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High-resolution climate change scenarios for North America

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Background

Projections of future climate produced by General Circulation Models (GCMs) have a coarse spatial resolution. As such they often require further processing before being used for climate change impact studies.

There are several approaches to generating these finer scale or higher resolution models. They include dynamical downscaling (e.g. Regional Climate Models - RCMs), statistical downscaling and statistical interpolation. RCMs are higher resolution climate change models driven by the conditions imposed by a "host" GCM (e.g., Laprise et al. 2003). Statistical downscaling methods correlate large-scale atmospheric processes to local scale meteorology and apply this information to GCM projections of future weather patterns to characterize future local climate (Wilby et al. 1998). Such approaches attempt to maintain physical consistency with the GCM representations of atmospheric processes, and can generate distributions (e.g. means and extremes) of simulated meteorological data usually at point locations. However both RCM and statistical downscaling are highly computationally intensive.

Statistical interpolation of GCM output is a simpler approach to obtaining higher resolution estimates from GCM models. Although lacking the physical detail of dynamical downscaling, these methods provide outputs that cover large regions and can capture the climate change signals simulated by the GCM. This approach can provide spatially and temporally consistent outputs useful for landscape-scale climate change studies (see also discussion in Houser et al., 2004). With this approach, the GCM data are normalized (i.e. changes are scaled relative to the GCM values for a baseline period, for example 1961-1990). This removes potential bias to make the scenario broadly consistent with actual historical observations. The overall approach is generally transparent and rapid.

We have developed a process that implements a statistical interpolation approach to generating high-resolution models (grids) from GCMs. We have applied the approach to several GCMs with results that cover all of North America. Our aim is to support landscape-scale climate change impact studies. This note briefly describes the process and products available.

Basic Approach

To begin, GCM scenario data were downloaded from either the IPCC data distribution centre (at http://ipcc-ddc.cru.uea.ac.uk), in the case of the Hadley Centre, CSIRO and ECHAM GCMs or from the Canadian Centre for Climate Modelling and Analysis (CCCma, http://www.cccma.bc.ec.gc.ca/data/cgcm2/cgcm2.shtml) in the case of the CGCM2 output. These data were "preprocessed" at the Northern Forestry Centre (NoFC). Preprocessing included extracting a subset covering North America, followed by some checks on validity, and special treatments of the humidity variables (which differ between GCMs). The exact number of grid points available for each monthly interpolation varied around 300 because each GCM operates on a different global grid. The final step was to format the data for the interpolation procedure. The data were then transferred (via the internet ftp protocol) to the Great Lakes Forestry Centre (GLFC) where the higher resolution grid versions of the GCMs were created. We have been using ANUSPLIN, a tool specifically developed for interpolating climate data. ANUSPLIN makes use of thin plate smoothing spline mathematics, formerly Laplacian smoothing splines (Wahba 1990; Hutchinson 1995).

The overall interpolation approach can be summarized as follows. Mean monthly differences in temperature between the GCM simulations and our chosen GCM baseline period (1961-1990) were calculated at each grid cell. Each grid cell is essentially treated as a "station" location. These data were interpolated to a 300 arc second (5 arc minute, approximately 10 km) grid. The grid covers all of North America and matches the same resolution as other Canadian/North American ANUSPLIN climate products that have been developed (see http://www.glfc.cfs.nrcan.gc.ca/landscape/climate_models_e.html). For other variables, including precipitation, the ratios of the GCM simulations to the simulated baseline period were interpolated. These interpolated differences and ratios can then be treated as climate anomalies relative to the means of the 1961-1990 baseline period.

