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Customized spatial climate models for Canada

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Introduction

The influence of climate is pervasive. At broad scales it drives plant/animal distributions, relative abundance and productivity. Weather – extreme heat and cold events – can affect human health. Precipitation affects hydroelectric power generation opportunities. Solar radiation affects plants but is also increasingly used as an energy source through photovoltaic panels. The list goes on. Thus there is a great need for high quality (read reliable) estimates of climate away from weather stations. This information can typically come in two forms – point estimates at specific locations such as research plots, farms, etc., and, secondly, point estimates at regular grid locations that can be used for various types of predictive models. Concern over the possible impacts of rapid climate change provides another important motivating factor for the development of spatially explicit climate models.

Over the last decade and a half the Canadian Forest Service has been working in partnership with several staff in Environment Canada's Meteorological Service of Canada (MSC), Professor Michael Hutchinson of the Australian National University (ANU) and others to develop a variety of climate models that cover both Canada and the United States. Much (but not all) of that work can be seen in interactive maps that can be accessed on the internet at: http://cfs.nrcan.gc.ca/subsite/glfc-climate. This short note is intended to document what models are available and the process by which one can obtain customized specific point estimates or pre-computed regular grid estimates (maps) that may be best suited to particular needs.

Please note that if your needs are estimates very near a weather station you should first examine the possibility of obtaining the data you require directly from Environment Canada (for example see: http://www.climate.weatheroffice.ec.gc.ca/climateData/canada_e.html.

The ANUSPLIN model

ANUSPLIN is a multi-variate non-parametric surface fitting approach to developing spatially continuous climate models. It makes use of thin plate-smoothing splines, which are a true multi-variate generalization of univariate splines, as described by Wahba (1990). They should not be confused with simple cubic polynomials. Earliest applications were described by Whaba and Wendelberger (1980) but the methodology has been further developed and made operational as a climate mapping tool by Professor Michael Hutchinson at the ANU over the last 20 years or so (e.g., Hutchinson and Bischof 1983; Hutchinson, 1995, 1991; Hutchinson and Gessler 1994). There are numerous peer-reviewed articles on *ANUSPLIN* that document the underlying mathematics. A key contribution of the method has been the systematic incorporation of elevation as a predictor, particularly for temperature and precipitation. The model has been applied in many regions around the world independent of the model's creator. Some relevant literature can be found at: http://cfs.nrcan.gc.ca/subsite/glfc-climate/anusplinreferences and the Australian National University web site: http://cres.anu.edu.au/outputs/anusplin.php. For details on various Canadian applications see Mackey et al. (1996), Price et al. (2000, 2004), McKenney et al. (2001, 2004, 2006a, b, c,). Those references also contain citations of other climate interpolation techniques.

When generating journal articles or other written reports we typically report on the quality of the models via the interpretation of model diagnostics, withheld data tests, examining mapped output and collaboration with various experts. For example, mean errors, mean absolute errors and root mean square errors as estimated at stations withheld from the model building phase are often used as metrics to assist evaluations. Models are developed iteratively after examination of both data and results. Many, but not all models have resulted in reports or journal articles. Most importantly models are not generated by simply setting up a computer command file and pushing a button. There are always issues to consider such as tradeoffs between model configuration and parameters and data concerns (e.g., sparseness, quality).

It may surprise many users that very few models result in an exact interpolation through the station values. A certain degree of smoothing is inherent with statistical models. With *ANUSPLIN* the extent of smoothing is optimized objectively by minimizing the predictive error of the fitted function as measured by generalized cross-validation (GCV). In other words, the model does not usually strive to be an exact interpolator at the station locations, but rather its aim is to minimize overall interpolation error at all points. Meteorological data also contain observing uncertainties. There is an issue of spatial compatibility of data that comes from different types of stations (volunteer, airports, automated), sometimes with differing sets of instruments and related measuring error characteristics. In addition, microclimatic variability also contributes to uncertainty, (e.g., due to spatial variability of precipitation two rain gauges even in close proximity will rarely yield identical rainfall amounts). Ideally both the modeller and the potential user will have a sense of the potential errors.

