1999b). The parameters of the weather generator can be conditioned upon a large-scale state (see Katz and Parlange, 1996; Wilby, 1998; Charles *et al.*, 1999a), or relationships between large-scale parameter sets and local-scale parameters can be developed (Wilks, 1999b).

10.6.2.2 Transfer functions

The more common transfer functions are derived from regression-like techniques or piecewise linear or non-linear interpolations. The simplest approach is to build multiple regression models with free atmosphere grid-cell values as predictors for surface variables such as local temperatures (e.g., Sailor and Li, 1999). Other regression models have used fields of spatially distributed variables (e.g., D. Chen *et al.*, 1999), principal components of geopotential height fields (e.g., Hewitson and Crane, 1992), Canonical Correlation Analysis (CCA) and a variant termed redundancy analysis (WASA, 1998) and Singular Value Decomposition (e.g., von Storch and Zwiers, 1999).

Most applications have dealt with monthly or seasonal rainfall (e.g., Busuioc and von Storch, 1996; Dehn and Buma, 1999); local pressure tendencies (a proxy for local storminess; Kaas *et al.*, 1996); climate impact variables such as salinity and oxygen (Heyen and Dippner, 1998; Zorita and Laine, 1999); sea

level (e.g., Cui *et al.*, 1996); and ecological variables such as abundance of species (e.g., Kröncke *et al.*, 1998). In addition statistics of extreme events such as storm surge levels (e.g., von Storch and Reichardt, 1997) and ocean wave heights (WASA, 1998) have been simulated.

An alternative to linear regression is piecewise linear or non-linear interpolation (Brandsma and Buishand, 1997; Buishand and Brandsma, 1999), for example, the "kriging" tools from geostatistics (Biau *et al.*, 1999). One application of this approach is a non-linear model of snow cover duration in Austria derived from European mean temperature and altitude (Hantel *et al.*, 1999). An alternative approach is based on Artificial Neural Networks (ANNs) that allow the fit of a more general class of statistical model (Hewitson and Crane, 1996; Trigo and Palutikof, 1999). For example, Crane and Hewitson (1998) apply ANN downscaling to GCM data in a climate change application over the west coast of the USA using atmospheric circulation and humidity as predictors to represent the climate change signal. The approach was shown to accurately capture the local climate as a function of atmospheric forcing. In application to GCM data, the regional results revealed significant differences from the co-located GCM grid cell, e.g., a significant summer increase in precipitation in the downscaled data (Figure 10.16).

10.6.2.3 Weather typing
This synoptic downscaling approach relates "weather classes" to local and regional climate variations. The weather classes may be defined synoptically or fitted specifically for downscaling purposes by constructing indices of airflow (Conway *et al.*, 1996). The frequency distributions of local or regional climate are then derived by weighting the local climate states with the relative frequencies of the weather classes. Climate change is then estimated by

determining the change of the frequency of weather classes. However, typing procedures contain a potentially critical weakness in assuming that the characteristics of the weather classes do not change.

In many cases, the local and regional climate states are derived by sampling the observational record. For example, Wanner *et al.* (1997) and Widmann and Schär (1997) used changing global to continental scale synoptic structures to understand and reconstruct Alpine climate variations. The technique was applied similarly for New Zealand (Kidson and Watterson, 1995) and to a study of changing air pollution mechanisms (Jones and Davies, 2000).

An extreme form of weather typing is the analogue method (Zorita *et al.*, 1995). A similar concept, although mathematically more demanding, is Classification And Tree Analysis (CART) which uses a randomised design for picking regional distributions (Hughes *et al.*, 1993; Lettenmaier, 1995). Both analogue and CART approaches return approximately the right level of variance and correct spatial correlation structures.

Weather typing is also used in statistical-dynamical downscaling (SDD), a hybrid approach with dynamical elements (Frey-Buness *et al.*, 1995 and see references in Appendix 10.4). GCM results of a multi-year climate period are disaggregated into non-overlapping multi-day episodes of quasi-stationary large-scale flow patterns. Similar episodes are then grouped in classes of different weather types, and, members of these classes are simulated with an RCM. The RCM results are statistically evaluated, and the frequency of occurrence of the respective classes determines their statistical weight. An advantage of the SDD technique over other empirical downscaling techniques is that it specifies a complete three-dimensional climate state. The advantage over continuous RCM simulations is the reduction in computing time, as demonstrated in Figure 10.17.
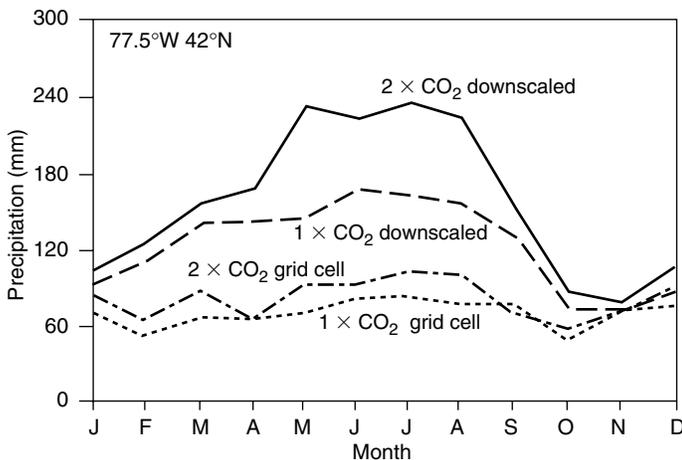
Figure 10.16: Climate change scenario of monthly mean precipitation (mm) over the Susquehanna river basin, USA. Monthly means derived using daily down-scaled precipitation generated with an Artificial Neural Network (ANN) and atmospheric predictors from 1xCO$_2$ and 2×CO$_2$ GCM simulations. Also shown are the GCM grid cell precipitation values from the co-located grid cell. From Crane and Hewitson (1998).
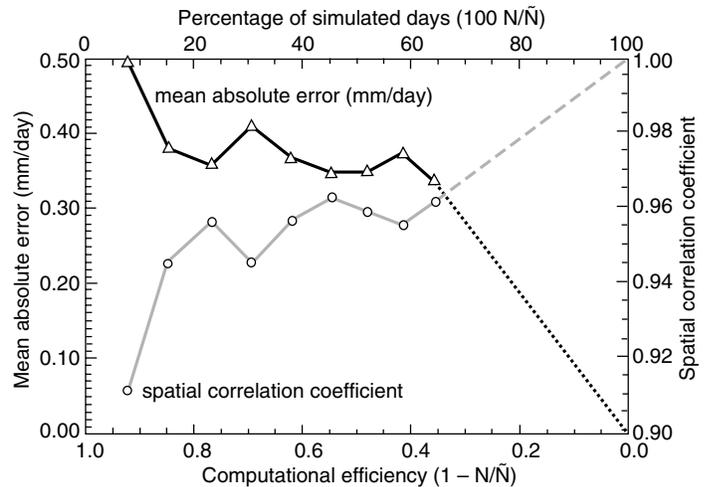
Figure 10.17: Similarity of time mean precipitation distributions obtained in a continuous RCM simulation and through statistical-dynamical downscaling (SDD) for different levels of disaggregation. Black line: mean absolute error (mm/day), grey line: spatial correlation coefficient. Horizontal axis: computational load of SDD. N is the number of days simulated in SDD, Ñ the number of days simulated with the continuous RCM simulation.

10.6.3 Issues in Statistical Downscaling

10.6.3.1 Temporal variance

Transfer function approaches and some weather typing methods suffer from an under prediction of temporal variability, as this is related only in part to the large-scale climate variations (see Katz and Parlange, 1996). Two approaches have been used to restore the level of variability: inflation and randomisation. In the inflation approach the variation is increased by the multiplication of a suitable factor (Karl *et al.*, 1990). A more sophisticated version is "expanded downscaling", a variant of Canonical Correlation Analysis that ensures the right level of variability (Bürger, 1996; Huth, 1999; Dehn *et al.*, 2000). In the randomisation approachs, the unrepresented variability is added as noise, possibly conditioned on synoptic state (Buma and Dehn, 1998; Dehn and Buma 1999; Hewitson, 1999; von Storch, 1999b).

Often weather generators have difficulty in representing low frequency variance, and conditioning the generator parameters on the large-scale state may alleviate this problem (see Katz and Parlange, 1996; Wilby, 1998; Charles *et al.*, 1999a). For example, Katz and Parlange (1993, 1996) modelled daily time-series of precipitation as a chain-dependent process, conditioned on a discrete circulation index. The results demonstrated that the mean and standard deviation of intensity and the probability of precipitation varied significantly with the circulation, and reproduced the precipitation variance statistics of the observations better than the unconditioned model. The method describes the mean precipitation as a linear function of the circulation state, and the standard deviation as a non-linear function (Figure 10.18).

10.6.3.2 Evaluation

The evaluation of downscaling techniques is essential but problematic. It requires that the validity of the downscaling functions under future climates be demonstrated, and that the
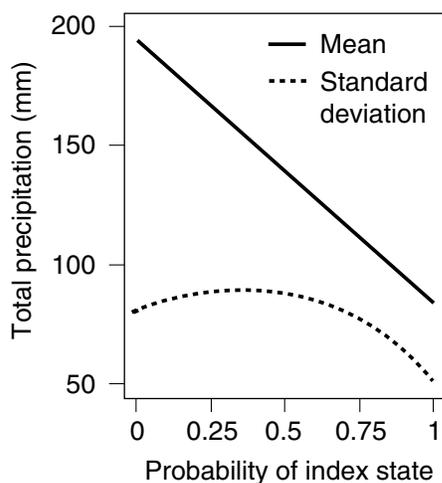

Figure 10.18: Hypothetical changes in mean and standard deviation of January total precipitation at Chico, California, as a function of changing probability that January mean sea level pressure is above normal.

predictors represent the climate change signal. It is not possible to achieve this rigorously as the empirical knowledge available is insufficient. The analysis of historical developments, e.g., by comparing downscaling models between recent and historical periods (Jacobeit *et al.*, 1998), as well as simulations with GCMs can provide support for these assumptions. However, the success of a statistical downscaling technique for representing present day conditions does not necessarily imply that it would give skilful results under changed climate conditions, and may need independent confirmation from climate model simulations (Charles *et al.*, 1999b).

The classical validation approach is to specify the downscaling technique from a segment of available observational evidence and then assess the performance of the empirical model by comparing its predictions with independent observed values. This approach is particularly valuable when the observational record is long and documents significant changes (greater than 50 years in some cases; Hanssen-Bauer and Førland (1998, 2000)). An example is the analysis of absolute pressure tendencies in the North Atlantic (Kaas *et al.*, 1996). As another example, Wilks (1999b) developed a downscaling function on dry years and found it functioned well in wet years.

An alternative approach is to use a series of comparisons between models and transfer functions (e.g., González-Rouco *et al.*, 1999, 2000). For instance, empirically derived links were shown to be incorporated in a GCM (Busuioc *et al.*, 1999) and a RCM (Charles *et al.*, 1999b). Then a climatic change due to doubling of CO_2 was estimated through the empirical link and compared with the result of the dynamical models. In both cases, the dynamical response was found consistent for the winter season, indicating the validity of the empirical approach, although less robust results were noted in the other seasons.

10.6.3.3 Choice of predictors

There is little systematic work explicitly evaluating the relative skill of different atmospheric predictors (Winkler *et al.*, 1997). This is despite the availability of disparate studies that evaluate a broad range of predictors, predictands and techniques (see Appendix 10.4). Useful summaries of downscaling techniques and the predictors used are also presented in Rummukainen (1997), Wilby (1998), and Wilby and Wigley (2000).

The choice of the predictor variables is of utmost importance. For example, Hewitson and Crane (1996) and Hewitson (1999) have demonstrated how the down-scaled projection of future change in mean precipitation and extreme events may alter significantly depending on whether or not humidity is included as a predictor. The downscaled results can also depend on whether absolute or relative humidity is used as a predictor (Charles *et al.*, 1999b). The implication here is that while a predictor may or may not appear as the most significant when developing the downscaling function under present climates, the changes in that predictor under a future climate may be critical for determining the climate change. Some estimation procedures, for example stepwise regression, are not able to recognise this and exclude variables that may be vital for climate change.

A similar issue exists with respect to downscaling temperature. Werner and von Storch (1993), Hanssen-Bauer and Førland (2000) and Mietus (1999) noted that low-frequency changes in local temperature during the 20th century could only partly be related to changes in circulation. Schubert (1998) makes a vital point in noting that changes of local temperature under doubled atmospheric CO_2 may be dominated by changes in the radiative properties of the atmosphere rather than circulation changes. These can be accounted for by incorporating the large-scale temperature field from the GCM as a surrogate indicator of the changed radiative properties of the atmosphere (Dehn and Buma, 1999) or by using several large-scale predictors, such as gridded temperature and circulation fields (e.g., Gyalistras *et al.*, 1998; Huth, 1999).

With the recent availability of global reanalyses (Kalnay *et al.*, 1996; Gibson *et al.*, 1997), the number of candidate predictor fields has been greatly enhanced (Solman and Nuñez, 1999). Prior to this the empirical evidence about the co-variability of regional/local predictands and large-scale predictors was limited mostly to gridded near surface temperature and/or air pressure. These "new" data sets allow significant improvements in the design of empirical downscaling techniques, in particular by incorporating knowledge about detailed meteorological processes. Taking advantage of these new data sets have allowed systematic evaluation of a broad range of possible predictors for daily precipitation. It has been found that indicators of mid-tropospheric circulation and humidity to be the most critical predictors, with surface flow and humidity information being important under orographic rainfall.

10.6.4 Intercomparison of Statistical Downscaling Methodologies

An increasing number of studies comparing different downscaling studies have emerged since the SAR. However, there is a paucity of systematic studies that use common data sets applied to different procedures and over the same geographic region. A number of articles discussing different empirical and dynamical downscaling approaches present summaries of the relative merits and shortcomings of different procedures (Giorgi and Mearns, 1991; Hewitson and Crane, 1996; Rummukainen, 1997; Wilby and Wigley, 1997; Gyalistras *et al.*, 1998; Kidson and Thompson, 1998; Biau *et al.*, 1999; Murphy, 1999; ; von Storch, 1999b; Zorita and von Storch, 1999; Murphy, 2000). However, these inter-comparisons vary widely with respect to predictors, predictands and measures of skill. Consequently, a systematic, internationally co-ordinated inter-comparison project would be particularly helpful in addressing this issue.

The most systematic and comprehensive study so far compared empirical transfer functions, weather generators, and circulation classification schemes over the same geographical region using climate change simulations and observational data (Wilby and Wigley, 1997; Wilby, 1998). This considered a demanding task to downscale daily precipitation for six locations over North America, spanning arid, moist tropical, maritime, mid-latitude, and continental climate regimes. Fourteen measures of skill were used, strongly emphasising daily statistics, and included

wet and dry spell length, 95th percentile values, wet-wet day probabilities, and several measures of standard deviation. Downscaling procedures in the study included two different weather generators, two variants of an ANN-based technique, and two stochastic/circulation classification schemes based on vorticity classes.

The results require careful evaluation as they indicate relative merits and shortcoming of the different procedures rather than recommending one over another. Overall, the weather generators captured the wet-day occurrence and the amount distributions in the data well, but were less successful at capturing the interannual variability, while the opposite results was found for the ANN procedures. The stochastic/circulation typing schemes, as something of a combination of the principles underlying the other methods, were a better all-round performer.

