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Spatial models of Canada- and North America-wide 1971/2000 minimum and maximum temperature, total precipitation and derived bioclimatic variables.

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Introduction

Spatial models of both Canada-wide and North America-wide 1971/2000 climate "normals" have been completed using the thin plate smoothing spline algorithms of ANUSPLIN http://cres.anu.edu.au/outputs/software.html. ANUSPLIN is a mathematically sophisticated yet operationally efficient approach to generating climate maps at varying spatial and temporal scales. The Canadian Forest Service has been working in partnership with several staff in Environment Canada's Meterological Service (MSC), Professor Michael Hutchinson of the Australian National University (the creator of ANUSPLIN) and others to develop a variety of climate models that cover both Canada and North America. Much of that work can be seen in interactive maps that can be accessed on the internet at: http://www.glfc.cfs.nrcan.gc.ca/landscape/climate_models_e.html.

The underlying motivation for the development of these models is the need to investigate plant/animal and climate relations. Climate is a pervasive broad-scale driver of the distribution, abundance and productivity of plants and animals. Because there is never a weather station near field research locations, there is a need to generate spatially reliable estimates of climate at locations often far away from the nearest weather station. In addition, the growing use of process models for forestry and other environmental modelling problems has created a further need for reliable regular-grid models of various climatic variables. Concern over the possible impacts of rapid climate change provides another important motivating factor for the development of spatially explicit climate models.

This note briefly reports on the development of spatial models of Canada-and North America-wide 1971/2000 30-year mean monthly minimum and maximum temperature, total precipitation and several derived bioclimatic variables. We report on the quality of the models via the interpretation of model accessed over the internet and examined. Canadian applications of ANUSPLIN that have been documented previously include Mackey et al. (1996), Price et al. (2000, 2004), and McKenney et al. (2001, 2004, 2005). Several other applications are currently being written up, including historical monthly models from 1901, extreme minimum temperature models for plant hardiness and weekly models.

Methods

Numerous peer-reviewed articles on ANUSPLIN document the underlying mathematics. These citations and other relevant literature can be found at the web sites noted above. 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 constructions based on 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.

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Model assessments are generally done through examination of automatically generated model diagnostics and in some cases withholding data from initial models and comparing estimated versus observed values at those specific locations. Three automatically generated diagnostics are used here. The SIGNAL is the degrees of freedom of the fitted spline and varies between zero and the number of stations used for interpolation. Hutchinson and Gessler (1994) suggest that the signal should generally not be greater than about half the number of data points when using SPLINA (less than ~2000-3000 stations) or 80-90% of the number of knots when using SPLINB (this version is used when there are a large number of stations). Models with a good signal provide a balance between data smoothing and exact interpolation. Models with a poor signal are typically closer to an exact interpolation and may result in steep unrealistic gradients between stations. Exact interpolation also implies no source data errors, which is normally an unrealistic conclusion. The square root of the GCV (RTGCV) is a measure of the predictive error of the surface. It is a robust, but somewhat conservative estimate of overall prediction error, since it includes the errors in the data. The root mean square model error (RTMSE) is an estimate of standard error after the estimated data error has been removed. The true error of the fitted model lies between the RTGCV and the RTMSE. Both RTGCV and RTMSE can be less accurate estimates of overall error when the data points are very unevenly distributed. Tables are used here to summarize the diagnostics. Figures are also provided to show the reduction in the data spread in the final fitted models.

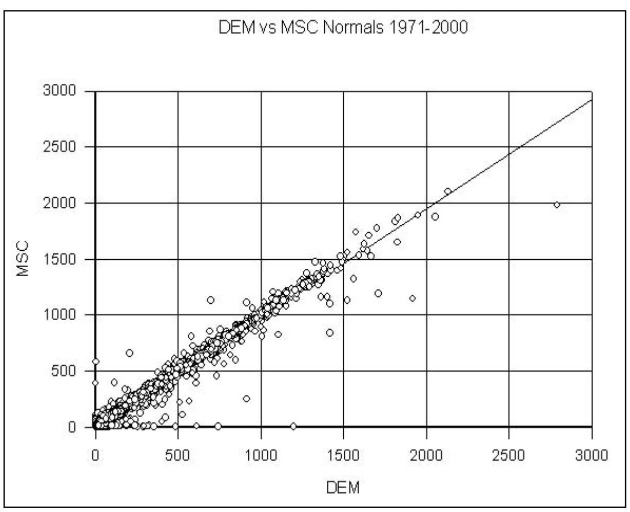

Figure 1. Digital elevation model (DEM) elevation values versus MSC station elevations (metres)