We can provide error estimate summaries automatically generated by the *ANUSPLIN* model and, if available, provide reference to a report specifically generated for those models. We leave it to users to assess whether the overall estimation errors are appropriate for their application or need. Models of longer term averages have lower error estimates than shorter time step models such as historical monthly or daily (e.g., plus/minus half a degree Celsius for temperature, 10-20% for precipitation and slightly larger for shorter time steps).

Models and variables available

Over the last 15 years or so many *ANUSPLIN* models have been developed, to the point where it can be confusing to keep track of what is available. Many models are built around three primary variables – minimum temperature, maximum temperature and precipitation as these are three important climate parameters that are tracked by Environment Canada. Each of these models incorporates a spatially varying dependence on elevation. We have built models for these at the monthly multi-year mean (normals), monthly, weekly and daily time steps. In addition, there are a number of other models such as radiation, lake evaporation, sunshine hours, extreme minimum temperature and others that have been developed for particular applications. Table 1 provides a listing of surfaces currently completed. Again note that this does not mean the models are perfect or could not be improved. Resources are scarce and we continually have to make judgements as to the costs of potential improvements compared to the benefits.

However, the whole story is not provided in Table 1. It is possible to generate additional variables of interest from the three primary variables identified above (minimum temperature, maximum temperature and precipitation) through other modelling procedures. Often these secondary variables are of most value to clients because the ecological or biological relevance of these are more intuitive. Examples include growing season length, start and end days of the growing season, etc. Table 2 provides a listing of the variables routinely available. These variables are available at the monthly multi-year mean (normals) and historical monthly time steps.

An internet mapper

Many of the models are available on interactive web sites. New models are added regularly so visit the climate home page for updates. The internet is used to visualize results, distribute data and create online mapping applications.

Our Climate page features the following:

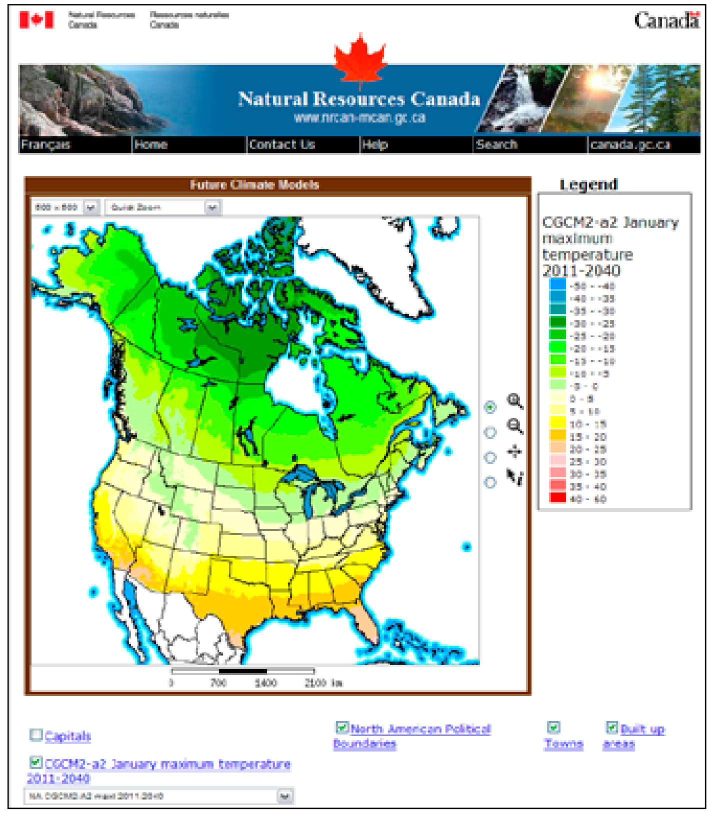
1. Multi-year mean (normals) surfaces and grids for Canada
2. Multi-year mean (normals) surfaces and grids for North America
3. Monthly historical surfaces and grids dating from 1900 for North America
4. Climate change experiments
5. Surfaces and grids of GCM and RCM climate change scenarios to support climate change impact studies.
6. Weekly mean (1961/90) and historical surfaces from 1961 (by special request)
7. Daily surfaces for parts of Canada from 1961 (by special request)
8. Other miscellaneous surfaces (including vapour pressure, sunshine hours, global radiation, potential evapotransporation and extreme minimum temperature). Some of these climate parameters are developed from much sparser networks than the precipitation and temperature networks. For example vapour pressure is derived from less than 200 stations across Canada.