A factor not yet fully evaluated in any comparative study is that of the temporal evolution of daily events which may be critical for some applications, e.g., hydrological modelling. While a downscaling procedure may correctly represent, for example, the number of rain days, the temporal sequencing of these may be as important. Zorita *et al.* (1995) and Zorita and von Storch (1997) compared a CART technique, a CCA and an ANN technique with the analogue technique, and found the simpler analogue technique performed as well as the more complicated methods.

A number of analyses have dealt with the relative merits of non-linear and linear approaches. For example, the relationships between daily precipitation and circulation indicators are often non-linear (Conway *et al.*, 1996; Brandsma and Buishand, 1997). Similarly, Corte-Real *et al.* (1995) applied multivariate adaptive regression splines (MARS) to approximate the non-linear relationships between large-scale circulation and monthly mean precipitation. In a comparison of kriging and analogues, Biau *et al.* (1999) and von Storch (1999c) show that kriging resulted in better specifications of averaged quantities but too low variance, whereas analogues returned the right variance but lower correlation. In general, it appears that downscaling of the short-term climate variance benefits from the use of non-linear models.

Most of the comparative studies mentioned above come to the conclusion that techniques differ in their success of specifying regional climate, and the relative merits and shortcomings emerge differently in different studies and regions. This is not surprising, as there is considerable flexibility in setting up a downscaling procedure, and the suitability of a technique and the adaptation to the problem at hand varies. This flexibility is a distinct advantage of empirical methods.

10.6.5 Summary and Recommendations

A broad range of statistical downscaling techniques has been developed in the past few years. Users of GCM-based climate information may choose from a large variety of methods conditional upon their needs. Weather generators provide realistic sequences of high temporal resolution events. With transfer functions, statistics of regional and local climate, such as conditional means or quantiles, may consistently be derived from GCM generated data. Techniques based on weather typing serve both purposes, but are less adapted to specific applications.

Downscaling means post-processing GCM data; it cannot account for insufficiencies in the driving GCM. As statistical techniques combine the existing empirical knowledge, statistical downscaling can describe only those links that have been observed in the past. Thus, it is based on the assumption that presently found links will prevail under different climate conditions. It may be, in particular, that under present conditions some predictors appear less relevant, but become significant in describing climate change. It is recommended to test statistical downscaling methods by comparing their estimates with high resolution dynamical model simulations. The advent of decades-long atmospheric reanalyses has offered the community many more atmospheric large-scale variables to incorporate as predictors.

Statistical downscaling requires the availability of long and homogeneous data series spanning the range of observed variance, while the computational resources needed are small. Therefore, statistical downscaling techniques are suitable tools for scientific communities without access to supercomputers and with little experience in process-based climate modelling. Furthermore, statistical techniques may relate directly GCM-derived data to impact relevant variables, such as ecological variables or ocean wave heights, which are not simulated by contemporary climate models.

It is concluded that statistical downscaling techniques are a viable complement to process-based dynamical modelling in many cases, and will remain so in the future.

10.7 Intercomparison of Methods

Few formal comparative studies of different regionalisation techniques have been carried out. To date, published work has mostly focused on the comparison between RCMs and statistical downscaling techniques. Early applications of RCMs for climate change simulations (Giorgi and Mearns, 1991; Giorgi *et al.*, 1994) compared the models against observations or against the driving GCMs, but not against statistical/empirical techniques.

Kidson and Thompson (1998) compared the RAMS (Regional Atmospheric Modelling System) dynamical model and a statistical regression-based technique. Both approaches were applied to downscale reanalysis data (ECMWF) over New Zealand to a grid resolution of 50 km. The statistical downscaling used a screening regression technique to predict local minimum and maximum temperature and daily precipitation, at both monthly and daily time-scales. The regression technique limits each regression equation to five predictors (selected from Empirical Orthogonal Functions (EOFs) of atmospheric fields). Both monthly and daily results indicated little difference in skill between the two techniques, and Kidson and Thompson (1998) suggested that, subject to the assumption of statistical relationships remaining viable under a future climate, the computational requirements do not favour the use of the dynamical model. They also noted, however, that the dynamical model performed better with the convective components of precipitation.

Bates *et al.* (1998) compared a south-western Australia simulation using the DARLAM (CSIRO Division of Atmospheric Research Limited Area Model) model with a down-scaled DARLAM simulation where the downscaling model had

been fitted independently to observational data. The downscaling reproduced observed precipitation probabilities and wet and dry spell frequencies while the DARLAM simulation under-estimated the frequency of dry spells and over estimated the probability of precipitation and the frequency of wet spells. In a climate change follow-on experiment, again using both methods, Charles *et al.* (1999b) found a small decrease in probability of precipitation under future climate conditions.

Murphy (1999) evaluated the UK Meteorological Office Unified Model (UM) RCM over Europe against a statistical downscaling model based on regression. Monthly mean surface temperature and precipitation anomalies were down-scaled using predictor sets chosen from a range of candidate variables similar to those used by Kidson and Thompson (1998) (EOFs of atmospheric fields). The results showed similar levels of skill for the dynamical and statistical methods, in line with the Kidson and Thompson (1998) study. The statistical method was nominally better for summertime estimates of temperature, while the dynamical model gave better estimates of wintertime precipitation. Again, the conclusion was drawn that the sophistication of the dynamical model shows little advantage over statistical techniques, at least for present day climates.

Murphy (2000) continued the comparative study by deriving climate change projections for 2080 to 2100 from a simulation with the HadCM2 AOGCM. The dynamical and statistical downscaling techniques were the same regional and statistical models as used by Murphy (1999). The statistical and dynamical techniques produced significantly different predictions of climate change, despite exhibiting similar skill when validated against present day observations. The study identifies two main sources of divergence between the dynamical and statistical techniques: firstly, differences between the strength of the observed and simulated predictor/predictand relationships, and secondly, omission from the regression equations of variables which represent climate change feedbacks, but are weak predictors of natural variability. In particular, the exclusion of specific humidity led to differences between the dynamical and statistical simulations of precipitation change. This point would seem to confirm the humidity issue raised in Section 10.6.3 (Hewitson and Crane 1996, Crane and Hewitson, 1998, Charles *et al.*, 1999b; Hewitson 1999).

Mearns *et al.* (1999) compared RCM simulations and statistical downscaling using a regional model and a semi-empirical technique based on stochastic procedures conditioned on weather types which were classified from circulation fields (700hPa geopotential heights). While Mearns *et al.* suggest that the semi-empirical approach incorporates more physical meaning into the relationships than a pure statistical approach does, this approach does impose the assumption that the circulation patterns are robust into a future climate in addition to the normal assumption that the cross-scale relationships are stationary in time. For both techniques, the driving fields were from the CSIRO AOGCM (Watterson *et al.*, 1995). The variables of interest were maximum and minimum daily temperature and precipitation over central-northern USA (Nebraska). As with the preceding studies, the validation under present climate conditions indicated similar skill levels for the dynamical and statistical approaches, with some advantage by the statistical technique.

In line with the Murphy (2000) study, larger differences were also noted by Mearns *et al.* (1999) when climate change projections were produced. Notably for temperature, the statistical technique produced an amplified seasonal cycle compared to both the RCM and CSIRO data, although similar changes in daily temperature variances were found in both the RCM and the statistical technique (with the statistical approach producing mostly decreases). The spatial patterns of change showed greater variability in the RCM compared with the statistical technique. Mearns *et al.* (1999) suggested that some of the differences found in the results were due to the climate change simulation exceeding the range of data used to develop the statistical model, while the decreases in variance were likely to be a true reflection of changes in the circulation controls. The precipitation results from Mearns *et al.* (1999) are different from earlier studies with the same RCM (e.g., Giorgi *et al.*, 1998) that produced few statistically significant changes.

Extending the comparison beyond simple methodological performance, Wilby *et al.* (2000) compared hydrological responses using data from dynamically and statistically downscaled climate model output for the Animas River basin in Colorado, USA. While not a climate change projection, the use of output from an RCM and a statistical downscaling approach to drive a distributed hydrological model exemplify the objective of the downscaling. The results indicate that both the statistical and dynamical methods had greater skill (in terms of modelling hydrology) than the coarse resolution reanalysis output used to drive the downscaling. The statistical method had the advantage of requiring very few parameters, an attribute making the procedure attractive for many hydrological applications. The dynmical model output, once elevation-corrected, provided better water balance estimates than raw or elevation-corrected reanalysis output.

Overall, the above comparative studies indicate that for present climate both techniques have similar skill. Since statistical models are based on observed relationships between predictands and predictors, this result may represent a further validation of the performance of RCMs. Under future climate conditions more differences are found between the techniques, and the question arises as to which is "more correct". While the dynamical model should clearly provide a better physical basis for change, it is still unclear whether different regional models generate similar downscaled changes. With regard to statistical/empirical techniques, it would seem that careful attention must be given to the choice of predictors, and that methodologies which internally select predictors based on explanatory power under present climates may exclude predictors important for determining change under future climate modes.

10.8 Summary Assessment

Today different modelling tools are available to provide climate change information at the regional scale. Coupled AOGCMs are the fundamental models used to simulate the climatic response to anthropogenic forcings and, to date, results from AOGCM simulations have provided the climate information for the vast majority of impact studies. On the other hand, resolution limita-

tions pose severe constraints on the usefulness of AOGCM information, especially in regions characterised by complex physiographic settings. Three classes of regionalisation techniques have been developed to enhance the regional information of coupled AOGCMs: high resolution and variable resolution time-slice AGCM experiments, regional climate modelling, and empirical/statistical and statistical/dynamical approaches.

Since the SAR, substantial progress has been achieved in all regionalisation methods, including better understanding of the techniques, development of a wide variety of modelling systems and methods, application of the techniques to a wide range of studies and regional settings, and reduction of model biases. Modelling work has indicated that regionalisation techniques enhance some aspects of AOGCM regional information, such as the high resolution spatial detail of precipitation and temperature, and the statistics of daily precipitation events. It is important to stress that AOGCM information is the starting point for the application of all regionalisation techniques, so that a foremost requirement in the simulation of regional climate change is that the AOGCMs simulate well the circulation features that affect regional climates. In this respect, indications are that the performance of current AOGCMs is generally improving.

Analysis of AOGCM simulations for broad (sub-continental scale) regions indicates that biases in the simulation of present day regionally and seasonally averaged surface climate variables, although highly variable across regions and models, are generally improved compared with the previous generation models. This implies increased confidence in simulated climatic changes. The performance of models in reproducing observed interannual variability varies across regions and models.

Regional analysis of AOGCM transient simulations extending to 2100, for different scenarios of GHG increase and sulphate aerosol effects, and with a number of modelling systems (some simulations include ensembles of realisations) indicate that the average climatic changes for the late decades of the 21st century compared to present day climate vary substantially across regions and models. The primary source of uncertainty in the simulated changes is associated with inter-model range of changes, with inter-scenario and intra-ensemble range of simulated changes being less pronounced. Despite the range of inter-model results, some common patterns of sub-continental scale climatic changes are emerging, and thus providing increased confidence in the simulation of these changes.

Work performed with all regionalisation techniques indicates that sub-GCM grid scale structure in the regional climate change signal can occur in response to regional and local forcings, although more work is needed to assess the statistical significance of the sub-GCM grid scale signal. In particular, modelling evidence clearly indicates that topography, land use and the surface hydrologic cycle strongly affect the surface climate change signal at the regional to local scale. This implies that the use of AOGCM information for impact studies needs to be taken cautiously, especially in regions characterised by pronounced sub-GCM grid scale variability in forcings, and that suitable regionalisation techniques should be used to enhance the AOGCM results over these regions.

Considerations of various types may enter the choice of the regionalisation technique, as different techniques may be most suitable for different applications and different working environments. High resolution AGCMs offer the primary advantage of global coverage and two-way interactions between regional and global climate. However, due to their computational cost, the resolution increase that can be expected from these models is limited. Variable resolution and RCMs yield a greater increase in resolution, with current RCMs reaching resolutions as fine as a few tens of kilometres or less. RCMs can capture physical processes and feedbacks occurring at the regional scale, but they are affected by the errors of the AOGCM driving fields, and they do not represent regional-to-global climate feedbacks. The effects of regional-to-global feedback processes depend on the specific problem and in many cases may not be important. Two-way GCM-RCM nesting would allow the description of such effects, and some research efforts in that direction are currently under way. Statistical downscaling techniques offer the advantages of being computationally inexpensive, of providing local information which is needed in many impact applications, and of offering the possibility of being tailored to specific applica-

tions. However, these techniques have limitations inherent in their empirical nature.

The combined use of different techniques may provide the most suitable approach in many instances. For example, a high-resolution AGCM simulation could represent an important intermediate step between AOGCM information and RCM or statistical downscaling models. The convergence of results from different approaches applied to the same problem can increase the confidence in the results and differences between approaches can help to understand the behaviour of the models.

Despite recent improvements and developments, regionalisation research is still a maturing process and the related uncertainties are still rather poorly known. One of the reasons for this is that most regionalisation research activities have been carried out independently of each other and aimed at specific objectives. Therefore a coherent picture of regional climate change via available regionalisation techniques cannot yet be drawn. More co-ordinated efforts are thus necessary to improve the integrated hierarchy of models, evaluate the different methodologies, intercompare methods and models and apply these methods to climate change research in a comprehensive strategy.

Appendix 10.1:

List of regional climate model simulations of duration longer than 3 months nested within analyses; also including oceanic RCMs (O-RCM).

References	Grid size	Duration	Region
a) Individual January/July present-day simulations			
Walsh and McGregor (1996)	125 km	7 × 1 month	Antarctica
Rinke *et al.* (1999)	55 km	11 × 1 month	Arctic
Takle *et al.* (1999)	50 km	7 × 2 months	USA
Katzfey (1999)	125 km	8 × 1 month	Australia
b) Seasonally-varying present-day simulations			
Giorgi *et al.* (1993a)	60 km	2 years	USA
Christensen *et al.* (1995)	56 km	20 months	Europe
Leung and Ghan (1995)	30 and 90 km	1 year	North-west USA
Kim (1997)	20 km	6 months	Western USA
Christensen *et al.* (1997)	26 to 57 km	11 months to 10 years	Europe
Jenkins (1997)	110 km	2 × 4 months	West Africa
Kidson and Thompson (1998)	50 km	5 years	New Zealand
McGregor *et al.* (1998)	44 km	1 year	Southeast Asia
Noguer *et al.* (1998)	50 km	10 years	Europe
Ruti *et al.* (1998)	30 km	19 months	Europe
Seth and Giorgi (1998)	60 km	2 × 4 months	USA
Leung and Ghan (1998)	90 km	3 years	North-west USA
Kauker (1998)	15 km	15 years	North Sea (O-RCM)
Christensen (1999)	55 km	7 × 1 year	Mediterranean area
Giorgi and Shields (1999)	60 km	3 years	USA
Giorgi *et al.* (1999)	60 km	13 month	East Asia
Small *et al.* (1999a)	60 km	5.5 years	Central Asia
van Lipzig (1999)	55 km	10 years	Antarctica
Liston and Pielke (1999)	50 km	1 year	USA
Hong and Leetmaa (1999)	50 km	4 × 3 months	USA
Christensen and Kuhry (2000)	16 km	15 years	Arctic Russia
Pan *et al.* (2000)	55 km	2 × 10 years	USA
Mabuchi *et al.* (2000)	30 km	6.5 years	Japanese Islands
Jacob and Podzun (2000)	55 km	10 years	Northern Europe
c) Seasonal tropical or monsoon simulations			
Bhaskaran *et al.* (1996)	50 km	4 months	Indian monsoon
Ji and Vernekar (1997)	80 km	3 × 5.5 months	Indian monsoon
Wei *et al.* (1998)	60 km	4 months	Temperate East Asia
Sun *et al.* (1999)	60 km	10 × 3 month	East Africa
Leung *et al.* (1999a)	60 km	3 × 3 month	East Asia
Chen and Fu (2000)	60 km	3 years	East Asia

[1995, 1] Third International Conference on Modelling of Global Climate Change and Variability, Hamburg, Germany, 4 to 8 September 1995.