After several trials with ANUSPLIN, "fixed signal" models based on a latitude and longitude interpolation were used. Fixed signal models are appropriate when there is a poor statistical relationship between the dependent and independent variables (in this case geographic position and the GCM change field). The signal in thin plate spline models is akin to the degrees of freedom in standard regression models. Initial model runs generated SIGNAL = 1 models, which are in fact an exact interpolation between the data points (i.e. GCM grid cell locations). The resultant steep gradients of temperature differences and precipitation ratios created "bull's eyes" which, in our opinion, were not believable or appropriate for the type of landscape-scale (country and continent-wide) models required for some potential users (including ourselves). GCM outputs should not be considered as precise forecasts of future climate, but instead as plausible scenarios of what could happen in the future given a trajectory of greenhouse gases (IPCC, 2000). Moreover, it is the temperature differences and precipitation ratios relative to the simulated 1961-1990 baseline GCM output that were interpolated, rather than the absolute values of these variables. This approach should remove any biased representation of current climate that may be present in a GCM output.

Trivariate ANUSPLIN models (i.e., an interpolation based on longitude, latitude and elevation) were also not developed. This is because the internal representation of elevation in the GCMs themselves is typically rather poor given their very coarse horizontal resolution. Separate trials affirmed this lack of elevation influences in the GCM change fields. In summary, fixed signal models, where SIGNAL = 0.6 resulted in more spatially coherent and smoothly varying models of the change fields. For further details of the underlying mathematics for thin plate splines see Hutchinson and Gessler (1994), Hutchinson (1995) or Wahba (1990). For an application of thin plate smoothing splines to actual Canadian climate data see McKenney et al. (2001) and Price et al., 2000.

As an added set of products, 30-year average change models have also been developed with these scenarios. This required several additional steps. First, ANUSPLIN surfaces of 30-year average change fields were created. These surfaces were then used to estimate the projected average changes at North American weather stations operating during the 1961/90 period. The average changes for 3 future periods (2011-2040, 2041-2070 and 2071-2100) were then added to the actual values of the 1961/90 period. This allowed for the generation of new ANUSPLIN surfaces of "actual" average values for these future periods. For these models we did in fact use the trivariate (elevation dependent) splines because there are statistically strong elevation dependencies in the1961/90 models and these dependencies remained (as would be expected).

With these surfaces it is possible to generate several bioclimatic variables (e.g. growing season length, precipitation during the growing season, etc.) that are often used in agricultural/ecological impact modeling and hence have greater interest to some potential users. The derived variables are possible because a daily sequence of temperature and precipitation can be generated from the primary monthly surfaces. This is done through a bessel interpolation whereby the daily sequence is forced to pass through the monthly means in a monotonic form (see Mackey et al. 1996 for details). It is important to realize that these are intended to represent average conditions and that in any given year there is noise that would influence the actual daily sequence of bioclimatic variables.

However, some users desire bioclimatic variables at a yearly time step, rather than 30-year averages. This created a challenge not only because of the caveat noted above about individual years being much more stochastic but also the computer disk space required for data storage. Nevertheless we decided to generate another resolution of models that would include some of the bioclimatic models at the yearly time step because we felt that it would provide a reasonable proxy. Users must realize that the bioclimatic models do NOT include the noise that would occur in any given year. The models were developed at a coarser resolution of 900 arc seconds (~30 km) to deal with the data storage problems.

As the GCM scenarios were interpolated at the GLFC they were then sent back to NoFC for packaging, distribution and use. The NoFC have prepared half-degree aggregated grids for CGCM2, HadCM3 and CSIRO change fields and have resampled the grids to a 10 km Lambert Conformal Conic projection for Canada.

Results

Eight GCM scenarios have been completed, packaged and are now available to users via FTP, with additional formats (notably including subsets for ten regions within North America, see Figure 1) planned for the near future. The eight scenarios include both of the IPCC SRES A2 and B2 emissions scenarios, as used to force simulations by each of the CGCM2, HadleyCM3, CSIRO Mk2 and ECHAM4 GCMs. (Some issues remain with the ECHAM4 temperature source data.) Table 1 provides a summary but in essence the period for the monthly models cover 1900 to 2100 for minimum and maximum temperature, precipitation, vapour pressure, 10m wind speed and global solar radiation.