We have removed some outliers for these models where data errors were particularly obvious, such as incorrect decimal points and very large outliers. Additional data quality efforts are being undertaken in collaboration with MSC staff. Outliers may arise due to data problems, incorrect coordinates and elevation values and/or particular micro-climate characteristics of the station that are difficult to represent in the meso-scale models being developed here. Figure 1 shows the discrepancies between elevation estimates provided by a ~100-150m Digital Elevation Model of Canada (Lawrence et al. 2005) and the station elevation values provided by MSC. These differences may be caused by errors in the DEM itself but also station locations and/or lack of precision in the station locations. Nevertheless the larger discrepancies require further investigation given the importance and value of elevation in spatial climate models and are continuing to be investigated. Remarkably, a large majority of stations (>95%) have elevations that are plus minus 0-100 meters of the DEM-generated values.

All models reported here are based on position (longitude and latitude) and elevation. Previous experience has confirmed that position and vertically exaggerated elevation are useful independent variables to be used for interpolation of monthly mean climate in Canada (see Hutchinson and Bischof 1983; Hutchinson 1995; McKenney et al. 2001). For monthly mean models these three independent variables often result in models that have standard errors of plus/minus half a degree for temperature and 10-20% for precipitation. These errors are generally considered to be consistent with measurement error and local variation below the resolution of the data network. Models presented here are for monthly mean minimum, maximum temperature and total precipitation. Bioclimatic variables such as growing season length and precipitation during the growing season were generated using these primary surfaces and the methods outlined in Mackey et al. (1996). That approach creates a daily sequence of minimum and maximum temperature and precipitation with the values monotonically forced through the monthly means. They are intended to represent average conditions only, as the weather in any given year would or could have different results. Table 1 provides a listing of the bioclimate variables that have been produced and are available.

The Canadian station data were averaged to provide "normal" estimates for the 1971/2000 period. These were received from Ron Hopkinson (MSC – Regina) with the assistance of Anna Deptuch-Staph (MSC - Downsview). We note that effort is continuing in MSC to further quality control these data. In addition, we note another effort in MSC to calibrate normals from upper air stations, so they may be used along the surface stations for interpolation. Milewska et al. (2005) has shown that surface stations alone cannot provide realistic representation of high elevation temperature inversions in remote northern regions.

The Canada-only models were developed in two ways. The first approach uses stations that have data for all months (Model 1) while the second includes

Table 1. Standard Bioclimate variables produced with the Canadian and North American surfaces (see http://cres.anu.edu.au/outputs/anuclim.php for information about ANUCLIM)

"ANUCLIM" VARIABLES	**Other selected bioclimatic variables**
01 Annual Mean Temperature	01 julian day number of start of growing season
02 Mean Diurnal Range (Mean[period max-min])	02 julian day number at end of growing season
03 Isothermality 2/7	03 number of days of growing season
04 Temperature Seasonality (C of V)	04 total precipitation for period 1
05 Max Temperature of Warmest Period	05 total precipitation for period 2
06 Min Temperature of Coldest Period	06 total precipitation for period 3
07 Temperature Annual Range (5-6)	07 total precipitation for period 4
08 Mean Temperature of Wettest Quarter	08 gdd above base_temp for period 1
09 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 relatively easily 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

additional stations that only operate for part of the year (Model 2). Some of our bioclimatic modeling requires ANUSPLIN surfaces for all 12 months within one model hence the need for Model 1. Since Model 1 has slightly fewer stations additional analyses were undertaken withholding 100 stations to further assess the quality of these surfaces. The results of the data-withholding exercise are being written up for journal presentation and are not included here but do confirm the strength of diagnostics reported here. The use of additional stations can generally improve surfaces hence it is recommended that users request Model 2 for most Canadian applications.

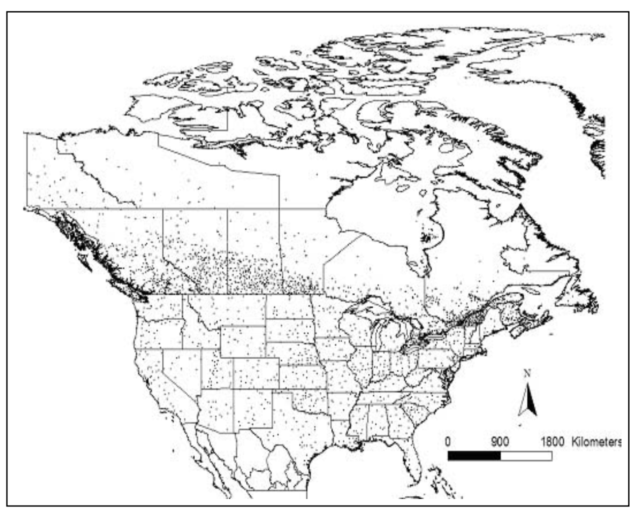

Figure 2. Spatial distribution of station data, 1971-2000 period.

