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Regional Climates in GCMs

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1. Introduction

Present generation global climate models (GCMs) are very effective at simulating the larger-scale features of the global climate system--reproducing the major continental scale climatic patterns when averaged on monthly-to-seasonal time frames. However, numerous studies have indicated that these models are less satisfactory for the analysis of short-term variability at regional or local scales; time and space scales that are essential for assessing climatic impacts on human societies (Grotch and MacCracken, 1991; IPCC, 1990).

A critical problem thus exists in moving from the global scale where current GCMs work best, to the regional and local scales (i.e. sub-continental and river basin scales) where climate change predictions are necessary for climate impact assessment. This research addresses these problems of scale translation--assessing the ability of GCMs to simulate synoptic-scale features of the atmospheric circulation, and using this information to derive sub-grid-scale distributions of temperature and precipitation.

The research described in this report represents the results of a one year pilot project, developing concepts and empirical methodologies for downscaling regional-scale climates from GCM simulations. The first four months were essentially devoted to data extraction, data processing, and software development. The remaining time was devoted to GCM validation studies, and the DOE support provided computer resources for a graduate student applying these techniques to an analysis of mountain snowpack in the Upper Colorado Basin.

2. Observed and Modeled Climate Data

2.1 Observational Data

The observational data consist of individual station observations of temperature and precipitation, as well as gridded products from the National Meteorological Center (NMC). The NMC data sets begin in 1976, are global in extent, with a 2.5° spatial resolution. Both data sets contain gridded sea level pressures, surface air temperatures, and geopotential heights.

2.2 The GENESIS Climate Model

GENESIS is described in Pollard and Thompson (1992). The model is a much modified version of the CCM1, developed and made available by Dr. S. Thompson at NCAR. Amongst other modifications, this model includes dynamical sea ice, a land-surface-transfer model, sub-grid plume convection, PBL mixing, a more complex cloud scheme, and a diurnal cycle. The output from the present-day simulations run at Penn State were archived as monthly averages; our analysis requires daily data and our first task was to reprocess the history tapes to derive daily grids. At this point we have produced ten years of daily data for the present-day control run (R15

resolution, mixed layer ocean with parameterized latitudinal ocean heat fluxes), and three years from a doubled CO₂ experiment. We are in the process of extracting the daily data for the AMIP run (present-day simulation driven with 10-years of observed sea surface temperatures).

3. Validation of GCM Synoptic-Scale Circulation

The mean January sea level pressure distributions from the NMC data and the ten year simulation of the GENESIS GCM are shown for the eastern U.S. in Figure 1. The observed and modelled fields show similar patterns, but the model has pressures that are 4mb to 14mb too low; the differences being greater in the north-east than south-west, resulting in pressure gradients that are much steeper in the model. A slightly larger window shows that the Icelandic Low appears to be displaced south and west in the model (being located south of Greenland). The NMC data also show a closed high pressure cell over the eastern U.S. with pressure increasing to the south-west, while the model shows a more zonal distribution with the high pressure cell being elongated east-west and again being displaced to the south. The implication is that the winter circulation is more intense in the model, and that the circulation features are displaced equatorward.

3.1 Spatial Variability

The principal components analysis results in five components for both data sets; there is very close agreement between the components (Table 1, Figure 2). The lowest overall correlations between matching NMC and GENESIS components are between NMC Component One and GENESIS Component Two, and NMC Component Five and GENESIS Component Four. These two pairs of components represent variance in the north-east and south-east parts of the region respectively, and reflect the areas of greatest difference in the mean sea level pressure maps. Note also that all of the matching pairs of components show lower correlations in their north-south gradients. The results show that the patterns of spatial variance are very similar in the two data sets, although the GENESIS patterns do appear to be displaced southward.

3.2 Temporal Variability

Two-dimensional frequency histograms are constructed for each component. One dimension of the histogram represents the frequency distribution of the component scores, the second dimension is the frequency distribution of change from one day to the next. In other words, for every frequency class the histograms show how the scores change the next day. The histograms for each matching pair of components are almost identical, showing that the temporal behavior of the components is also very similar for the modelled and the observed data. As a

Figure 1. Mean January Sea Level Pressure: Observed (left) and GENESIS (right)

GENS: COLA/MOP

GENS: COLA/MOP

GENS: COLA/MOP

GENS: COLA/MOP

GENS: COLA/MOP

GENS: COLA/MOP

Figure 2. NMC (left) and GENESIS (right) Loading Patterns

GRAB: COLA/MOP

GRAB: COLA/MOP

GRAB: COLA/MOP

GRAB: COLA/MOP

Figure 2. Continued

Table 1: Correlation Coefficients Between the NMC and GENESIS Components

Components		Correlation Coefficients			
NMC	GENESIS	average	grid-point to grid- point	north-south gradient	east-west gradient
1	2	0.84	0.97	0.67	0.88
2	1	0.93	0.98	0.87	0.95
3	5	0.94	0.97	0.88	0.97
4	3	0.92	0.97	0.82	0.98
5	4	0.91	0.97	0.83	0.93

further check, the standard deviations of the daily pressure at each grid-point are plotted in Figure 7. The modelled and the observed data are very similar. Both data sets show the same variability, again indicating that the day-to-day variability in the model is very realistic.