Our weekly and daily surfaces are not currently on the internet because of the sheer volume or size of all the files but interested users can contact us with special requests. If possible we will endeavour to assist.

The mapper is user friendly. Just select your subject of interest and point and click your way through the options.

For example, “climate change experiments” will take you to a page where you choose the period of interest, model scenario and climate variables (see Figure 1 below). Then clicking “send” takes you to the mapper. Here you can select the layer you want and zoom, query and save the image for use as desired in your own publication. Our mapper is not a Geographic Information System (GIS) but it does have some GIS functionality like turning on and off layers (e.g., towns and cities).

Figure 1. Example web mapper.



To explore the internet mapper further, go to: http://cfs.nrcan.gc.ca/subsite/glfc-climate/climate and follow the links to the models of interest.

Obtaining estimates at specific locations

Estimates may be provided for specific locations. This can be particularly useful for researchers investigating the statistical relationship between climate and their phenomena of interest. Examples of situations where we have provided this service include health researchers appending precipitation estimates to farm locations to assist investigating health risks from farm run-off. We have also provided estimates to wildlife ecologists and forest growth and yield modelers and hydrologists. To make a request, researchers should contact us with their specific interest. A file of locations of interest, including elevation, will need to be provided in ASCII format as follows.

Id x y z
1 -64.45 48.65 121.00
2 -64.4667 48.6167 257.00
RED_RD -68.5761 46.3276 3200.00

where:
Id – Station Identification, alphanumeric 0-20 characters with no spaces
x – Longitude in decimal degrees
y – Latitude in decimal degrees
z – Elevation in metres

The locations should be as precise as possible e.g., longitude and latitude to 4 decimal places. If elevation values are not available we are able to generate elevation estimates using a Digital Elevation Models (K. Lawrence pers comm).

Obtaining grids or mapped data

The models shown on the internet mapper have for the most part been resolved at a 300 arcsecond (~10km) resolution using a Digital Elevation Model (DEM) of that resolution. A DEM is a computer-based regular grid model of the topography of an area. To facilitate the development of our climate models we have constructed several DEMs of Canada (K. Lawrence pers comm.). The DEMs provide a means to generate map estimates because they give latitude and longitude coordinates and elevation values in a regular grid. It may be possible to obtain grid resolutions other than 300 arcseconds for specific applications. Requests are assessed on a case-by-case basis. Contact the authors for further details.

Conclusions

There is a growing demand for spatially reliable climate models at various time and spatial resolutions for ever-increasing environmental applications. This note has provided some details about how point and/or grid estimates of climate can be obtained for our models. Models are most valuable when they are used – we hope to encourage their use by making our work accessible. Contact any of the authors for further details if required.

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Table 1. List of models potentially available