[2000, 2] Submitted to Research Activities in Atmospheric and Oceanic Modelling. (CAS/JSC Working Group on Numerical Experimentation Report) [Geneva]: WMO.

[2000, 3] 80th AMS Annual Meeting, Long Beach, California, 9 to 14 January 2000.

Appendix 10.2:

List of regional climate model simulations of duration longer than 3 months nested within a GCM present day simulation; also including oceanic RCMs (O-RCM) and variable resolution GCMs (var.res.GCM).

References	Grid size	Duration	Region
a) Perpetual January simulation			
McGregor and Walsh (1993)	250 km	10 months	Australia
b) Individual January/July simulations			
Giorgi (1990)	60 km	6 × 1 month	USA
Marinucci and Giorgi (1992)	70 km	5 × 1 month	Europe
McGregor and Walsh (1994)	125 km/60 km	10 × 1 month	Tasmania
Marinucci *et al.* (1995)	20 km	5 × 1 month	Europe (Alps)
Walsh and McGregor (1995)	125 km	10 × 1 month	Australasia
Podzun *et al.* (1995)	55 km	5 × 1 month	Europe
Rotach *et al.* (1997)	20 km	5 × 1 month	Europe (Alps)
Joubert *et al.* (1999)	125 km	20 × 1 month	South Africa
c) Seasonally-varying simulations			
Giorgi *et al.* (1994)	60 km	3.5 years	USA
Dèquè and Piedelievre (1995)	T21-T200	10 years	Europe (var.res.GCM)
Hirakuchi and Giorgi (1995)	50 km	5 years	East Asia
Jones *et al.* (1995)	50 km	10 years	Europe
McGregor *et al.* (1995)	125 km	10 years	Australasia
Giorgi and Marinucci (1996b)	50 km	5 years	Europe
Giorgi *et al.* (1997)	50 km	5 years	Europe
Krinner *et al.* (1997)	~100 km	5 years	Antarctica (var.res.GCM)
Jenkins and Barron (1997)	108 km	7 months	USA – AMIP
Jacob and Podzun (1997)	55 km	4 years	Europe
Walsh and McGregor (1997)	125 km	5 × 18 months	Australasia – AMIP
Christensen *et al.* (1998)	57 and 19 km	9 years	Scandinavia
Krinner and Genthon (1998)	~100 km	3 years	Greenland (var.res.GCM)
Dèquè *et al.* (1998)	~60 km	10 years	Europe
Giorgi *et al.* (1998)	50 km	5 years	USA
Katzfey *et al.* (1998)	60 and 125 km	20 years	Australia
Laprise *et al.* (1998)	45 km	5 years	West Canada
Machenhauer *et al.* (1998)	19 to 70 km	5 to 30 years	Europe
McGregor *et al.* (1998)	44 km	10 years	Southeast Asia
Noguer *et al.* (1998)	50 km	10 years	Europe
Renwick *et al.* (1998)	50 km	10 years	New Zealand
Böhm *et al.* (1998)	55 km	13 month	Northern South America
Kauker (1998)	15 km	5 years	North Sea (O-RCM)
Leung and Ghan (1999a)	90 km	7 years	North-west USA
Gallardo *et al.* (1999)	50 km	10 years	Iberian Peninsula
Leung *et al.* (1999b)	90 km	2 years	North-west USA
Haugen *et al.* (1999)	55 km	20 years	North-west Europe
Jacob and Podzun (2000)	55 km	10 years	Northern Europe
Pan *et al.* (2000)	55 km	2 × 10 years	USA
Rummukainen *et al.* (2000)	44 km	10 years	Europe
Kato *et al.* (2001)	50 km	10 years	East Asia
Gao *et al.* (2000)	60 km	5 year	China
Chen and Fu (2000)	60 km	3 years	East Asia
c) Seasonal tropical or monsoon simulations			
Jacob *et al.* (1995)	55 km	6 months	Indian monsoon
Bhaskaran *et al.* (1998)	50 km	10 years	India – AMIP
Hassel and Jones (1999)	50 km	20 years	Indian monsoon

[1995, 1] Third International Conference on Modelling of Global Climate Change and Variability, Hamburg, Germany, 4 to 8 September 1995.

[1998, 2] International Conference on The Role of Topography in Modelling Weather and Climate. International Centre for Theoretical Physics, Trieste, Italy, 22 to 26 June 1998.

[2000, 3] Submitted to Research Activities in Atmospheric and Oceanic Modelling. (CAS/JSC Working Group on Numerical Experimentation Report) [Geneva]: WMO.

Appendix 10.3:

List of regional climate model simulations of duration longer than 3 months nested within a GCM climate change simulation; also including oceanic RCMs (O-RCM) and variable resolution GCMs (var.res.GCM).

References	Grid size	Duration	Region
a) Individual January/July 2×CO$_2$ simulations			
Giorgi *et al.* (1992)	70 km	5 × 1 month	Europe
McGregor and Walsh (1994)	60 km	10 × 1 month	Tasmania
Rotach *et al.* (1997)	20 km	5 × 1 month	Europe (Alps)
b) Seasonally-varying 2×CO$_2$ time-slice simulations			
Giorgi *et al.* (1994)	60 km	3.5 years	USA
Hirakuchi and Giorgi (1995)	50 km	5 years	East Asia
McGregor *et al.* (1995)	125 km	10 years	Australasia
Giorgi *et al.* (1997)	50 km	3 years	Europe
Jones *et al.* (1997)	50 km	10 years	Europe
Dèquè *et al.* (1998)	About 60 km	10 years	Europe (var.res.GCM)
Giorgi *et al.* (1998)	50 km	5 years	USA
Joubert *et al.* (1998)	125 km	10 years	Southern Africa
Laprise *et al.* (1998)	45 km	5 years	West Canada
Machenhauer *et al.* (1998)	19 to 70 km	5 to 30 years	Europe
McGregor *et al.* (1998)	44 km	10 years	South-east Asia
Renwick *et al.* (1998)	50 km	10 years	New Zealand
Kauker (1998)	15 km	5 years	North Sea (O-RCM)
Räisänen *et al.* (1999)	44 km	10 years	Europe
Hassel and Jones (1999)	50 km	20 years	Indian monsoon
Gallardo *et al.* (1999)	50 km	10 years	Iberian Peninsula
Haugen *et al.* (1999)	55 km	20 years	North-west Europe
Leung and Ghan (1999b)	90 km	8 years	North-west USA
Pan *et al.* (2000)	55 km	2 × 10 years	USA
Kato *et al.* (2001)	50 km	10 years	East Asia
Gao *et al.* (2000)	60 km	5 year	China
c) Seasonally-varying fully transient CO$_2$ simulations			
McGregor *et al.* (1999)	125 km	140 years	Australasia
McGregor *et al.* (1999)	60 km	140 years	South-east Australia

[1995, 1] Third International Conference on Modelling of Global Climate Change and Variability, Hamburg, Germany, 4 to 8 September 1995.

[1998, 2] IntInternational Conference on The Role of Topography in Modelling Weather and Climate. IntInternational Centre for Theoretical Physics,Trieste, Italy, 22 to 26 June 1998.

Appendix 10.4: Examples of downscaling studies.

Technique (utilised in the above categories):
- WG = weather generators (e.g.: Markov-type procedures, conditional probability).
- TF = transfer functions (e.g.: Regression, canonical correlation analysis, and artificial neural networks).
- WT = weather typing (e.g.: cluster analysis, self-organising map, and extreme value distribution).

Predictor variables: C = circulation based (e.g.: sea level pressure fields and geopotential height fields).
T = temperature (at surface or on one or more atmospheric levels). TH = thickness between pressure levels.
VOR = vorticity. W = wind related. Q = specific humidity (at surface or on one or more atmospheric levels).
RH = relative humidity (at surface or on one or more atmospheric levels). Cld = cloud cover.
ZG = spatial gradients of the predictors. O = other.

Predictands: T (temperature); Tmax (maximum temperature); Tmin (minimum temperature); P (precipitation).

Region is the geographic domain.

Time is the time-scale of the predictor and predictand: H (hourly), D (daily), M (monthly), S (seasonal), and A (annual).

Region	Technique	Predictor	Predictand	Time	Author (s)
Africa					
South Africa	TF	C	P	D	Hewitson and Crane, 1996
America					
USA	WT	T	Tmax, Tmin	D	Brown and Katz, 1995
USA	WG	C	P	D	Zorita *et al.*, 1995
USA	WG, TF	C, T, VOR	P	D	Wilby and Wigley, 1997
USA	TF	C, Q	P	D	Crane and Hewitson, 1998
USA	WG, TF	C, T, VOR	T, P	D	Wilby *et al.*, 1998a, b
USA	WG, WT	C	T, P	D	Mearns *et al.*, 1999
USA	TF	C, T, RH, W	T	D	Sailor and Li, 1999
USA	WG		P	D	Bellone *et al.*, 1999
Mexico and USA	TF	C, TH, O	P	D	Cavazos, 1997
Mexico and USA	TF, WT	C, TH, Q	P	D	Cavazos, 1999
Central Argentina	TF	C, W	T, Tmax, Tmin	M	Solman and Nuñez, 1999
Asia					
Japanese coast	TF	C	Sea level	M	Cui *et al.*, 1995, 1996
Chinese coast	TF		Sea level variability	M	Cui and Zorita, 1998
Oceania					
New Zealand	WT	C	Tmax, Tmin, P	D	Kidson and Watterson, 1995
New Zealand	TF	C, TH, VOR, W	T, P	D	Kidson and Thompson, 1998
Australia	TF	C	Tmax, Tmin	D	Schubert and Henderson-Sellers, 1997
Australia	TF	C	Tmax, Tmin	D	Schubert, 1998
Australia	WT	C, T	P		Timbal and McAvaney, 1999
Australia	WT				Schnur and Lettenmaier, 1999
Europe					
Europe	WG	VOR, W			Conoway *et al.*, 1996
Europe	WG, TF	C, P, Tmax, Tmin, O	T, P	D	Semenov and Barrow, 1996
Europe	TF	C, W, VOR, T, Q, O	T, P	M	Murphy, 1998a, b
Europe	TF	C	T, P, vapour pressure	D	Weichert and Bürger, 1998
Germany	TF	T	Phenological event		Maak and van Storch, 1997
Germany	TF	C	Storm surge	M	Von Storch and Reichardt, 1997
Germany	TF		Salinity		Heyen and Dippner, 1998
Germany	WT		Thunderstorms	D	Sept, 1998

Region	Technique	Predictor	Predictand	Time	Author (s)
Germany	TF		Ecological variables		Krönke *et al.*, 1998
Iberian Peninsula	WG	C	P	D	Cubash *et al.*, 1996
Iberian Peninsula	TF	C	Tmax, Tmin	D	Trigo and Palutikof, 1998
Iberian Peninsula	TF		T, P		Boren *et al.*, 1999
Iberian Peninsula	TF		T, P		Ribalaygua *et al.*, 1999
Spain (and USA)	TF	C	Tmax, Tmin	D	Palutikof *et al.*, 1997
Spain (and USA)	TF	C	Tmax, Tmin	D	Winkler *et al.*, 1997
Spain	WT			D	Goodess and Palutikof, 1998
Portugal	TF	C	P	M	Corte-Real *et al.*, 1995
Portugal	WT	C		D	Corte-Real *et al.*, 1999
The Netherlands	WT	C, VOR, W	T, P	D,M	Buishand and Brandsma, 1997
Norway	TF	C, O	T, P and others	M	Benestad, 1999a, b
Norway (glaciers)	TF	C, O	Local weather	D	Reichert *et al.*, 1999
Romania	TF	C	P	M	Busuioc and von Storch, 1996
Romania	TF	C	P	M	Busuioc *et al*, 1999
Switzerland	TF		P		Buishand and Klein Tank, 1996
Switzerland	TF		P		Brandsma and Buishand, 1997
Switzerland	TF			D	Widmann and Schär, 1997
Switzerland	WG	C	Local Weather	H	Gyalistras *et al.*, 1997
Switzerland	TF		P		Buishand and Brandsma, 1999
Poland	TF	C	T, sea level, wave height, salinity, wind, run-off	D,M	Mietus, 1999
Alps	WT				Fuentes and Heimann, 1996
Alps	TF	C, T	T, P	M	Fischlin and Gylistras, 1997
Alps	WT	C	Snow		Martin *et al.*, 1997
Alps	WT				Fuentes *et al.*, 1998
Alps	TF	C, T	T, P,		Gyalistras *et al.*, 1998
Alps,	TF	C, T	Snow cover		Hantel *et al.*, 1998
Alps	WT	C, T	Landslide activity		Dehn, 1999a, b
Alps	WT		T, P	D	Heimann and Sept, 1999
Alps	WT		P	D	Fuentes and Heimann, 1999
Alps	TF, WG	C, T	Weather statistics	M	Riedo *et al.*, 1999
Alps	TF	C	P	M	Burkhardt, 1999
Mediterranean	TF	C, P	T		Palutikof and Wigley, 1995
Mediterranean	TF	C	P	S	Jacobeit, 1996
North Atlantic	TF	C	Pressure tendencies	M	Kaas *et al.*, 1996
North Atlantic	TF	C	Wave height	M	WASA, 1998
North Sea	TF		Ecological variables		Dippner, 1997a, b
North Sea coast	TF	C	Sea level	M	Langenberg *et al.*, 1999
Baltic Sea	TF	SLP	Sea level	M	Heyen *et al.*, 1996
Region not specified					
	WT				Frey-Buness *et al.*, 1995
	WT	C			Matyasovszky and Bogardi, 1996
	WT				Enke and Spekat, 1997
	TF	C, VOR, W			Kilsby *et al.*, 1998
	TF		Ecological variables		Heyen *et al.*, 1998
	TF		P		Biau *et al.*, 1999
	WG	P	P	D	Wilks, 1999
	WT		P	D	Zorita and von Storch, 1999

References

Appenzeller, C., T.F. Stocker and M. Anklin, 1998: North Atlantic Oscillation dynamics recorded in Greenland ice cores. *Science,* **282**, 446–449.

Arritt, R., D.C. Goering and C.J. Anderson, 2000: The North American monsoon system in the Hadley Centre coupled ocean-atmosphere GCM. *Geophys. Res. Lett.,* **27**, 565-568.

Bailey, D.A., A.H. Lynch and K.S. Hedström, 1997: The impact of ocean circulation on regional polar simulations using the Arctic regional climate system model. *Ann. Glaciol*., **25**, 203-207.