Table 1. Variables and simulation periods

Model A2, B2, Scenarios	Variables	Years
CGCM2 (Canadian)	Minimum, maximum temperature, vapour pressure, precipitation, solar radiation, wind speed	1900-2100 30 year averages and annual models
HADCM3 (Hadley, UK)	Same	1950-2099 30 year averages and annual models
CSIRO Mk2 (Australian)	Same	1961-2100 30 year averages and annual models
ECHAM4 * (European Community)	Same	1900-2100

Notes:
SEEDGROW variables only for annual models (see Table 2); Both BIOCLIM, SEEDGROW variables for 30-year average models (Table 2). 30 year average models were generated for the periods 2011-2040, 2041-2070 and 2071-1200 (or 2099 in the Hadley model).
* This data is under review for reasons stated in text.

Table 2. Bioclimatic variables generated from the high resolution GCM products (Bioclim and "Seedgrow" variables generated for the 30-year average models; Seedgrow variables only for the annual models*)

BIOCLIM	SEEDGROW
Annual Mean Temperature	Julian day number of start of growing season
Mean Diurnal Range(Mean(period max-min)) Isothermality 2/7	Julian day number at end of growing season
Temperature Seasonality (C of V)	Number of days of growing season
Max Temperature of Warmest Period	Total precipitation for period 1
Min Temperature of Coldest Period	Total precipitation for period 3
Temperature Annual Range (5-6)	Gdd above base_temp for period 3
Mean Temperature of Wettest Quarter	Annual mean temperature
Mean Temperature of Driest Quarter	Annual minimum temperature
Mean Temperature of Warmest Quart	Annual maximum temperature
Mean Temperature of Coldest Quarter	Mean temperature for period 3
Annual Precipitation	Temperature range for period 3
Precipitation of Wettest Period	
Precipitation of Driest Period	
Precipitation Seasonality(C of V)	
Precipitation of Wettest Quarter	
Precipitation of Driest Quarter	
Precipitation of Warmest Quarter	
Precipitation of Coldest Quarter	

Notes:
Period 1 - 3 months prior to the start of the growing season;
Period 2 - the first 6 weeks of the growing season;
Period 3 - the growing season;
Period 4 - the difference between period 3 and period 2.
*To generate "Bioclim" variables ANUSPLIN surfaces are required for "actual" values, not differences or ratios. Surfaces for "actual" values were only generated for the 30-year average periods.

These data sets are available in NetCDF format by contacting David Price or Dan McKenney. To date using the ftp and/or dvd capacity at the NoFC and GLFC has proved the most effective mechanism for transferring data as it is requested. Users/clients to date have included University of Sheffield in the UK, the USDA Forest Service in Oregon and Ohio, University of Toronto, Lakehead University, Woods Hole Research Center and the Canada Centre for Remote Sensing. Data have also been made available to Fluxnet-Canada researchers.

Table 2 summarizes the annual and 30-year average bioclimate variables that have been generated from the GCM scenario data. For consistency, these were created at the same 300 arc second resolution as the monthly scenario grids.