The North America-wide models include both Canadian and United States (U.S.) data. The U.S. data – COOP NDP-070 daily data for 1876-1997 (Easterling et al. 1999) (with updates to the year 2000 provided by Tim Owen, pers. comm), came from United States Historical

Climate Network, (Asheville, North Carolina). These data have been used in analysis of trends in maximum and minimum temperature, temperature extremes, daily temperature range and climate change impact assessment (New et al. 1999, 2000; Easterling et al. 1997). The Canadian data were obtained from the Meteorological Service of Canada (MSC) (DLY04 1961-2000). The two sources were initially processed separately. The U.S. data was converted to metric units and then merged with the MSC data. Before creating the surfaces all data were converted to metric units including the elevation values at each climate station. Figure 2 visualizes the station locations across North America. Canadian stations are particularly sparse in northern regions. Station numbers are provided in the results tables.

Results

Overall the surfaces appear to be of high quality – signals are within recommended limits in most cases, and RTGCVs and RTMSEs are as anticipated and hoped for. Tables 2 and 3 summarize the diagnostics for the Canada-wide models, while Figures 3, 4 and 5 visualize the reduction in the data spread in the final fitted models for Model 1. The Model 1 and 2 diagnostics are very similar, indicating the robustness of the models and hence the potential redundancy of any given station (particularly in the more station-dense areas. Nevertheless the addition of precipitation stations can generally always improve estimates in most areas. The figures show the difference between the observed and estimated values at each station as estimated from the final model 1 (all year-round data included). Recall that the intent is not an exact interpolation but rather a model that provides reliable estimates away from the station locations. The RTGCV values provide a spatially averaged standard error estimate. Thus plus and minus approximately 2 times the RTGCV provides the ~95% confidence limits on the estimates. Table 4 provides the diagnostics for the North America-wide models (Figures like 3, 4 and 5 are not repeated for Model 2 or the North America models because have essentially the same fit and would be redundant).

Almost all RTMSEs are less than a degree for temperature with minimum temperature values slightly higher than maximum temperature, which is consistent with previous results and for minimum temperature reflects the more complex nature of cold air drainage patterns and microtopography influences that are not picked up in the modelling process. RTGCVs are slightly higher than RTMSEs in all cases. Precipitation is inherently more spatially complex especially in winter when most precipitation in Canada falls as snow, which is much more difficult to measure. The precipitation RTGCV and RTMSE values are larger in the winter months as would be expected in both the Canadian and North American models.

Table 2. Surface Diagnostics for Model 1 – year-round operating stations only

Maximum Temperature							
Month	**Points**	**Signal**	**Ratio**	**Mean**	**Stdev**	**rtgcv**	**Rtmse**
1	2595	853.7	0.33	-6.21	6.50	1.04	0.49
2	2595	676.6	0.26	-3.64	6.12	0.90	0.40
3	2595	782.4	0.30	1.80	5.47	0.77	0.35
4	2595	942.7	0.36	9.07	4.64	0.71	0.34
5	2595	1223.4	0.47	15.93	4.11	0.71	0.35
6	2595	1264.0	0.49	20.44	3.48	0.73	0.37
7	2595	1366.7	0.53	23.31	3.17	0.72	0.36
8	2595	1186.3	0.46	22.56	3.20	0.71	0.35
9	2595	946.8	0.36	17.33	3.34	0.71	0.34
10	2595	989.9	0.38	10.47	3.74	0.50	0.24
11	2595	1297.0	0.50	2.12	5.02	0.55	0.28
12	2595	1178.4	0.45	-3.97	5.95	0.77	0.38
Minimum Temperature							
Month	**Points**	**Signal**	**Ratio**	**Mean**	**Stdev**	**rtgcv**	**Rtmse**
1	2596	1094.7	0.42	-15.59	7.93	1.38	0.68
2	2596	981.0	0.38	-13.67	7.36	1.35	0.65
3	2596	1105.1	0.43	-8.55	6.18	1.06	0.53
4	2596	1048.7	0.40	-1.90	4.45	0.75	0.37
5	2596	1066.8	0.41	3.87	3.27	0.74	0.37
6	2596	1117.0	0.43	8.57	2.76	0.80	0.39
7	2596	1356.4	0.52	11.26	2.71	0.84	0.42
8	2596	1193.6	0.46	10.54	2.82	0.92	0.46
9	2596	1116.5	0.43	6.13	3.13	0.93	0.46
10	2596	1258.8	0.48	0.84	3.77	0.86	0.43
11	2596	1382.9	0.53	-5.62	5.82	0.86	0.43
12	2596	1367.8	0.53	-12.48	7.26	1.16	0.58
Precipitation							
Month	**Points**	**Signal**	**Ratio**	**Mean**	**Stdev**	**rtgcv**	**Rtmse**
1	3070	1421.3	0.46	78.54	77.24	15.40	7.67
2	3070	1512.5	0.49	61.21	63.83	12.30	6.15
3	3070	1568.2	0.51	64.49	55.74	12.20	6.07
4	3070	1465.4	0.48	60.14	43.18	10.40	5.18
5	3070	1541.5	0.50	70.01	30.15	9.54	4.77
6	3070	268.8	0.41	79.69	25.26	10.60	5.20
7	3070	1221.9	0.40	76.62	26.75	10.50	5.13
8	3070	981.8	0.32	74.44	28.39	10.30	4.82
9	3070	1286.9	0.42	73.93	38.28	11.50	5.65
10	3070	1775.9	0.58	78.38	68.87	12.50	6.14
11	3070	1661.8	0.54	87.18	88.70	15.40	7.68
12	3070	1565.5	0.51	85.91	84.08	16.10	8.03