Bailey, D.A. and A.H. Lynch, 2000a: Development of an Antarctic regional climate system model: Part I: Sea ice and large-scale circulation, *J. Climate*, **13**, 1337-1350.

Bailey, D.A. and A.H. Lynch, 2000b: Development of an Antarctic regional climate system model: Part II Station validation and surface energy ballance, *J. Climate*, **13**, 1351-1361.

Barrow, E., M. Hulme and M. Semenov, 1996: Effect of using difference methods in the construction of climate change scenarios: examples from Europe. *Clim. Res*., **7**, 195–211.

Bates, B., S.P. Charles and J.P. Hughes, 1998: Stochastic downscaling of numerical climate model simulations. *Env. Modelling and Software,* **13**, 325–331.

Baur, F., P. Hess and H. Nagel, 1944: Kalender der Grosswetterlagen Europas 1881-1939. Bad Homburg, 35 pp.

Beersma, J.J. and T.A. Buishand, 1999: A simple test for equality of variances in monthly climate data. *J. Climate,* **12**, 1770-1779.

Bellone, E., J.P. Hughes and P. Guttrop, 2000: A hidden Markov model for downcaling synoptic atmospheric patterns to precipitation amounts. *Clim. Res*., **15**, 1-12.

Benestad, R.E., 1999: Pilot Studies on Enhanced Greenhouse Gas Scenarios for Norwegian Temperature and Precipitation from Empirical Downscaling, DNMI-Klima report 18/99, Norwegian Met. Inst., PO Box 43 Blindern, N0313 Oslo, Norway.

Benestad, R.E., I. Hanssen-Bauer, E.J. Førland, K.A. Iden and O.E. Tveito, 1999: Evaluation of monthly mean data fields from the ECHAM4/OPYC3 control integration, DNMI-Klima report 14/99, Norwegian Met. Inst., P.O. Box 43 Blindern, N0313 Oslo, Norway.

Bengtsson, L., M. Botzet and M. Esch, 1995: Hurricane-type vortices in a general circulation model. *Tellus,* **47A**, 175–196.

Bengtsson, L., M. Botzet and M. Esch, 1997: Numerical simulation of intense tropical storms. Hurricanes: Climate and Socioeconomics Impacts, Springer, 67–92.

Bengtsson, L., M. Botzet and M. Esch, 1996: Will greenhouse gas induced warming over the next 50 years lead to higher frequency and greater intensity of hurricanes? *Tellus,* **48A**, 57–73.

Bhaskaran B., R.G. Jones, J.M. Murphy and M. Noguer, 1996: Simulations of the Indian summer monsoon using a nested regional climate model: Domain size experiments. *Clim. Dyn*., **12**, 573–587.

Bhaskaran, B. and J.F.B. Mitchell, 1998: Simulated changes in southeast Asian monsoon precipitation resulting from anthropogenic emissions. *Int. J. Climatology*, **18**, 1455-1462.

Bhaskaran, B., J.M. Murphy and R.G. Jones, 1998: Intraseasonal Oscillation in the Indian Summer Monsoon Simulated by Global and nested Regional Climate Models. *Mon. Wea*. *Rev*., **126**, 3124–3134.

Biau, G., E. Zorita, H. von Storch and H. Wackernagel, 1999: Estimation of precipitation by kriging in EOF space. *J. Climate,* **12**, 1070–1085.

Boer, G.J., G. Flato and D. Ramsden, 2000b: A transient climate change simulation with greenhouse gas and aerosol forcing: projected climate for the 21st century. *Clim. Dyn*., **16**, 427-450.

Boer, G.J., G. Flato, M.C. Reader and D. Ramsden, 2000a: A transient climate change simulation with greenhouse gas and aerosol forcing: experimental design and comparison with the instrumental record for the 20th century. *Clim. Dyn.,* **16**, 405-426.

Böhm, U., R. Podzun and D. Jacob, 1998: Surface Water Balance Estimation for a Semi-Arid Region using a Regional Climate Model and Comparison of Water Balance Components with Global Circulation Model Output and Analysis Data. *Phys. Chem. Earth*, **23**, 405-411.

Brandsma, T. and T. A. Buishand, 1997: Statistical linkage of daily precipitation in Switzerland to atmospheric circulation and temperature. *J. Hydrology*, **198**, 98–123.

Brown, B. G. and R. W. Katz, 1995: Regional analysis of temperature extremes: Spatial analog for climate change? *J. Climate*, **8**, 108–119.

Buishand, T.A. and J.J. Beersma, 1996: Statistical tests for comparison of daily variability in observed and simulated climates. *J. Climate*, **10**, 2538–2550.

Buishand, T.A. and A.M.G. Klein Tank, 1996: Regression model for generating time series of daily precipitation amounts for climate change impact studies. *Stochastic Hydrology and Hydraulics*, **10**, 87–106.

Buishand, T.A. and T. Brandsma, 1997: Comparison of circulation classification schemes for predicting temperature and precipitation in the Netherlands, *Int. J. Climatol*., **17**, 875–889.

Buishand, T.A. and T. Brandsma, 1999: The dependence of precipitation on temperature at Florence and Livorno. *Clim. Res*., **12**, 53–63.

Buma, J. and M. Dehn, 1998: A method for predicting the impact of climate change on slope stability. *Environmental Geology*, **35**, 190–196.

Buma, J. and M. Dehn, 2000: The impact of climate change on a landslide in South East France, simulated using different GCM-scenarios and downscaling methods for local precipitation. *Clim. Res.,* **15**, 69-81.

Bürger, G., 1996: Expanded downscaling for generating local weather scenarios *Clim. Res*., **7**, 111–128.

Bürger, G., 1997: On the disaggregation of climatological means and anomalies. *Clim. Res*., **8**, 183–194.

Burkhardt, U., 1999: Alpine precipitation in a tripled CO_2 climate. *Tellus,* **51A**, 289–303.

Busuioc, A. and H. von Storch, 1996: Changes in the winter precipitation in Romania and its relation to the large scale circulation. *Tellus,* **48A**, 538–552.

Busuioc, A., H. von Storch and R. Schnur, 1999: Verification of GCM generated regional precipitation and of statistical downscaling estimates. *J. Climate*, **12**, 258–272.

Carril, A. F,C.G. Menéndez and M.N. Nuñez, 1997: Climate Change Scenarios over the South American Region: An Intercomparison of Coupled General Atmosphere-Ocean Circulation Models. *Int. J. Climatol.*, **17**, 1613–1633.

Cavazos, T., 1997: Downscaling large-scale circulation to local rainfall in North-Eastern Mexico. *Int.. J. Climatology,* **17**, 1069-1082.

Cavazos, T., 1999: Large-Scale Circulation Anomalies Conducive to Extreme Precipitation Events and Derivation of Daily Rainfall in Northeastern Mexico and Southeastern Texas. *J. Climate,* **12**, 1506-1523.

Charles, S.P., B.C. Bates, and J.P. Hughes, 1999a: A spatio-temporal model for downscaling precipitation occurrence and amounts. *J. Geophys. Res*., **104**, 31657-31669.

Charles, S.P., B.C. Bates, P.H. Whetton and J.P. Hughes, 1999b: Validation of downscaling models for changed climate conditions: Case study of southwestern Australia. *Clim. Res.,* **12**, 1-14.

Chase T.N., R.A. Pielke, T.G.F. Kittel, R.R. Nemani and S.W. Running, 2000: Simulated impacts of historical land cover changes on global climate in northern winter. *Clim. Dyn.* , **16**, 93-106.

Chen, D, C. Hellstroem and Y. Chen, 1999: Preliminary analysis and statistical downscaling of monthly temperature in Sweden. Department of Physical Geography, Göteborg, C 16 1999, 76 pp.

Chen, M., and C. Fu, 2000: A nest procedure between regional and global climate models and its application in long term regional climate simulation. *Chinese J. Atmos. Sci*., **24**, 233-262.

Christensen, J.H., O.B. Christensen and B. Machenhauer, 1995: On the performance of the HIRHAM limited area regional climate model over Europe, Third Int. Conference on Modelling of Global Climate Change and Variability, Hamburg, Germany, 4-8 September 1995.

Christensen J.H., O.B. Christensen, P. Lopez, E. van Meijgaard and M. Botzet, 1996: The HIRHAM4 Regional Atmospheric Climate Model. *DMI Sci. Rep*., 96-4., 51pp. DMI, Copenhagen.

Christensen J.H., B. Machenhauer, R.G. Jones, C. Schär, P.M. Ruti, M. Castro and G. Visconti, 1997: Validation of present-day regional climate simulations over Europe: LAM simulations with observed boundary conditions. *Clim. Dyn*., **13**, 489–506.

Christensen O.B., J.H. Christensen, B. Machenhauer and M. Botzet, 1998: Very high-resolution regional climate simulations over Scandinavia – Present climate. *J. Climate*, **11**, 3204-3229.

Christensen O.B., 1999: Relaxation of soil variables in a regional climate model. *Tellus*, **51A**, 674-685.

Christensen J.H. and P. Kuhry, 2000: High resolution regional climate model validation and permafrost simulation for the East-European Russian Arctic. *J. Geophys. Res.*, **105**, 29647-29658.

Cocke, S.D. and T.E. LaRow, 2000: Seasonal Prediction using a Regional Spectral Model embedded within a Coupled Ocean-Atmosphere Model. *Mon. Wea. Rev*., **128**, 689-708.

Conway, D., 1998: Recent climate variability and future climate change scenarios for the British Isles. *Prog. Phys. Geog*., **22**, 350-374.

Conway, D., R.L. Wilby and P.D. Jones, 1996: Precipitation and air flow indices over the British Isles, *Clim. Res*., **7**, 169–183.

Copeland, J.H., R.A. Pielke and T.G.F. Kittel, 1996: Potential climatic impacts of vegetation change: A regional modeling study. *J. Geophys. Res*., **101**, 7409–7418.

Corte-Real, J., H. Xu and B. Qian, 1999: A weather generator for obtaining daily precipitation scenarios based on circulation patterns. *Clim. Res*., **12**, 61–75.

Corte-Real, J., X. Zhang and X. Wang, 1995: Downscaling GCM information to regional scales: a non-parametric multivariate regression approach, *Clim. Dyn*., **11,** 413–424.

Cowpertwait, P.S.P. and P.E. O'Connel, 1997: A regionalized Neymann-Scott model of rainfall with convective and stratiform cells, *Hydrology and Earth Sciences*, **1**, 71–80.

Crane, R.G. and B.C. Hewitson, 1998: Doubled CO_2 climate change scenarios for the Susquehanna Basin: Precipitation. *Int. J. Climatology,* **18**, 65–76.

Cubasch, U., H. von Storch, J. Waszkewitz and E. Zorita, 1996: Estimates of climate change in southern Europe using different downscaling techniques. *Clim. Res*., **7**, 129–149.

Cubasch, U., J. Waszkewitz, G. Hegerl and J. Perlwitz, 1995: Regional climate changes as simulated in time-slice experiments. *Clim. Change*, **31**, 273–304.

Cui, M. and E. Zorita, 1998: Analysis of the sea-level variability along the Chinese coast and estimation of the impact of a CO_2-perturbed atmospheric circulation. *Tellus*, **50A**, 333–347.

Cui, M., H. von Storch and E. Zorita, 1995: Coastal sea level and the large-scale climate state: A downscaling exercise for the Japanese Islands. *Tellus,* **47A**, 132–144.

Cui, M., H. von Storch and E. Zorita, 1996: Coast sea level and the large-scale climate state: a downscaling exercise for the Japanese Islands. *Studia Marina Sinica* **36**, 13–32 (in Chinese).

Dai, A., F. Giorgi and K. Trenberth, 1999: Observed and model simulated precipitation diurnal cycles over the continental United States. *J. Geophys. Res*., **104**, 6377–6402.

Daly, C., R.P. Neilson and D.L. Phillips, 1994: A statistical-topographic model for mapping climatological precipitation over mountainous terrain. *J. Appl. Met*., **33**, 140-158.

Dehn, M., 1999a: Szenarien der klimatischen Auslösung alpiner Hangrutschungen. Simulation durch Downscaling allgemeiner Zirkulationsmodelle der Atmosphäre. PhD thesis, Bonn. Bonner Geographische Abhandlungen, 99. Bonn, 99pp.

Dehn, M., 1999b: Application of an analog downscaling technique for assessment of future landslide activity - a case study in the Italian Alps. *Clim. Res.,* **13**, 103-113.

Dehn, M., and J. Buma, 1999: Modelling future landslide activity based on general circulation models. *Geomorphology,* **30**, 175-187.

Dehn, M., G. Bürger, J. Buma and P. Gasparetto, 2000: Impact of climate change on slope stability using expanded downscaling. *Engineering Geology,* **55**, 193-204.

Delworth, T.L., J.D. Mahlman and T.R. Knutson, 1999: Changes in heat index associated with CO_2-induced global warming. *Clim. Change*, **43**, 369-386.

Déqué, M. and J. P. Piedelievre, 1995: High resolution climate simulation over Europe. *Clim. Dyn*., **11**, 321–339.

Déqué, M., P. Marquet and R. G. Jones, 1998: Simulation of climate change over Europe using a global variable resolution general circulation model. *Clim. Dyn*., **14**, 173-189.

Dickinson R.E., R.M. Errico, F. Giorgi and G.T. Bates, 1989: A regional climate model for western United States. *Clim. Change*, 15, 383–422.

Dippner, J. W., 1997a: Recruitment success of different fish stocks in the North Sea in relation to climate variability. *Dtsche Hydrogr. Z.*, **49**, 277-293

Dippner, J.W., 1997b: SST anomalies in the North Sea in relation to the North Atlantic Oscillation and the influence on the theoretical spawning time of fish. *Dtsche Hydrogr. Z.,* **49**, 267-275.

Doherty, R. and Mearns, L.O., 1999: A Comparison of Simulations of Current Climate from Two Coupled Atmosphere - Ocean GCMs Against Observations and Evaluation of Their Future Climates. Report to the NIGEC National Office. National Center for Atmospheric Research, Boulder, Colorado, 47pp.

Durman, C.F., J.M. Gregory, D.H. Hassell and R.G. Jones, 2001. The comparison of extreme European daily precipitation simulated by a global and a regional climate model for present and future climates. *Quart. J. R.. Met. Soc.*, (in press).

Emanuel, K.A., 1987: The dependence of hurricane intensity on climate. *Nature,* **326**, 483-485.

Emanuel, K., 2000: A statistical analysis of tropical cyclone intensity. *Mon. Wea. Rev*., **128**, 1139-1152.

Enke, W and A. Spekat, 1997: Downscaling climate model outputs into local and regional weather elements by classification and regression. *Clim. Res*., **8**, 195–207.

Fernandez-Partagas, J. and H.F. Diaz, 1996: Atlantic hurricanes in the second half of the 19th Century. *Bull. Am. Met. Soc.*, **77**, 2899-2906.

Fischlin, A. and D. Gyalistras, 1997: Assessing impacts of climate change on forests in the Alps. *Glob. Ecol. Biogeogr. Lett*., 6, 19–37.