Several reports and papers have been generated

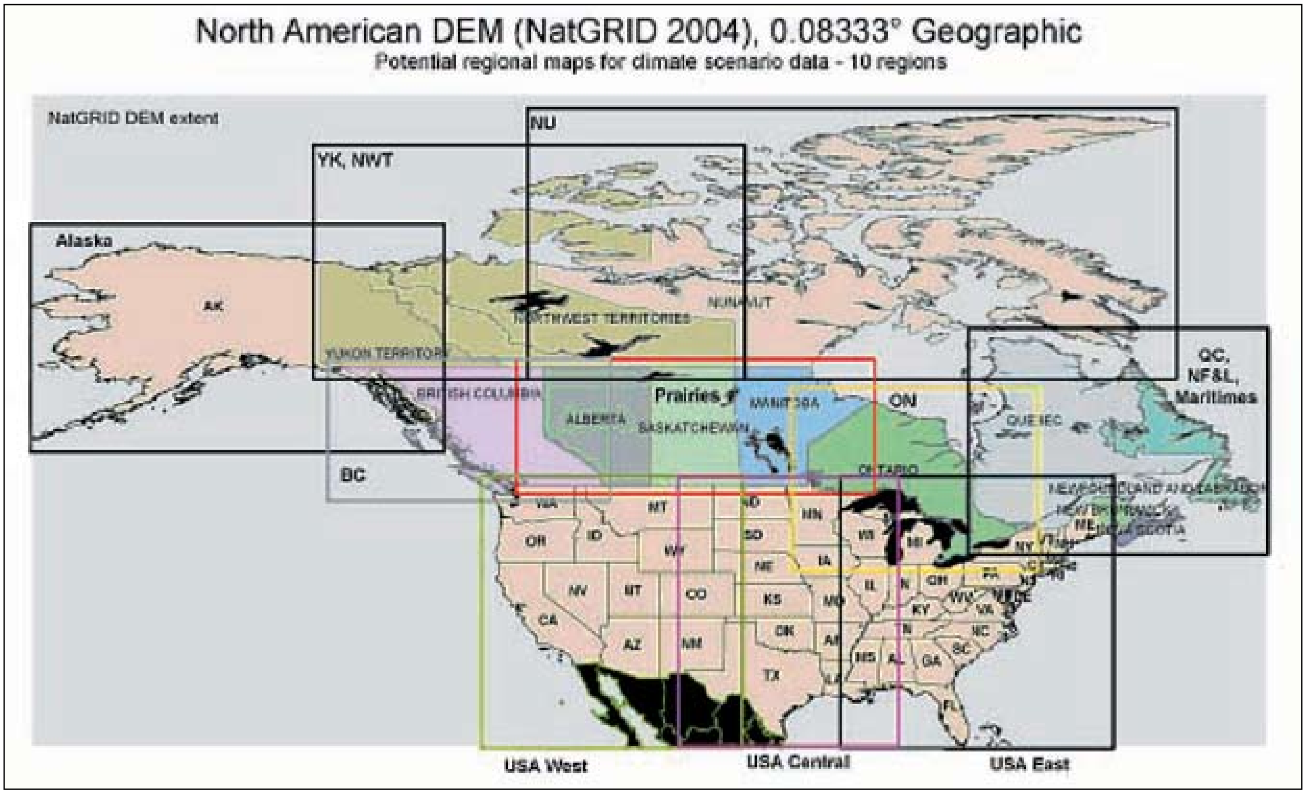

Figure 1. Regions for climate scenario data

from this work. Our application and automation of ANUSPLIN to GCM data is further detailed in Price et al. (2004). A similar effort with CGCM1 data used in an agricultural application is documented in Bootsma et al. (2005a, 2005b).

Summary and Concluding Comments

We have developed a transparent and rapid approach to the provision of high resolution GCM data for climate change impact studies. While the process is highly automated it is clear that complete automation is not achievable or desirable. There will always be some data quality issues/questions that arise during different steps of the process that require human intervention and professional judgement. Examples of problems/challenges include problems with the source data and new interpretations required by specific users (Price et al. 2004). Some errors in the temperature data seemed to be present with the ECHAM data, a problem that is still not entirely resolved. In the case of the CSIRO Mk2 GCM precipitation for some months in dry regions was projected to increase by factors of 500-1000 relative to current 30-year normals. This occurred because the GCM underestimated present-day dryness (e.g., by predicting a 30-year average of say, 1 mm per month, when the observed data reported 10 mm), but then projected a significant increase in future rainfall with very high interannual variability. Intuitively, a 500 fold increase seems highly unlikely, but given the uncertainty in predicting possible changes in extremes and uncertainty, it may be possible. Judgement is required to put a cap on changes expressed in these terms. One indication for an acceptable limit may come from the actual historical record (which showed that monthly precipitation can vary by factors of 20 or more relative to 30-year normals, in some parts of North America).

We anticipate greater interest and awareness of these products as more people become aware of their availability and applicability. Besides being available through contacting the senior authors, an interactive web page is under production that will allow users to view, zoom and query some of the bioclimate models.

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