Paramater	Units	Time step	Time period	Country Region	Surface title
Vapour Pressure	kPa	1	1961-1990	CA	Vapour Pressure
Relative Humidity	%	1	1961-1990	CA/NA	Relative Humidity
Wind Speed	Km/h	1	1961-1990	CA/NA	Wind Speed
Sunshine	hours	1	1961-1990	CA	Total Hours of Bright Sunshine
Sunshine	hours	1	1961-1990	CA	Mean Daily Sunshine Hours
Solar Radiation	MJ/m²	1	1961-1990	CA/NA	Global Radiation
Solar Radiation	MJ/m²	1	1971-2000	CA	Global Radiation
Solar Radiation	MJ/m²	1	1974-1993	CA	Global Radiation CERES data base for Photovoltaic Energy in Canada
Potential Evapotranspiration	mm	1	1961-1990	CA	Potential Evapotranspiration Bonan Model
Evaporation	mm	1	1961-1990	CA	Pan Evaporation
Evaporation	mm	1	1961-1990	CA	Lake Evaporation
Snow Depth	mm	1	1961-1990	CA	30 year Normals Snow Depth for stations with 30 years of record
Snow Depth	mm	1	1961-1994	CA	34 average Snow Depth for stations with more than 5 years of record
Snow Water Equivalent Observed	mm	1	1961-1990	CA	30 year average Snow Water Equivalent Observed from MSC OBS_SWE database
Minimum Temperature	°C	1	1930-1960	CA	30 year average Minimum Temperature
Maximum Temperature	°C	1	1930-1960	CA	30 year average Maximum Temperature
Precipitation	mm	1	1930-1960	CA	30 year average Precipitation
Minimum Temperature	°C	1	1961-1990, 1971-2000	CA/ NA	30 year Normals Minimum Temperature all months and by month
Minimum Temperature	°C	1	1961-1990, 1971-2000	CA/NA	30 year Normals Minimum Temperature for Standard Error Maps
Maximum Temperature	°C	1	1961-1990, 1971-2000	CA/ NA	30 year Normals Maximum Temperature all months and by month
Maximum Temperature	°C	1	1961-1990, 1971-2000	CA/NA	30 year Normals Maximum Temperature for Standard Error Maps
Precipitation	mm	1	1961-1990 1971-2000	CA/NA	30 year Normals Precipitation all months and by month
Precipitation	mm	1	1961-1990, 1971-2000	CA/NA	30 year Normals Precipitation for Standard Error Maps
Extreme Minimum Temperature	°C	1	1961-1990	NA	30 year Means Extreme Daily Minimum Temperature
Extreme Minimum Temperature	°C	1	1974-1986	NA	12 year Means Extreme Daily Minimum Temperature
Extreme Minimum Temperature	°C	1	1971-2000	NA	30 year Means Extreme Daily Minimum Temperature GCM 30 year, Future Projection Abstract
Maximum Temperature	°C	1	2011-2040, 2041-2070, 2071-2100	NA	30 year averages CGCM2, CSIRO, A2/B2 Scenarios Maximum Temperature
Minimum Temperature	°C	1	2011-2040, 2041-2070, 2071-2100	NA	30 year averages CGCM2, CSIRO, A2/B2 Scenarios Minimum Temperature
Precipitation	mm	1	2011-2040, 2041-2070, 2071-2100	NA	30 year averages CGCM2, CSIRO, A2/B2 Scenarios Precipitation
Maximum Temperature	°C	1	2011-2040, 2041-2070, 2071-2099	NA	30 year averages HadCM3, NCARPCM, A2/B2 Scenarios Maximum Temperature
Minimum Temperature	°C	1	2011-2040, 2041-2070, 2071-2099	NA	30 year averages HadCM3, NCARPCM, A2/B2 Scenarios Minimum Temperature
Precipitation	mm	1	2011-2040, 2041-2070, 2071-2099	NA	30 year averages HadCM3, NCARPCM, A2/B2 Scenarios Precipitation
Probable Maximum Snow Pack (PMP) for Quebec and SWE	mm	1	1900-2000	QUE	100 year average of Modelled Snow Pack for 365 stations and Snow Water Equivalent From 261 stations
Potential Evapotranspiration	mm	2	1958-1993	CA	Potential Evapotranspiration Bonan Model Historical
Snow Depth	mm	2	1961-1994	CA	Historical Snow Depth
Snow Water Equivalent Observed	mm	2	1961-1990	CA	Historical Snow Water Equivalent Observed form MSC OBS_SWE database
Minimum Temperature	°C	2	1961-2000	NA	Historical Extreme Daily Minimum Temperature
Maximum Temperature	°C	2	1901-2003	NA	Historical Maximum Temperature all months and by month
Minimum Temperature	°C	2	1901-2003	NA	Historical Minimum Temperature all months and by month
Precipitation	mm	2	1901-2003	NA	Historical Precipitation all months and by month