Flato, G.M., Boer, G.J., Lee, W.G., McFarlane, N.A., Ramsden, D., Reader, M.C. and Weaver, A.J., 2000: The Canadian Centre for Climate Modelling and Analysis global coupled model and its climate. *Clim. Dyn.*, **16**, 451-467.

Foufoula-Georgiou, E., and D.P. Lattenmaier, 1987: A Markov renewal model for rainfall occurrences. *Water. Resour. Res*., **23**, 875-884.

Frei C., C. Schär, D. Lüthi and H.C. Davies, 1998: Heavy precipitation processes in a warmer climate. *Geophys. Res. Lett*., **25**, 1431–1434.

Frei, C. and C. Schär, 1998: A precipitation climatology for the Alps from high resolution rain guage observations. *Int. J. Climatol*., **18**, 873–900.

Frey-Buness, F., D. Heimann and R. Sausen, 1995: A statistical-dynamical downscaling procedure for global climate simulations. *Theor. Appl. Climatol*., **50**, 117–131.

Fu, C.B., H.L.Wei, M.Chen, B.K.Su, M.Zhao and W.Z. Zheng, 1998: Simulation of the evolution of summer monsoon rainbelts over Eastern China from a regional climate model, *Scientia Atmospherica Sinica*, **22**, 522–534.

Fuentes, U. and D. Heimann, 1996: Verification of statistical-dynamical downscaling in the Alpine region. *Clim. Res*., **7**, 151–186.

Fuentes, U., and D. Heimann, 1999: An improved statistical-dynamical downscaling scheme and its application to the Alpine precipitation climatology. *Theor. Appl. Climatol.*, **65**, 119-135.

Fyfe, J.C., 1999: On climate simulations of African Easterly waves. *J. Climate*, **12**, 6, 1747-1769.

Fyfe, J.C. and G.M. Flato, 1999: Enhanced Climate Change and its Detection over the Rocky Mountains. *J. Climate*, **12**, 230–243.

Gallardo, C., M.A. Gärtner, J.A. Prego and M. Castro, 1999: Multi-year simulations with a high resolution Regional Climate Model over the Iberian Peninsula: Current climate and $2\times CO_2$ scenario. Internal Report, Dept. Geofísica y Meteorología, 45 pp. (Available in English on request from: Facultad de Física, Universidad Complutense, 28040 Madrid, Spain).

Gao, X., Z. Zhao Y. Ding, R. Huang and F. Giorgi, 2001: Climate change due to greenhouse effects in China as simulated by a regional climate model, *Acta Meteorologica Sinica,* in press.

GCIP, 1998: Global Energy and Water Cycle Experiment (GEWEX) Continental-Scale International Project. A Review of Progress and Opportunities. National Academy Press, Washington, D. C., 99 pp.

Gibson J. K., P. Källberg, S. Uppala, A. Hernández, A Nomura and E. Serrano, 1997, ERA description. ECMWF Reanalysis Project Report Series 1, ECMWF, Reading, 66 pp.

Giorgi F., 1990: Simulation of regional climate using a limited area model nested in a general circulation model. *J. Climate,* **3**, 941–963.

Giorgi, F., G.T Bates and S.J. Nieman, 1993a: The multiyear surface climatology of a regional atmospheric model over the western United States. *J. Climate*, **6**, 75–95.

Giorgi, F., C.S. Brodeur and G.T. Bates, 1994: Regional climate change scenarios over the United States produced with a nested regional climate model. *J. Climate*, **7**, 375–399.

Giorgi, F. and R. Francisco, 2000a: Uncertainties in regional climate change predictions. A regional analysis of ensemble simulations with the HadCM2 GCM. *Clim. Dyn.*, **16**, 169-182.

Giorgi, F. and R. Francisco, 2000b: Evaluating uncertainties in the prediction of regional climate change. *Geophys. Res. Lett*, **27**, 1295-1298.

Giorgi, F., J.W. Hurrell, M.R. Marinucci and M. Beniston, 1997: Elevation signal in surface climate change: A model study. *J. Climate*, **10**, 288–296.

Giorgi, F.,Y. Huang, K. Nishizawa and C. Fu, 1999: A seasonal cycle simulation over eastern Asia and its sensitivity to radiative transfer and surface processes. *J. Geophys. Res.*, **104**, 6403-6424.

Giorgi, F. and M.R. Marinucci, 1996a: An investigation of the sensitivity of simulated precipitation to model resolution and its implications for climate studies. *Mon. Wea. Rev.*, **124**, 148-166.

Giorgi, F. and M.R. Marinucci, 1996b: Improvements in the simulation of surface climatology over the European region with a nested modeling system. *Geophys. Res. Lett.*, **23**, 273–276.

Giorgi, F., M.R. Marinucci, G.T. Bates and G. DeCanio, 1993b: Development of a second-generation regional climate model (RegCM2). Part II: Convective processes and assimilation of lateral boundary conditions. *Mon. Wea. Rev.*, **121**, 2814–2832.

Giorgi, F., M.R. Marinucci, G.T. Bates, 1993c: Development of a second-generation regional climate model (RegCM2). Part I: Boundary-layer and radiative transfer processes. *Mon. Weath. Rev.*, **121**, 2794–2813.

Giorgi, F., M.R Marinucci and G. Visconti, 1992: A $2\times CO_2$ climate change scenario over Europe generated using a limited area model nested in a general circulation model. 2. Climate change scenario. *J. Geophys. Res.*, **97**, 10011–10028.

Giorgi, F. and L.O. Mearns, 1991: Approaches to the simulation of regional climate change: a review, *Rev. Geophys.*, **29**, 191–216.

Giorgi, F. and L.O. Mearns, 1999: Regional climate modeling revisited. An introduction to the special issue. *J. Geophys. Res.*, **104**, 6335–6352.

Giorgi, F., L.O. Mearns, C. Shields and L. Meyer, 1996: A regional model study of the importance of local vs. remote controls in maintaining the drought 1988 and flood 1993 conditions in the central U.S. *J. Climate*, **9**, 1150–1162.

Giorgi, F., L.O. Mearns, C. Shields and L. McDaniel, 1998: Regional nested model simulations of present day and $2\times CO_2$ climate over the Central Plains of the U.S. *Clim. Change*, **40**, 457–493.

Giorgi, F. and C. Shields, 1999: Tests of precipitation parameterizations available in the latest version of the NCAR regional climate model (RegCM) over the continental U.S. *J. Geophys. Res.*, **104**, 6353–6376.

Goodess, C. and J. Palutikof, 1998: Development of daily rainfall scenarios for southeast Spain using a circulation-type approach to downscaling. *Int.. J. Climatol.*, **18**, 1051-1083.

Gregory, J.M. and J.F.B. Mitchell, 1995: Simulation of daily variability of surface temperature and precipitation over Europe in the current and $2\times CO_2$ climates using the UKMO climate model. *Quart. J. R. Met. Soc.*, **121**, 1451-1476.

Gregory, J.M., J.F.B. Mitchell and A.J. Brady, 1997: Summer drought in northern midlatitudes in a time-dependent CO_2 climate experiment. *J. Climate*, **10**, 662-686.

González-Rouco, F., H. Heyen, E. Zorita and F. Valero, 1999: Testing the validity of a statistical downscaling method in simulations with global climate models. GKSS Report 99/E/29, GKSS Research Centre, Geesthacht, Germany.

González-Rouco, F., H. Heyen, E. Zorita and F. Valero, 2000: Agreement between observed rainfall trends and climate change simulations in the southwest of Europe. *J. Climate*, **13**, 3057-3065.

Gupta,V.K. and E. Waymire, 1991: On lognormality and scaling in spatial rainfall averages? *Non-linear variability in geophysics*, 175-183.

Gyalistras, D., A. Fischlin and M. Riedo, 1997: Herleitung stündlicher Wetterszenarien unter züküftigen Klimabedingungen. In: Fuhrer, J. (ed), Klimaänderungen und Grünland - eine Modellstudie über die Auswirkungen zukünftiger Klimaveränderungen auf das Dauergrünland in der Schweiz. vdf, Hochschulverlag AG an der ETH Zürich, 207-276.

Gyalistras, D., C. Schär, H.C. Davies and H. Wanner, 1998: Future Alpine climate. In: Cebon, P., U. Dahinden, H.C. Davies, D. Imboden, and C.C. Jaeger (eds) Views from the Alps. Regional Perspectives on Climate Change. Cambridge, Massachusetts: MIT Press, 171–223.

Hanssen-Bauer, I. and E.J. Førland 1998: Long-term trends in precipitation and temperature in the Norwegian Arctic: can they be explained by changes in atmospheric circulation patterns? *Clim. Res.*, **10**, 143–153.

Hanssen-Bauer I. and E.J. Førland 2000: Temperature and precipitation variations in Norway and their links to atmospheric circulation. *Int. J. Climatology.*, **20**, 1693-1708.

Hantel, M., M. Ehrendorfer and A. Haslinger, 1999: Climate sensitivity of snow cover duration in Austria. *Int.. J. Climatology.*, **20**, 615-640.

Hassell, D. and R.G. Jones, 1999: Simulating climatic change of the southern Asian monsoon using a nested regional climate model (HadRM2), HCTN 8, Hadley Centre for Climate Prediction and Research, London Road, Bracknell, UK.

Haugen, J.E., D. Bjørge and T.E. Nordeng, 1999: A 20-year climate change experiment with HIRHAM, using MPI boundary data. RegClim Techn. Rep. No. 3, 37–44. Available from NILU, P.O. Box 100, N-2007 Kjeller, Norway.

Heimann, D. and V. Sept, 2000: Climatic change of summer temperature and precipitation in the Alpine region - a statistical-dynamical assessment. *Theor. Appl. Climatol.*, **66**, 1-12.

Henderson-Sellers A, H. Zhang, G. Berz, K. Emanuel, W. Gray, C. Landsea, G. Holland, J. Lighthill, S.-L. Shieh, P. Webster and K. McGuffie, 1998: Tropical cyclones and global climate change: a

post-IPCC assessment. *Bull. Am. Met. Soc.*, **79**, 19-38.

Hennessy, K.J., J.M. Gregory and J.F.B. Mitchell, 1997: Changes in daily precipitation under enhanced greenhouse conditions. *Clim. Dyn.*, **13**, 667–680.

Hennessy, K.J., P.H. Whetton, J.J. Katzfey, J.L. McGregor, R.N. Jones, C.M. Page and K.C. Nguyen, 1998: Fine-resolution climate change scenarios for New South Wales. Annual report 1997-1998, research undertaken for the New South Wales Environmental Protection Authority. Chatswood, N.S.W., NSW Environment protection Authority, 48 pp.

Hewitson, B.C., 1999: Deriving regional precipitation scenarios from general circulation models, Report K751/1/99, Water Research Commission, Pretoria, South Africa.

Hewitson, B.C., and Crane, R.G., 1992: Large-scale atmospheric controls on local precipitation in tropical Mexico. *Geophys. Res. Lett.*, **19**(18), 1835-1838.

Hewitson, B.C., and Crane, R.G., 1996: Climate downscaling: Techniques and application, *Clim. Res.*, **7**, 85-95.

Heyen, H., and J. W. Dippner, 1998: Salinity in the southern German Bight estimated from large-scale climate data. *Tellus,* **50A**, 545–556.

Heyen, H., E. Zorita and H. von Storch, 1996: Statistical downscaling of monthly mean North Atlantic air-pressure to sea-level anomalies in the Baltic Sea. *Tellus*, **48A**, 312–323.

Heyen, H., H. Fock and W. Greve, 1998: Detecting relationships between the interannual variability in ecological time series and climate using a multivariate statistical approach - a case study on Helgoland Roads zooplankton. *Clim. Res.,* **10**, 179–191.

Hirakuchi, H., Giorgi, F., 1995: Multiyear present-day and $2 \times CO_2$ simulations of monsoon climate over eastern Asia and Japan with a regional climate model nested in a general circulation model. *J. Geophys. Res.*, **100**, 21105–21125.

HIRETYCS, 1998. Final report of the HIRECTYCS project, European Commission Climate and Environment Programme, Brussels.

Holland, G.J., 1997: The maximum potential intensity of tropical cyclones. *J. Atmos. Sci.* **54**, 2519-2541.

Hong, S.-Y., and H. - M. H. Juang, 1998: Orography blending in the lateral boundary of a regional model, *Mon. Wea. Rev.*, **126**, 1714-1718.

Hong, S.Y. and A. Leetmaa, 1999: An evaluation of the NCEP RCM for Regional Climate Modeling. *J. Climate*, **12**, 592-609.

Hostetler, S.W., F. Giorgi, G.T. Bates and P.J. Bartlein, 1994: Lake-atmosphere feedbacks associated with paleolakes Bonneville and Lahontan. *Science*, **263**, 665–668.

Hostetler, S.W., P.J. Bartlein, P.U. Clark, E.E. Small and A.M. Solomon, 2000: Simulated influence of Lake Agassiz on the climate of Central North America 11,000 years ago. *Nature*, **405**, 334-337.

Hughes, J. P., D.P. Lettenmaier, and P. Guttorp, 1993: A stochastic approach for assessing the effect of changes in synoptic circulation patterns on gauge precipitation. *Water Resour. Res.*, **29** (10), 3303–3315.

Hughes, J.P., P. Guttorpi and S.P. Charles, 1999: A non-homogeneous hidden Markov model for precipitation occurrence. *Appl. Statist.*, **48**, 15–30.

Hulme, M. and O. Brown, 1998: Portraying climate scenario uncertainties in relation to tolerable regional climate change. *Clim. Res.,* **10**, 1–14.

Hulme, M., E.M. Barrow, N. Arnell, P.A. Harrison, T.E. Downing and T.C. Johns, 1999: Relative impacts of human-induced climate change and natural climate variability. *Nature*, **397**, 688–691.

Hulme, M., J. Crossley, D. Lister, K.R. Briffa and P.D. Jones, 2000: Climate observations and GCM validation Interim Annual Report to the Department of the Environment, Transport and the Regions, April 1999 to March 2000, CRU, Norwich, UK.

Huth, R., 1997: Continental-scale circulation in the UKHI GCM. *J. Climate*, **10**, 1545–1561.

Huth, R., 1999: Statistical downscaling in central Europe: Evaluation of methods and potential predictors. *Clim. Res.*, **13**, 91-101.

IPCC, 1990: Climate Change: The IPCC Scientific Assessment. [J.T. Houghton , G.J. Jenkins and J.J. Ephraums, (Eds.)], Cambridge University Press, Cambridge, 365 pp.

IPCC, 1996:Climate change 1995: The Science of Climate Change. Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change [J.T. Houghton, L.G. Meira Filho, B.A. Callander, N. Harris, A. Kattenberg and K Maskell (eds.)], Cambridge University Press, Cambridge, 572 pp.

Jacob, D. and R. Podzun, 1997: Sensitivity study with the Regional Climate Model REMO, *Meteorol. Atmos. Phys.*, **63**, 119-129.

Jacob, D. and R. Podzun, 2000: In: Research Activities in Atmospheric and Oceanic Modelling. (CAS/JSC Working Group on Numerical Experimentation Report) [Geneva]: WMO, February 2000, **30**, 7.10-7.11

Jacob, D., R. Podzun, M. Lal and U. Cubasch, 1995: Summer monsoon climatology as simulated in a regional climate model nested in a genearl circulation model, Third Int. Conference on Modelling of Global Climate Change and Variability, Hamburg, Germany, 4-8 September 1995.