3.3 The Synoptic-Scale Circulation of the GENESIS GCM

The analysis shows that the January synoptic-scale circulation of the GENESIS model is very realistic over the eastern United States. The model shows synoptic-scale features that are similar to the observed patterns, and have day-to-day changes that match the observed variability at each grid-point; if the daily pressure maps were presented as daily departures from the January mean, there would be almost no difference between the observed and modelled circulations. However, the GCM features are displaced south by about five degrees, and actual pressures in the model are much lower than observed.

4. Circulation-Precipitation Relationships

4.1 Neural Net-Based Transfer Functions

Transfer functions between the atmospheric circulation and grid-point or station temperature and precipitation are derived using a neural net. The input to the net is a sequence of time-lagged sea level pressure and geopotential heights for the surrounding region; the output is the local temperature or precipitation. In the analyses proposed here, the actual data inputs will be the component scores from the principal components analysis of the sea level pressure and 500mb height fields. Apart from reducing the number of input variables, there is a further advantage in using the components as an index of circulation in that the orthogonality of the inputs is useful later when it comes to analyzing the physical basis of the circulation - temperature/precipitation relationships.

This approach uses a simple feed-forward, back-propagation algorithm (Rummelhart et al., 1986) with a random 75% sample of days used for training the net; the remaining 25% of the days are retained as a test data set. As similar circulation patterns may result from several different sequences of events, and as the relationship between the circulation and local climate is strongly influenced by that sequence of events, then the data are input to the net in a similar lagged sequence. In other words, to predict the temperature on day N_0 , the net uses the circulation from day $N_0, N_{-1}, N_{-2}, \dots, N_{-n}$; the time-lag (n) being determined by experimentation.

An example net configuration is shown in Figure 3. The net is constructed of several layers, where each layer contains one or more individual processing modules (nodes). Data are passed from layer to layer through the net, with each node receiving data from every node in the

Figure 3. Schematic Structure of a Feed-Forward Neural Net.

preceding layer, and passing data to every node in the next layer. Each link in the net carries a weight and each node thus receives a weighted input from the nodes in the previous layer, sums these, and outputs some non-linear function of the summed value to the nodes in the next layer. The network is initialized with random weights and is then trained to represent some relationship between input and output. The training is accomplished using a sample set of input data for which the desired output value is known, and adjusting the weights in an iterative procedure that minimizes the output error. At the end of each iteration (one pass through the training data), the test data are passed through the net and the Root Mean Square Error (RMSE) of the net outputs for the test data calculated. Further iterations of the training procedure are performed, interspersed with calculating the RMSE of the net for the test data, until no further improvement is obtained in the test data RMSE over 30 iterations.

Neural nets can be constructed with any number of nodes and levels; if the net has enough complexity it has the ability to reproduce any arbitrary non-linear function (Cybenko, 1989; Hornick et al., 1990). In the present context, this approach has the advantage of not pre-supposing any particular variance structure, and it is particularly effective at finding the non-linear relationships characteristic of many atmospheric processes.

4.2 Model Validation

The neural net, once it has been trained, embodies a complex non-linear transfer function relating the local climate to the large-scale circulation; the correlation between the observed and predicted outcomes (temperature or precipitation), together with the RMSE of the transfer function predictions, demonstrate the strength of this relationship. Whatever the explained variance obtained, one can then argue that the remaining variance must be due to local or "environmental" effects. For any point, these numbers give an indication of how well one may expect to reproduce the local climate simply from the GCM circulation, or whether it may be more advantageous to go the more expensive route of employing an embedded meso-scale model in the GCM simulation.

The correlation between the observed and predicted outcomes gives a single empirical measure of the circulation-local climate relationship; it provides no physical explanation for this relationship. This can be approached, however, through the construction of a net sensitivity parameter (Hewitson and Crane 1994). Essentially, a large number of nets are constructed where, for each net, one of the input variables is perturbed very slightly and the change in the net output then reflects the sensitivity of the net to that variable (in this case a component of the atmospheric circulation). The sensitivity can be computed for every day in the data set, resulting in a matrix of values that describe the temporal sensitivity of the local climate to specific (spatial) features of the

circulation. At every grid-point, station, or group of stations for which the transfer functions are derived, the end result is a time-series of circulation sensitivity maps that provide the basis for a physical explanation of the circulation-climate relationship at that location.

This analysis can be carried out at the GCM resolution (i.e. aggregating the high resolution data to the resolution of the GCM grid, predicting the temperature and precipitation on that grid, and determining the sensitivity of the predictions to specific changes in the circulation fields). In this case, the analysis can be performed on both the observational and GCM simulated data, and the results compared to determine whether the model exhibits the same internal consistencies between circulation and local (grid-point) climate as those found in the observational data.

The daily rainfall data from ten stations in the Susquehanna river basin are averaged together and are used with the circulation data to derive transfer functions between the sea level pressure distributions and local rainfall. The approach is the same as that described in Section 3.3.2, with the transfer functions computed using neural nets. The net is trained using three-day lagged sea level component scores to produce the rainfall on the third day. The results are only preliminary, but have so far produced correlations (between the observed and predicted rainfall) of approximately 0.7 to 0.8 depending on the net configuration. Similar results have been produced for the upper Colorado Basin, where the net is used to predict the snowfall through the winter season for several different snow regions.

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