Paramater	Units	Time step	Time period	Country Region	Surface title
Maximum Temperature	°C	2	1900-2100	NA	CGCM2, A2/B2 Scenarios Maximum Temperature Annual changes relative to 1961/90
Minimum Temperature	°C	2	1900-2100	NA	CGCM2, A2/B2 Scenarios Minimum Temperature Annual changes relative to 1961/90
Precipitation	mm/day	2	1900-2100	NA	CGCM2, A2/B2 Scenarios Precipitation Annual changes relative to 1961/90
Solar Radiation	W/m^2	2	1900-2100	NA	CGCM2, A2/B2 Scenarios Solar Radiation Annual changes relative to 1961/90
Wind Speed	m/s	2	1900-2100	NA	CGCM2, A2/B2 Scenarios Wind Speed Annual changes relative to 1961/90
Vapour Pressure	kPa	2	1900-2100	NA	CGCM2, A2/B2 Scenarios Vapour Pressure Annual changes relative to 1961/90
Maximum Temperature	°C	2	1961-2100	NA	CSIRO, A2/B2 Scenarios Maximum Temperature Annual changes relative to 1961/90
Minimum Temperature	°C	2	1961-2100	NA	CSIRO, A2/B2 Scenarios Minimum Temperature Annual changes relative to 1961/90
Precipitation	mm/day	2	1961-2100	NA	CSIRO, A2/B2 Scenarios Precipitation Annual changes relative to 1961/90
Wind Speed	m/s	2	1961-2100	NA	CSIRO, A2/B2 Scenarios Wind Speed Annual changes relative to 1961/90
Vapour Pressure	kPa	2	1961-2100	NA	CSIRO, A2/B2 Scenarios Vapour Pressure Annual changes relative to 1961/90
Solar Radiation	W/m^2	2	1961-2100	NA	CSIRO, A2/B2 Scenarios Global Radiation Annual changes relative to 1961/90
Maximum Temperature	°C	2	1950-2099	NA	HadCM3, A2/B2 Scenarios Maximum Temperature Annual changes relative to 1961/90
Minimum Temperature	°C	2	1950-2099	NA	HadCM3, A2/B2 Scenarios Minimum Temperature Annual changes relative to 1961/90
Precipitation	mm/day	2	1950-2099	NA	HadCM3, A2/B2 Scenarios Precipitation Annual changes relative to 1961/90
Wind Speed	m/s	2	1950-2099	NA	HadCM3, A2/B2 Scenarios Wind Speed Annual changes relative to 1961/90
Vapour Pressure	kPa	2	1950-2099	NA	HadCM3, A2/B2 Scenarios Vapour Pressure Annual changes relative to 1961/90
Solar Radiation	W/m^2	2	1950-2099	NA	HadCM3, A2/B2 Scenarios Global Radiation Annual changes relative to 1961/90
Solar Radiation	W/m^2	2	1961-2099	NA	NCARPCM, A2/B2 Scenarios Global Radiation Annual changes relative to 1961/90
Maximum Temperature	°C	2	1961-2099	NA	NCARPCM A2/B2 Scenarios Maximum Temperature Annual changes relative to 1961/90
Minimum Temperature	°C	2	1961-2099	NA	NCARPCM, A2/B2 Scenarios Minimum Temperature Annual changes relative to 1961/90
Precipitation	mm/day	2	1961-2099	NA	NCARPCM, A2/B2 Scenarios Precipitation Annual changes relative to 1961/90
Wind Speed	m/s	2	1961-2099	NA	NCARPCM, A2/B2 Scenarios Wind Speed Annual changes relative to 1961/90
Vapour Pressure	kPa	2	1961-2099	NA	NCARPCM, A2/B2 Scenarios Vapour Pressure Annual changes relative to 1961/90
Maximum Temperature	°C	2	2011-2100	CA	Annual values CGCM2 A2/B2 Scenarios Maximum Temperature
Minimum Temperature	°C	2	2011-2100	CA	Annual values CGCM2 A2/B2 Scenarios Minimum Temperature
Snow Depth	mm	3	1961-1990	CA	30 year average of Daily Snow Depth for 244 Julian days over the winter period
Snow water Equivalent Estimated	mm	3	1961-1995	CA	Historical Daily Snow Water Equivalent (estimated at station locations) for 1^{st} , 15^{th} , 29^{th} day for Jan-May and Oct-Dec.
Snow Water Equivalent Observed	mm	3	1961-1990	CA	Historical Daily Snow Water Equivalent for 1^{st}, 15^{th}, 29^{th} day for Jan-Jun and Nov-Dec
Minimum Temperature	°C	3	1961-2003	CA	Historical Daily Minimum Temperature
Maximum Temperature	°C	3	1961-2003	CA	Historical Daily Maximum Temperature
Precipitation	mm	3	1961-2003	CA	Historical Total Daily Precipitation
Solar Radiation	MJ/m2	4	1956-2003	CA	Global Radiation Historical Weekly
Evaporation	mm	4	1961-2000	CA	Pan A Evaporation Weekly
Minimum Temperature	°C	4	1961-2003	CA	Historical Weekly Mean Minimum Temperature
Maximum Temperature	°C	4	1961-2003	CA	Historical Weekly Mean Maximum Temperature
Precipitation	°C	4	1961-2003	CA	Historical Weekly Total Precipitation
Snow Water Equivalent Observed	mm	4	1961-1990	CA	30 year average Snow Water Equivalent for 1^{st} and 4^{th} week for Jan-June and Nov-Dec,