Jacobeit, J., 1996: Atmospheric circulation changes due to increased greenhouse warming and its impact on seasonal rainfall in the Mediterranean area. In: Climate Variability and Climate Change - Vulnerability and Adaptation, I. Nemesová (Ed.), Proceedings, Prague, Czech Republic, September 11-15, 1995, 71–80

Jacobeit, J. C. Beck and A. Philipp, 1998 : Annual to decadal variability in climate in Europe - objectives and results of the German contribution to the European climate research project ADVICE. - Würzburger Geographische Manuskripte 43, 163 pp.

Jenkins, G. S., 1997: The 1988 and 1990 summer season simulations for West Africa. *J. Climate*, **10**, 51255–1272.

Jenkins, G. S. and E.J. Barron, 1997: Global climate model and coupled regional climate model. *Global Planet. Change*, **15**, 3–32.

Ji, Y. and A.D. Vernekar, 1997: Simulation of the Asian summer monsoons of 1987 and 1988 with a regional model nested in a global GCM. *J. Climate*, **10**, 1965–1979.

Jóhannesson, T., T. Jónsson, E. Källén and E. Kaas, 1995: Climate change scenarios for the Nordic countries. *Clim. Res.*, **5**: 181–195.

Johns, T.C. , 1999: Initial assessment of global response to greenhouse gas increases in a high resolution atmospheric timeslice experiment compared to the HadCM3 coupled model. DETR report, March 1999, Hadley Centre for Climate Prediction and Research, London Road, Bracknell, UK.

Jones, J.M. and T.D. Davies, 2000: Investigation of the climatic influence of air and precipitation chemistry over Europe, and applications to a downscaling methodology to assess future acidic deposition. *Clim. Res*. **14**, 7-24.

Jones, R.G., 1999: The response of European climate to increased greenhouse gases simulated by standard and high resolution GCMs. DETR report, March 1999, Hadley Centre for Climate Prediction and Research, London Road, Bracknell, UK.

Jones, R.G., D. Hassel and K. Ward, 1999: First results from the Hadley Centre's new regional climate model including effects of enhanced resolution. DETR report, March 1999, Hadley Centre for Climate Prediction and Research, London Road, Bracknell, UK.

Jones, R.G., J.M. Murphy and M. Noguer, 1995: Simulations of climate change over Europe using a nested regional climate model. I: Assessment of control climate, including sensitivity to location of lateral boundaries. *Quart. J. R. Met. Soc.*, **121**, 1413–1449.

Jones, R.G., J.M. Murphy, M. Noguer and A.B. Keen, 1997: Simulation of climate change over Europe using a nested regional climate model. II: Comparison of driving and regional model responses to a doubling of carbon dioxide. *Quart. J. R.. Met. Soc.*, **123**, 265–292.

Jones, R.N., K.J. Hennessy, C.M. Page, A.B. Pittock, R. Suppiah, K.J.E.

Walsh and P.H. Whetton, 2000: An analysis of the effects of the Kyoto protocol on Pacific Island countries, part Two: Regional climate change scenarios and risk assessment methods. CSIRO/SPREP, in press.

Joubert, A.M. and P.D. Tyson, 1996: Equilibrium and fully coupled GCM simulations of future Southern African climates. *South African Journal of Science,* **92,** 471–484.

Joubert, A.M., S.J. Mason and J.S. Galpin, 1996: Droughts over southern Africa in a doubled-CO_2 climate. *Int. J. Climatology*, **16**, 1149-1156.

Joubert, A., J.J. Katzfey and J. McGregor, 1998: Int. Conference on The Role of Topography in Modelling Weather and Climate. Int. Centre for Theoretical Physics, Trieste, Italy, 22-26 June 1998.

Joubert, A.M., J.J. Katzfey, J.L. McGregor, and K.C. Nguyen, 1999: Simulating mid-summer climate over Southern Africa using a nested regional climate model. *J. Geophys. Res.,* **104**, 19015-19025.

Kaas, E., T.-S. Li and T. Schmith, 1996: Statistical hindcast of wind climatology in the North Atlantic and Northwestern European region. *Clim. Res*., **7**, 97–110.

Kalnay, E., M. Kanamitsu, R. Kistler, W. Collins, D. Deaven, L. Gandin, M. Iredell, S. Saha, G. White, J. Woollen, Y. Zhu, M. Chelliah, W. Ebisuzaki, W. Higgins, J. Janowiak, K.C. Mo, C. Ropelewski, J. Wang, A. Leetmaa, R. Reynolds, R. Jenne and D. Joseph, 1996: The NCEP/NCAR 40-Year Reanalysis Project. *Bull. Am. Met. Soc*., **77**, 437–471.

Karl, T.R., W.C. Wang, M.E. Schlesinger, R.W. Knight, D. Portman, 1990: A method of relating general circulation model simulated climate to observed local climate. Part I: Seasonal statistics. *J. Climate,* **3**, 1053-1079.

Kattenberg, A, F. Giorgi, H. Grassl, G. A. Meehl, J. F. B. Mitchell, R. J. Stouffer, T. Tokioka, A. J. Weaver, T. M. L. Wigley, 1996. Climate Models – Projections of Future Climate. In : *Climate Change 1995: The Science of Climate Changs. Contribution of Working Group I to the Second Assessment Report of the IPCC*. [Houghton, J.T., Meira Filho, L.G., Callander, B.A., Harris, N., Kattenberg, A. and Varney, S. K. (eds.)]. Cambridge University Press, Cambridge, 285-357.

Kato, H., H. Hirakuchi, K. Nishizawa, and F. Giorgi, 1999: Performance of the NCAR RegCM in the simulations of June and January climates over eastern Asia and the high-resolution effect of the model, *J. Geophys. Res*., **104**, 6455-6476.

Kato, H., K. Nishizawa, H. Hirakuchi, S. Kadokura, N. Oshima and F. Giorgi. 2001: Performance of the RegCM2.5/NCAR-CSM nested system for the simulation of climate change in East Asia caused by global warming. *J. Met. Soc. Japan* (in press*).*

Katz, R. W. and M. B. Parlange, 1993: Effects of an index of atmospheric circulation on stochastic properties of precipitation. *Water Resour. Res.,* **29,** 2335–2344.

Katz, R.W. and M.B. Parlange, 1995: Generalizations of chain-dependent processes: Application to hourly precipitation. *Water Resour. Res.*, **31**, 1331-1341.

Katz, R.W. and M. B. Parlange, 1996: Mixtures of stochastic processes: applications to statistical downscaling. *Clim. Res*., **7**, 185–193.

Katzfey, J.J., 1999: Storm tracks in regional climate simulations: Verification and changes with doubled CO_2. *Tellus*, **51A**, 803-814.

Katzfey, J.J. and K.L. McInnes, 1996: GCM simulations of eastern Australian cutoff lows. *J. Climate*, **9**, 2337–2355.

Katzfey, J.J., J. McGregor and P.H. Whetton, 1998: Int. Conference on The Role of Topography in Modelling Weather and Climate. Int. Centre for Theoretical Physics, Trieste, Italy, 22-26 June 1998.

Kauker, F.,1998: Regionalization of climate model results for the North sea. PhD thesis University of Hamburg, 109 pp.

Kharin, V.V. and F.W. Zwiers, 2000: Changes in the extremes in an ensemble of transient climate simulations with a coupled atmosphere-ocean GCM. *J. Climate*, **13**, 3760-3788.

Kida, H., T. Koide, H. Sasaki and M. Chiba, 1991: A new approach to coupling a limited area model with a GCM for regional climate simulations. *J. Met. Soc. Japan*., **69**, 723-728.

Kidson, J. W. and I.G. Watterson, 1995: A synoptic climatological evaluation of the changes in the CSIRO nine-level model with doubled CO_2 in the New Zealand region. *Int. J. Climatology.*, **15**, 1179–1194.

Kidson, J.W. and C.S. Thompson, 1998: Comparison of statistical and model-based downscaling techniques for estimating local climate variations. *J. Climate*, **11**, 735–753.

Kilsby, C.G., P.S.P. Cowpertwait, P.E. O'Connell and P.D. Jones, 1998: Predicting rainfall statistics in England and Wales using atmospheric circulation variables. *Int. J. Climatology*, **18**, 523-539.

Kim, J., 1997: Precipitation and snow budget over the southwestern United States during the 1994-1995 winter season in a mesoscale model simulation. *Water. Resour. Res*., **33**, 2831-2839.

Kim, J., N.L. Miller, A.K. Guetter and K.P. Georgakakos, 1998: River flow response to precipitation and snow budget in California during the 1994-95 winter. *J. Climate*, **11**, 2376–2386.

Kittel, T.G.F., F. Giorgi and G.A. Meehl, 1998: Intercomparison of region al biases and doubled CO_2-sensitivity of coupled atmospheric-ocean general circulation model experiments. *Clim. Dyn*., **14**, 1–15.

Klein, W.H. and H.R. Glahn, 1974: Forecasting local weather by means of model output statistics, *Bull. Amer. Met. Soc.*, **55**, 1217-1227.

Knutson, T.R. and R.E. Tuleya, 1999: Increased hurricane intensities with CO_2-induced warmings as simulated using the GFDL hurricane prediction system. *Clim. Dyn*., **15**, 503-519.

Knutson, T.R., R.E. Tuleya and Y. Kurihara, 1998: Simulated increase of hurricane intensities in a CO_2-warmed world. *Science*, **279**, 1018–1020.

Knutson, T.R., R.E. Tuleya, W. Shen and I. Ginis, 2000: Impact of CO_2-induced warming on hurricane intensities as simulated in a hurricane model with ocean coupling. *J. Climate*, **14**, 2458-2468.

Kothavala, Z., 1997: Extreme precipitation events and the applicability of global climate models to study floods and droughts. *Math. and Comp. in Simulation*, **43**, 261-268.

Krinner G, C. Genthon, Z.-X. Li and P. Le Van, 1997: Studies of the Antarctic climate with a stretched grid GCM, *J. Geophys. Res.,* **102**, 13731-13745.

Krinner G. and C. Genthon, 1998: GCM simulations of the Last Glacial Maximum surface climate of Greenland and Antarctica, *Clim. Dyn.,* **14**, 741-758.

Krishnamurti, T.N., R. Correa-Torres, M. Latif and G. Daughenbaugh, 1998: The impact of current and posssssibly future sea surface temper-ature anomalies on the frequency of Atlantic hurricanes. *Tellus*, **50A,** 186-210.

Kröncke, I., J.W. Dippner, H. Heyen and B. Zeiss, 1998: Long-term changes in macrofauna communities off Norderney (East Frisia, Germany) in relation to climate variability. *Mar. Ecol. Prog. Series,* **167**, 25–36.

Labraga, L.C. and M. Lopez, 1997: A comparison of the climate response to increased carbon dioxide simulated by general circulation models with mixed-layer and dynamic ocean representations in the region of South America. *Int. J. Climatology*, **17**, 1635–1650.

Lal, M., U. Cubasch, J. Perlwitz and J. Waszkewitz, 1997: Simulation of the Indian monsoon climatology in ECHAM3 climate model: sensitivity to horizontal resolution. *Int. J. Climatology,* **17**, 847-858.

Lal M., G.A. Meehl and J.M. Arblaster, 2000: Simulation of Indian summer monsoon rainfall and its intraseasonal variability in the NCAR climate system model. *J. Climate,* in press.

Lal, M., P.H. Whetton, A.B. Pittock, and B. Chakraborty, 1998a: Simulation of present-day climate over the Indian subcontinent by general circulation models. *Terrestrial Atmospheric and Oceanic Sciences*, **9**, 69–96.

Lal, M., P.H. Whetton, A.B. Pittock, and B. Chakraborty, 1998b: The greenhouse gas-induced climate change over the Indian subcontinent

as projected by general circulation model experiments. *Terrestrial Atmospheric and Oceanic Sciences*, **9**, 673–690.

Lamb, H.H., 1972: British Isles weather types and a register of daily sequence of circulation patterns, 1861–1971. Geophysical Memoir 116, HMSO, London, 85 pp.

Landsea, C.W., 1997: Comments on "Will greenhouse gas induced warming over the next 50 years lead to higher frequency and greater intensity of hurricanes?", *Tellus*, **49A**, 622–623.

Langenberg, H, A. Pfizenmayer, H. von Storch and J. Sndermann, 1999: Storm related sea level variations along the North Sea coast: natural variability and anthropogenic change. *Cont. Shelf Res.* **19**, 821–842.

Laprise R., D. Caya, M. Giguère, G. Bergeron, H. Côte, J.-P. Blanchet, G.J. Boer and N.A. McFarlane, 1998: Climate and climate change in western Canada as simulated by the Canadian regional climate model. *Atmosphere-Ocean*, **36**, 119–167.

Lettenmaier, D., 1995: Stochastic Modeling of precipitation with applications to climate model downscaling. In: H. von Storch and A. Navarra (eds) "Analysis of Climate Variability: Applications of Statistical Techniques", Springer Verlag, 197–212 (ISBN 3-540-58918-X).

Leung, L.R. and S.J. Ghan, 1995: A subgrid parameterization of orographic precipitation. *Theor. Appl. Climatol.*, **52**, 95-118.

Leung, L.R. and S.J. Ghan, 1998: Parameterizing subgrid orographic precipitation and surface cover in climate models. *Mon. Wea. Rev.*, **126**, 3271-3291.

Leung, L.R. and S.J. Ghan, 1999a: Pacific Northwest climate sensitivity simulated by a regional climate model driven by a GCM. Part I: control simulations. *J. Climate*, **12**, 2010-2030.

Leung, L.R. and S.J. Ghan, 1999b: Pacific Northwest climate sensitivity simulated by a regional climate model driven by a GCM. Part II: $2 \times CO_2$ simulations. *J. Climate*, **12**, 2031-2053.

Leung, L.R., Wigmosta, M. S., Ghan, S.J., Epstein, D.J., Vail, L.W., 1996: Application of a subgrid orographic precipitation/surface hydrology scheme to a mountain watershed. *J. Geophys. Res.*, **101**, 12803–12817.

Leung, L.R., S.J. Ghan, Z.C. Zhao, Y. Luo, W.-C. Wang, and H.-L. Wei, 1999a: Intercomparison of regional climate simulations of the 1991 summer monsoon in eastern Asia. *J. Geophys. Res.*, 104, 6425–6454.

Leung, L.R., A.F. Hamlet, D.P. Lettenmaier and A. Kumar, 1999b: Simulations of the ENSO hydroclimate signals in the Pacific Northwest Columbia River Basin. *Bull. Am. Met. Soc.*, **80**(11), 2313-2329.

Liston, G.E. and R.A. Pielke, 2000: A climate version of the regional atmospheric modeling system. *Theor.l Appl. Climatol.*, **66**, 29-47..

Liston, G.E., R.A. Pielke, Sr., and E.M. Greene, 1999: Improving first-order snow-related deficiencies in a regional climate model. *J. Geophysical Res.*, **104** (D16), 19559-19567.

Luterbacher, J., C. Schmutz, D. Gyalistras, E. Xoplaki and H. Wanner, 1999: Reconstruction of monthly NAO and EU indices back to AD 1675. *Geophys. Res. Lett.,* **26**, 2745-2748.

Lüthi, D., A. Cress, H.C. Davies, C. Frei and C. Schär, 1996: Interannual variability and regional climate simulations. *Theor. Appl. Climatol.*, **53**, 185–209.

Lynch, A. H., W.L. Chapman, J.E. Walsh. and G. Weller, 1995: Development of a regional climate model of the western Arctic. *J. Climate*, **8**, 1555–1570.

Lynch, A.H., M.F. Glück, W.L. Chapman, D.A. Bailey,= and J.E. Walsh, 1997a: Remote sensing and climate modeling of the St. Lawrence Is. Polynya, *Tellus*, **49A**, 277-297.

Lynch, A.H., D.L. McGinnis, W.L. Chapman and J.S. Tilley, 1997b: A Multivariate comparison of two land surface models integrated into an Arctic regional climate system model. *Ann. Glaciol.*, **25**, 127-131.

Lynch, A.H., D.L. McGinnis, and D.A. Bailey, 1998: Snow-albedo feedback and the spring transition in a regional climate system model: Influence of land surface model, *J. Geophys. Res.*, **103**,

29037-29049.

Maak, K. and H. von Storch, 1997: Statistical downscaling of monthly mean temperature to the beginning of flowering of Galanthus nivalis L. in Northern Germany. *Int. J. Biometeor.*, **41**, 5–12.

Mabuchi, K., Y. Sato and H. Kida, 2000: Numerical study of the relationships between climate and the carbon dioxide cycle on a regional scale. *J. Met. Soc. Japan,* **78**, 25-46.

Machenhauer, B., M. Windelband, M. Botzet, R. Jones and M. Déqué, 1996: Validation of present-day regional climate simulations over Europe: Nested LAM and variable resolution global model simulations with observed or mixed layer ocean boundary conditions. MPI Reprot No. 191, MPI, Hamburg, Germany.

Machenhauer, B., M. Windelband, M. Botzet, J.H. Christensen, M. Deque, R. Jones, P.M. Ruti and G. Visconti, 1998: Validation and analysis of regional present-day climate and climate change simulations over Europe. MPI Report No.275, MPI, Hamburg, Germany.

Marinucci, M. R. and F. Giorgi, 1992: A $2 \times CO_2$ climate change scenario over Europe generated using a limited area model nested in a general circulation model 1. Present-day seasonal climate simulation. *J. Geophys. Res.*, **97**, 9989–10009.

Marinucci, M. R., F. Giorgi, M. Beniston, M. Wild, P. Tschuck, A. Ohmura and A. Bernasconi, 1995: High resolution simulations of January and July climate over the western alpine region with a nested regional modeling system. *Theor. Appl. Climatol.*, **51**, 119–138.

Martin, E., B. Timbal and E. Brun, 1997: Downscaling of general circulation model outputs: simulation of the snow climatology of the French Alps and sensitivity to climate change. *Clim. Dyn.*, **13**, 45–56.

Martin, G.M., 1999: The simulation of the Asian summer monsoon, and its sensitivity to horizontal resolution, in the UK Meteorological Office Unified Model. *Quart. J. R. Met. Soc.*, **125**, 1499-1525.

Maslanik, J.A., A.H. Lynch and M. Serreze, 2000: A case study simulation of Arctic regional climate in a coupled model. *J. Climate*. **13**, 383-401.

May, W., 1999: A time-slice experiment with the ECHAM4 AGCM at high resolution: The experimental design and the assessment of climate change as compared to a greenhouse gas experiment with ECHAM4/OPYC at low resolution, DMI Scientific Report 99-2, DMI, Copenhagen.

May, W. and E. Roeckner, 2001: A time-slice experiment with the ECHAM4 AGCM at high resolution: The impact of resolution on the assessment of anthropogenic climate change, *Clim. Dyn.*,(in press*).*

McDonald, R. 1999: Changes in tropical cyclones as greenhouse gases are increased. PMSR report, March 1999, Hadley Centre for Climate Prediction and Research, London Road, Bracknell, UK.

McGregor, J.L., 1997: Regional climate modelling. *Meteorology and Atmospheric Physics*. **63**,105-117.

McGregor, J.L., J.J. Katzfey and K.C. Nguyen, 1995: Seasonally-varying nested climate simulations over the Australian region, Third Int. Conference on Modelling of Global Climate Change and Variability, Hamburg, Germany, 4-8 September 1995.

McGregor, J.L., J.J. Katzfey and K.C. Nguyen, 1998: Fine resolution simulations of climate change for southeast Asia. Final report for a Research Project commissioned by Southeast Asian Regional Committee for START (SARCS), Aspendale, Vic.: CSIRO Atmospheric Research. VI, 15, 35pp.

McGregor, J.L., J.J. Katzfey and K.C. Nguyen, 1999: Recent regional climate modelling experiments at CSIRO. In: Research Activities in Atmospheric and Oceanic Modelling. H. Ritchie (ed). (CAS/JSC Working Group on Numerical Experimentation Report; 28; WMO/TD – no. 942) [Geneva]: WMO. P. 7.37–7.38.

McGregor, J.L., K. Walsh, 1993: Nested simulations of perpetual January climate over the Australian region. *J. Geophys. Res.*, **98**, 23283–23290.

McGregor, J. L., K. Walsh, 1994: Climate change simulations of Tasmanian precipitation using multiple nesting. *J. Geophys. Res.*, **99**,

20889–20905.

McGuffie, K., A. Henderson-Sellers, N. Holbrook, Z. Kothavala, O. Balachova and J. Hoekstra, 1999: Assessing simulations of daily temperature and precipitation variability with global climate models for present and enhanced greenhouse conditions, *Int. J. Climatol.* **19**, 1–26.

Mearns, L.O., I. Bogardi, F. Giorgi, I. Matayasovszky and M. Palecki, 1999: Comparison of climate change scenarios generated daily temperature and precipitation from regional climate model experiments and statistical downscaling, *J. Geophys. Res.*, **104**, 6603–6621.

Mearns, L. O., 1999: The effect of spatial and temporal resolution of climate change scenarios on changes in frequencies of temperature and precipitation extremes. In: S. Hassol and J. Katzenberger, Elements of Change 1998, Session 2: Climate Extremes: Changes, Impacts, and Projections. Aspen: Aspen Global Change Institute, 316-323.

Mietus M., 1999. The role of regional atmospheric circulation over Europe and North Atlantic in formation of climatic and oceanographic condition in the Polish coastal zone, Research Materials of Institute of Meteorology and Water Management, Meteorological Series, 29, 147pp (in Polish with English summary).

Miller, N.L. and J. Kim, 1997: The Regional Climate System Model. In: 'Mission Earth: Modeling and simulation for a sustainable global system', M.G. Clymer and C.R. Mechoso (eds.), Society for Computer Simulation International, 55-60.

Murphy, J.M., 1999: An evaluation of statistical and dynamical techniques for downscaling local climate. *J. Climate*, **12**, 2256-2284.

Murphy, J.M., 2000: Predictions of climate change over Europe using statistical and dynamical downscaling techniques. *Int. J. Climatology.*, **20**, 489-501.

New, M., M. Hulme, and P. Jones, 1999: Representing Twentieth-century space-time climate variability. Part 1: development of a 1961-1990 mean monthly terrestrial climatology. *J. Climate*, **12**, 829–856.

New, M., M. Hulme, and P. Jones, 2000: Representing Twentieth-century space-time climate variability. Part 2: development of a 1901-1996 mean monthly terrestrial climatology. *J. Climate*, **13**, 2217-2238.

Noguer, M., 1994: Using statistical techniques to deduce local climate distributions. An application for model validation. *Met. Apps.*, **1**, 277–287.

Noguer M., R.G. Jones and J.M. Murphy, 1998: Sources of systematic errors in the climatology of a nested regional climate model (RCM) over Europe. *Clim. Dyn.*, **14**, 691–712.

O'Connell, P. E. 1999: Producing rainfall scenarios for hydrologic impact modelling. In: G. Kiely et al., (editors). Abstract Volume from the EU Environmental and Climate Programme Advanced Study Course on European Water Resources and Climate Change Processes, 53pp.

Osborn, T.J. and M. Hulme, 1997: Development of a relationship between station and grid-box rain-day frequencies for climate model evaluation. *J. Climate,* **10**, 1885–1908.

Osborn, T.J. and M. Hulme, 1998: Evaluation of the European daily precipitation characteristics from the Atmospheric Model Intercomparison Project, *Int. J. Climatology,* **18**, 505–522.

Osborn,T.J., D. Conway, M. Hulme, J.M. Gregory and P.D. Jones, 1999: Air flow influences on local climate: observed and simulated mean relationships for the UK. *Clim. Res.*, **13**, 173-191.

Palutikof, J.P., J.A. Winkler, C.M. Goodess and J.A. Andresen, 1997: The simulation of daily temperature time series from GCM output. Part 1: Comparison of model data with observations, *J. Climate*, **10**, 2497–2513.

Pan, Z., E. S. Takle, M. Segal and R. Arritt, 1999: Simulation of potential impacts of man-made land use changes on U.S. summer climate under various synoptic regimes, *J. Geophys. Res.*, **104**, 6515-6528.

Pan, Z., J.H. Christensen, R.W. Arritt., W.J. Gutowski, E.S. Takle and F. Otieno, 2000: Evaluation of uncertainties in regional climate change simulations. *J. Geophys, Res.,* in press.

Parlange, M.B. and R.W. Katz, 2000: An extended version of the Richardson model for simulationg daily weather variables. *J. Appl. Meteorol.*, **39**, 610-622.

Perica, S. and E. Foufoula-Georgiou, 1996a: Linkage of scaling and thermodynamic parameters of rainfall: Results from midlatitude mesoscale convective systems, *J. Geophys. Res.*, **101**, 7431-7448.

Perica, S. and E. Foufoula-Georgiou, 1996b: Model for multiscale dissaggregation of spatial rainfall based on coupling meteorological and scaling descriptions, *J. Geophys. Res.*, **101(D21)**, 26347-26361.

Pielke, R.A., Jr., and C.W. Landsea, 1998: Normalized hurricane damages in the United States: 1925-95. *Weath. Forecast.*, **13**, 621-631.

Pielke, R.A., Sr., W.R. Cotton, R.L. Walko, C.J. Tremback, W.A. Lyons, L.D. Grasso, M.E. Nicholls, M.D. Moran, D.A. Wesley, T.J. Lee and J.H. Copeland, 1992: A comprehensive meteorological modeling system—RAMS, *Meteor. Atmos. Phys.*, **49**, 69-91.

Pielke, R.A., Sr., R.L. Walko, L. Steyaert, P.L. Vidale, G.E. Liston and W.A. Lyons, 1999: The influence of anthropogenic landscape changes on weather in south Florida. *Mon. Wea. Rev.*, **127**, 1663-1673.

Pittock, A.B., M.R. Dix, K.J. Hennessy, D.R. Jackett, J.J. Katzfey, T.J. McDougall, K.L. McInnes, S.P. O'Farrell, I.N. Smith, R. Suppiah, K.J.E. Walsh, P.H. Whetton and S.G. Wilson, 1995: Progress towards climate change scenario and impact studies for the southwest Pacific. In: The science and impacts of climate change in the Pacific islands, Apia, Western Samoa. Apia, Western Samoa: Conference on the Science and Impacts of Climate Change in the Pacific Islands. 15-2, 21-46.

Podzun, R., A. Cress, D. Majewski and V. Renner, 1995: Simulation of European climate with a limited area model. Part II: AGCM boundary conditions. *Contrib. Atmos. Phys.*, **68**, 205–225.

Qian, Y. and F. Giorgi, 1999: Interactive coupling of regional climate and sulfate aerosol models over East Asia. *J. Geophys. Res.*, **104**, 6501–6514.

Raab, B. and H. Vedin (Eds.), 1995: Climate, Lakes and Rivers: National Atlas for Sweden. SNA Publishing, 176pp and 198 plates.

Racksko, P., L. Szeidl and M. Semenov, 1991: A serial approach to local stochastic weather models. *Ecological Modeling,* **57**, 27–41.

Räisänen, J., 1998: Intercomparison studies of general circulation model simulations of anthropogenic climate change. Academic dissertation presented at the Faculty of Science, Department of Metererology, Report 57, University of Helsinki, 50pp.

Räisänen, J., M. Rummukainen, A. Ullerstig, B. Bringfelt, U. Hansson and U. Willén, 1999: The first Rossby Centre regional climate scenario - dynamical downscaling of CO_2-induced climate change in the HadCM2 GCM. SMHI Reports Meteorology and Climatology No. 85, 56 pp. Swedish Meteorological and Hydrological Institute, SE-601 76 Norrköping, Sweden.

Reichert, B.K., L. Bengtsson and Ove Åkesson, 1999: A statistical modeling approach for the simulation of local paleoclimatic proxy records using GCM output. *J. Geophys. Res.* **104**(D16), 19071–19083.

Renwick, J. A., J.J. Katzfey, K.C. Nguyen and J.L. McGregor, 1998: Regional model simulations of New Zealand climate. *J. Geophys. Res.*, **103**, 5973–5982.

Richardson, C.W., 1981: Stochastic simulation of daily precipitation, temperature, and solar radiation. *Water Resour. Res.*, **17**(1),182–190.

Riedo, M., D. Gyalistras, A Fischlin and J. Fuhrer, 1999: Using an ecosystem model linked to GCM derived local weather scenarios to analyse effects of climate change and elevated CO_2 on dry matter production and partitioning, and water use in temperate managed graslands. *Global Change Biol.*, **5**, 213–223.

Rinke A. and K. Dethloff, 1999: Sensitivity studies concerning initial and boundary conditions in a regional climate model of the Arctic, *Clim.*

Res., **14**, 101-113.

Rinke, A., K. Dethloff and J.H. Christensen, 1999: Arctic winter climate and its interannual variations simulated by a regional climate model. *J. Geophys. Res.*, **104**, 19027–19038.

Risbey, J. and P. Stone, 1996: A case study of the adequacy of GCM simulations for input to regional climate change assessments. *J. Climate*, **9**, 1441–1467.

Roebber, P.J. and L.F. Bosart, 1998: The sensitivity of precipitation to circulation details. Part I: An analysis of regional analogs. *Mon. Wea. Rev.*, **126**, 437–455.

Roldan, J. and D.A. Woolhiser, 1982, Stochastic daily precipitation models. 1. A comparison of occurrence processes. *Water Resour. Res.*, **18**, 1451-1459.

Rotach, M.W., M.R.M. Marinucci, M. Wild, P. Tschuck, A. Ohmura, M. Beniston, 1997: Nested regional simulation of climate change over the Alps for the scenario of doubled greenhouse forcing. *Theor. Appl. Climatol.*, **57**, 209–227.

Royer, J.-F., F. Chauvin, B. Timbal, P. Araspin and D. Grimal, 1998: A GCM study of the impact of greenhouse gas increase on the frequency of occurrence of tropical cyclones. *Clim. Change*, **38**, 307-343.

Rummukainen, M., 1997: Methods for statistical downscaling of GCM simulations, RMK No 80, Swedish Meteorological and Hydrological Institute, Norrköping, Sweden.

Rummukainen, M., J. Räisänen, B. Bringfelt, A. Ullerstig, A. Omstedt, U. Willen, U. Hansson and C. Jones, 2000: RCA1 Regional Climate Model for the Nordic Region – Model Description and Results from the Control Run Downscaling of Two GCMs. *Clim. Dyn.*, (in press).