1 – Monthly mean
2 – Historical or Monthly projections
3 – Daily
4 – Weekly

Country Region
CA – Canada
NA – North America
QUE–Quebec

Surface title
GCM – General Circulation Model
CGCM2 – Canadian General Circulation Model 2
CSIROMk2 – Commonwealth Scientific and Industrial Research Organization Model 2
HadCM3 – Hadley Centre Coupled Model 3
NCAR PCM–National Centre of Atmospheric Research Parallel Climate Model

Table 2. Standard Bioclimatic variables produced with the Canadian and North American surfaces at the monthly mean and historical monthly time steps (see http://cres.anu.edu.au/outputs/anuclim.php for information about *ANUCLIM*)

"ANUCLIM" VARIABLES	**Other selected bioclimatic variables**
1. Annual Mean Temperature	01 julian day number of start of growing season
2. Mean Diurnal Range (Mean(period max-min))	02 julian day number at end of growing season
3. Isothermality 2/7	03 number of days of growing season
4. Temperature Seasonality (C of V)	04 total precipitation for period 1
5. Max Temperature of Warmest Period	05 total precipitation for period 2
6. Min Temperature of Coldest Period	06 total precipitation for period 3
7. Temperature Annual Range (5-6)	07 total precipitation for period 4
8. Mean Temperature of Wettest Quarter	08 gdd above base_temp for period 1
9. Mean Temperature of Driest Quarter	09 gdd above base_temp for period 2
10. Mean Temperature of Warmest Quarter	10 gdd above base_temp for period 3
11. Mean Temperature of Coldest Quarter	11 gdd above base_temp for period 4
12. Annual Precipitation	12 annual mean temperature
13. Precipitation of Wettest Period	13 annual minimum temperature
14. Precipitation of Driest Period	14 annual maximum temperature
15. Precipitation Seasonality (C of V)	15 mean temperature for period 3
16. Precipitation of Wettest Quarter	16 temperature range for period 3
17. Precipitation of Driest Quarter	
18. Precipitation of Warmest Quarter	
19. Precipitation of Coldest Quarter	

Note: Growing seasons vary for each plant species. The growing season here was determined using temperature-based rules, starting when the mean daily temperature was greater than or equal to 5 degrees Celsius for 5 consecutive days beginning March 1. The growing season ends when the average minimum temperature is less than -2 degrees Celsius beginning August 1. These rules are aimed more towards defining a growing season for tree species than agricultural crops as they are more clearly related to a frost free period. Other rules can be applied and may be available upon request.

Period 1 - 3 months prior to the start of the growing season

Period 2 - the 1st six weeks of the growing season

Period 3 - the growing season

Period 4 - the difference between period 3 and period 2

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