Ruti P.M., C. Cacciamani, T. Paccagnella, A. Bargagli and C. Cassardo, 1998: LAM multi-seasonal numerical integrations: performance analysis with different surface schemes. *Contrib. Atmos. Phys.*, **71**, 321–346.

SAR, see IPCC (1996a).

Sailor, D.J. and X. Li, 1999: A semiempirical downscaling approach for predicting regional temperature impacts associated with climatic change. *J. Climate,* **12**, 103–114.

Schär C., C. Frei, D. Lüthi and H.C. Davies, 1996: Surrogate climate change scenarios for regional climate models. *Geophys. Res. Lett.*, **23**, 669–672.

Schnur, R., and D. Lettenmaier, 1998: A case study of statistical downsc-scaling in Australia using weather classification by recursive partitioning. *J. Hydrol.*, **212**–123, 362–379.

Schubert, S. 1998: Downscaling local extreme temperature changes in south-eastern Australia from the CSIRO Mark2 GCM. *Int. J. Climatol.*, **18**, 1419–1438.

Schubert, S. and A. Henderson-Sellers, 1997: A statistical model to downscale local daily temperature extremes from synoptic-scale atmospheric circulation patterns in the Australian region. *Clim. Dyn.*, **13**, 223-234.

Semenov, M.A. and E.M. Barrow, 1997: Use of a stochastic weather generator in the development of climate change scenarios. *Clim. Change*, **35**, 397–414.

Sept, V., 1998: Untersuchungen der Gewitteraktivitt im sddeustchen Raum mitteln statistisch-dynamischer Regionalisierung. Deutsches Zentrum für Luft- und Raumfahrt e.V., Forschungsbericht 98–27, 113 pp.

Seth, A. and F. Giorgi, 1998: The effects of domain choice on summer precipitation simulation and sensitivity in a regional climate model, *J. Climate*, **11**, 2698–2712.

Small, E.E., F. Giorgi and L.C. Sloan, 1999a: Regional climate model simulation of precipitation in central Asia: Mean and interannual variability. *J. Geophys. Res.*, **104**, 6563–6582.

Small, E.E., L.C. Sloan, S. Hostetler and F. Giorgi, 1999b: Simulating the water balance of the Aral Sea with a coupled regional climate-lake model. *J. Geophys. Res.*, **104**, 6583–6602.

Smith, J. A. and A. F. Karr, 1985: Statistical inference for point process models of rainfall, *Water Resour. Res.*, **21**(1), 73-80.

Solman, S.A. and M.N. Nuñez, 1999: Local estimates of global change: a statistical downscaling approach. *Int. J. Climatology,*. **19**, 835–861.

Starr, V.P., 1942: Basic principles of weather forecasting. Harper Brothers Publishers, New York, London, 299pp.

Stendel, M. and E. Röckner 1998: Impacts of horizontal resolution on simulated climate statistics in ECHAM4. MPI report 253, MPI, Hamburg, Germany.

Stratton, R.A. 1999a: A high resolution AMIP integration using the Hadley Centre model HadAM2b. *Clim. Dyn.*, **15**, 9–28.

Stratton, R.A. 1999b: The impact of increasing resolution on the HadAM3 climate simulation. HCTN 13, Hadley Centre, The Met. Office, Bracknell, UK.

Sun, L., F.H.M. Semazzi, F. Giorgi and L. Ogallo, 1999: Application of the NCAR regional climate model to eastern Africa. 2. Simulations of interannual variability of short rains. *J. Geophys. Res.*, **104**, 6549–6562.

Takle, E.S., W.J. Gutowski, R.W. Arritt, Z. Pan, C.J. Anderson, R.S. da Silva, D. Caya, S.-C. Chen, F. Giorgi, J.H. Christensen, S.-Y. Hong, H.-M. H. Juang, J. Katzfey, W.M. Lapenta, R. Laprise, P. Lopez, G.E. Liston, J. McGregor, A. Pielke and J.O. Roads, 1999: Project to intercompare regional climate simulation (PIRCS)): Description and initial results. *J. Geophys. Res.*, **104**, 19443-19461.

Tett, S.F.B., T.C. Johns and J.F.B. Mitchell, 1997: Global and Regional Variability in a coupled AOGCM. *Clim. Dyn.*, **13**, 303–323.

Timbal, B. and B.J. McAvaney, 1999: A downscaling procedure for Australia. BMRC scientific report 74.

Trigo, R.M. and J.P. Palutikof, 1999: Simulation of daily temperatures for climate change scenarios over Portugal: a neural network model approach. *Clim. Res.* **13**, 61-75.

Tsutsui, J., A. Kasahara and H. Hirakuchi, 1999: The impacts of global warming on tropical cyclones - a numerical experiment with the T42 version of NCAR CCM2. Proceedings of the 23rd Conference on Hurricanes and tropical meteorology, 10-15 January 1999, Dallas, American Meteorological Society, 1077–1080.

Tsutsui, J.-I. and A. Kasahara, 1996: Simulated tropical cyclones using the National Center for Atmospheric Research community climate model. *J. Geophys. Res.*, **101**, 15013–15032.

Tsvetsinskaya, E., L.O. Mearns and W.E. Easterling, 2000: Investigating the effect of seasonal plant growth and development in 3-dimensional atmospheric simulations. *J. Climate*, in press.

van Lipzig, 1999: The surface mass balance of the Antarctic ice sheet, a study with a regional atmospheric model, Ph. D. thesis, Utrecht University, 154 pp.

von Storch, H., 1995: Inconsistencies at the interface of climate impact studies and global climate research. Meteorol. Zeitschrift 4 NF, 72–80.

von Storch, H., 1999a: The global and regional climate system. In: H. von Storch and G. Flöser: Anthropogenic Climate Change, Springer Verlag, ISBN 3-540-65033-4, 3–36.

von Storch., H., 1999b: Representation of conditional random distribu-tions as a problem of "spatial" interpolation. In. J. Gómez-Hernández, A. Soares and R. Froidevaux (Eds.): geoENV II - Geostatistics for Environmental Applications. Kluwer Adacemic Publishers, Dordrecht, Boston, London, ISBN 0-7923-5783-3, 13–23.

von Storch, H., 1999c: On the use of "inflation" in downscaling. *J. Climate,* **12**, 3505-3506.

von Storch, H., H. Langenberg and F. Feser, 2000: A spectral nudging technique for dynamical downscaling purposes, *Mon. Wea. Rev.*, **128**, 3664-3673.

von Storch, H. and H. Reichardt, 1997: A scenario of storm surge statis-tics for the German Bight at the expected time of doubled atmospheric carbon dioxide concentration. *J. Climate,* **10**,

2653–2662.

von Storch, H., E. Zorita and U. Cubasch, 1993: Downscaling of global climate change estimates to regional scales: An application to Iberian rainfall in wintertime. *J. Climate,* **6**, 1161–1171.

von Storch, H., and F.W. Zwiers, 1999: Statistical Analysis in Climate Research, Cambridge University Press, ISBN 0 521 45071 3, 494 pp.

Wallis, T.W.R. and J.F. Griffiths, 1997. Simulated meteorological input for agricultural models. *Agricultural and Forest Meteorology*, **88**, 241-258.

Walsh, K. and J.L McGregor, 1995: January and July climate simulations over the Australian region using a limited area model. *J. Climate*, **8**, 2387–2403.

Walsh, K. and J.L McGregor, 1996: Simulations of Antarctic climate using a limited area model. *J. Geophys. Res.*, **101**, 19093–19108.

Walsh, K. and J.L. McGregor, 1997: An assessment of simulations of climate variability over Australia with a limited area model. *Int. J. Climatology*, **17**, 201–233.

Walsh J.E and J.J. Katzfey, 2000: The impact of climate change on the poleward movement of tropical cyclone-like vortices in a regional model. *J. Climate*, in press.

Walsh J.E. and B.F. Ryan, 2000: Tropical cyclone intensity increase near Australia as a result of climate change. *J. Climate,* **13**, 3029-3036.

Walsh, K. and I.G. Watterson, 1997: Tropical cyclone-like vortices in a limited area model: comparison with observed climatology. *J. Climate*, **10**, 2240-2259.

Wanner, H., R. Rickli, E. Salvisberg, C. Schmutz and M. Schepp, 1997: Global climate change and variability and its influence on Alpine climate - concepts and observations. *Theor. Appl. Climatol.,* **58**, 221–243.

Warner, T. T., R.A. Peterson and R.E. Treadon, 1997: A tutorial on lateral conditions as a basic and potentially serious limitation to regional numerical weather prediction. *Bull. Am. Met.. Soc.*, **78**, 2599-2617.

WASA, 1998: Changing waves and storms in the Northeast Atlantic? *Bull. Am. Met. Soc.* **79**, 741–760.

Watterson, I.G., M.R. Dix, H.B. Gordon and J.L McGregor, 1995: The CSIRO nine-level atmospheric general circulation model and its equilibrium present and doubled CO_2 climate, *Australian Meteorological Magazine*, **44**, 111–125.

Wei, H. and C. Fu, 1998: Study of the sensitivity of a regional model in response to land cover change over Northern China. *Hydrological processes*, **12**, 2249-2265.

Wei, H., Fu, C., Wang, W.-C., 1998: The effect of lateral boundary treatment of regional climate model on the East Asian summer monsoon rainfall simulation. *Chinese J. Atmos. Sci.*, **22**, 231–243.

Weichert, A. and G. Bürger, 1998: Linear versus nonlinear techniques in downscaling. *Clim. Res.*, **10**, 83–93.

Weisse, R., H. Heyen and H. von Storch, 2000: Sensitivity of a regional atmospheric model to a state dependent roughness and the need of ensemble calculations. *Mon. Wea. Rev.*, **128**, 3631-3642.

Werner, P.C. and F.-W. Gerstengarbe, 1997: A proposal for the development of climate scenarios. *Clim. Res.*, **8**, 171-182.

Werner, P.C. and H. von Storch, 1993: Interannual variability of Central European mean temperature in January/February and its relation to the large-scale circulation. *Clim. Res.*, **3**, 195–207**.**

Whetton, P.H., M.H. England, S.P. O'Farrell, I.G. Watterson and A.B. Pittock, 1996a: Global comparison of the regional rainfall results of enhanced greenhouse coupled and mixed layer ocean experiments: implications for climate change scenario development. *Clim. Change*, **33**, 497–519.

Whetton P.H., J.J. Katzfey, K.J. Hennesey, X. Wu, J.L. McGregor and K. Nguyen, 2001: Using regional climate models to develop fine resolution scenarios of climate change: An example for Victoria,

Australia. *Clim. Res*., **16**, 181-201.

Whetton, P. H., A.B. Pittock, J.C. Labraga, A.B. Mullan and A.M. Joubert, 1996b: Southern Hemisphere climate: comparing models with reality. In: Climate change: developing southern hemisphere perspectives. T. W. Giambelluca, and A. Henderson-Sellers (Eds.). (Research and Developments in Climate and Climatology) Chichester: Wiley, 89–130.

Widmann, M. and C. Schär, 1997: A principal component and long-term trend analysis of daily precipitation in Switzerland. *Int. J. Climatology*, **17**, 1333–1356.

Widmann, M. and C.S. Bretherton, 2000: Validation of mesoscale precipitation in the NCEP reanalysis using a new gridcell dataset for the northwestern United States. *J. Climate*, **13**, 1936-1950.

Wilby, R.L., 1998: Statistical downscaling of daily precipitation using daily airflow and seasonal teleconnection indices. *Clim. Res*. **10**:163–178.

Wilby, R.L., H. Hassan and K. Hanaki, 1998a: Statistical downscaling of hydrometeorological variables using general circulation model output. *J. Hydrology*, **205**, 1–19.

Wilby, R.L., T.M.L. Wigley, D. Conway, P.D. Jones, B.C. Hewitson, J. Main and D.S.Wilks, 1998b: Statistical downscaling of general circulation model output: A comparison of methods, *Water Resou. Res.*, **34**, 2995–3008.

Wilby, R.L. and T.M.L. Wigley, 1997: Downscaling general circulation model output: a review of methods and limitations. *Prog. Phys. Geography*, **21**, 530–548.

Wilby, R.L. and Wigley, T.M.L., 2000: Precipitation predictors for downscaling: observed and General Circulation Model relationships. *Int. J. Climatology*, **20**, No. 6, 641-661.

Wilby, R.L., L.E. Hay, W.J. Gutowski, R.W. Arritt, E.S. Takle, Z. Pan, G.H. Leavesley and M.P. Clark, 2000: Hydrological responses to dynamically and statistically downscaled climate model output. *Geophys. Res. Lett*., **27**, No. 8, p1199.

Wild, M., A. Ohmura, H. Gilgen and E. Roeckner, 1995: Regional climate simulation with a high resolution GCM: surface radiative fluxes. *Clim. Dyn*., **11**, 469-486.

Wild, M., L. Dümenil, and J.P. Schulz, 1996: Regional climate simulation with a high resolution GCM: surface hydrology. Climate Dynamics, **12**, 755-774.

Wild M., A. Ohmura and U. Cubasch, 1997: GCM simulated surface energy fluxes in climate change experiments. *J. Climate*, **10**, 3093-3110.

Wilks, D. S., 1999a: Interannual variability and extreme-value characteristics of several stochastic daily precipitation models. *Agric. For. Meteorol*., **93**, 153–169.

Wilks, D., 1999b: Multisite downscaling of daily precipitation with a stochastic weather generator. *Clim. Res.*, **11,** 125–136.

Wilks, D. S. and R. L. Wilby, 1999: The weather generator game: A review of stochastic weather models. *Prog. Phys. Geography*, **23**, 329-358.

Williamson, D.L., 1999: Convergence of atmospheric simulations with increasing horizontal resolution and fixed forcing scales. *Tellus*, **51A**, 663-673.

Winkler, J.A., J.P. Palutikof, J.A. Andresen and C.M. Goodess, 1997: The simulation of daily temperature time series from GCM output: Part II: Sensitivity analysis of an empirical transfer function methodology. *J. Climate,* **10**, 2514–2535.

Yoshimura, J., M. Sugi and A. Noda, 1999: Influence of greenhouse warming on tropical cyclone frequency simulated by a high-resolution AGCM. Proceedings of the 23rd Conference on Hurricanes and tropical meteorology, 10-15 January 1999, Dallas, American Meteorological Society, 1081–1084.

Zorita, E., J. Hughes, D. Lettenmaier, and H. von Storch, 1995: Stochastic characterisation of regional circulation patterns for climate model diagnosis and estimation of local precipitation. *J.*

Climate, **8**, 1023–1042.

Zorita, E., and A. Laine, 1999: Dependence of salinity and oxygen concentrations in the Baltic Sea on the large-scale atmospheric circulation. *Clim. Res.*, **14**, 25-34.

Zorita, E. and H. von Storch, 1997: A survey of statistical downscaling techniques. GKSS report 97/E/20.

Zorita, E. and H. von Storch, 1999: The analog method - a simple statistical downscaling technique: comparison with more complicated methods. *J. Climate*, **12**, 2474-2489.

Zwiers, F.W. and V.V. Kharin, 1997: Changes in the extremes of climate simulated by CCC GCM2 under CO_2 doubling. *J. Climate*, **11**, 2200-2222.