The easiest way for most users to assess the models is probably to actually examine the maps generated from the final models. The following url gives links to an internet mapper that provides both the Canadian Model 1 and 2 results resolved with a 300 arc second (~10km grid) DEM (follow the 1971/2000 Canadian model link).

www.glfc.cfs.nrcan.gc.ca/landscape/climate_models_e.html

While the internet mapper is not a Geographic Information System (GIS) it does have some GIS functions. When a user first accesses the URL, they will see the January precipitation for both models. Doing a query will return the grid estimates for both models. Users can display other grids or the station data by "adding layers". Users can also change the map size and focus on a particular province or subregion by using

Table 3. Surface diagnostics for Model 2 – includes stations that may operate only during part of the year

Maximum Temperature

Month	Points	Signal	Ratio	Mean	Stdev	rtgcv	Rtmse
1	2836	935.2	0.33	-6.244	6.51	1.11	0.52
2	2852	680.9	0.24	-3.670	6.14	0.97	0.41
3	2861	751.3	0.26	1.757	5.42	0.82	0.36
4	2857	956.7	0.33	9.059	4.60	0.77	0.36
5	3016	1352.7	0.45	15.756	4.12	0.77	0.38
6	3067	1492.0	0.49	20.193	3.54	0.78	0.39
7	3052	1611.5	0.53	23.044	3.26	0.73	0.36
8	3042	1301.6	0.43	22.283	3.32	0.75	0.37
9	3010	1004.7	0.33	17.133	3.39	0.75	0.36
10	2872	993.5	0.35	10.386	3.79	0.54	0.26
11	2839	1276.1	0.45	2.012	5.08	0.61	0.30
12	2813	1252.1	0.45	-4.011	5.95	0.81	0.40

Minimum Temperature

Month	Points	Signal	Ratio	Mean	Stdev	rtgcv	Rtmse
1	2837	1175.2	0.41	-15.640	7.96	1.45	0.71
2	2853	978.5	0.34	-13.729	7.40	1.40	0.67
3	2862	1163.2	0.41	-8.638	6.18	1.09	0.54
4	2860	1096.7	0.38	-1.966	4.44	0.79	0.38
5	3017	1310.9	0.43	3.712	3.26	0.79	0.39
6	3068	1388.3	0.45	8.373	2.79	0.82	0.41
7	3053	1695.9	0.56	11.039	2.76	0.86	0.43
8	3043	1651.9	0.54	10.314	2.88	0.96	0.48
9	3010	1612.2	0.54	5.935	3.16	0.99	0.49
10	2872	1373.1	0.48	0.742	3.80	0.89	0.44
11	2840	1418.8	0.50	-5.737	5.88	0.94	0.47
12	2814	1449.9	0.52	-12.531	7.27	1.21	0.60

Precipitation

Month	Points	Signal	Ratio	Mean	Stdev	rtgcv	Rtmse
1	3287	1465.1	0.45	78.120	76.35	15.50	7.67
3	3289	1487.0	0.45	64.140	55.29	12.60	6.26
4	3335	1544.7	0.46	59.480	43.29	11.10	5.52
5	3544	1578.5	0.45	68.900	29.90	10.40	5.16
6	3612	1432.2	0.40	80.270	25.27	11.30	5.53
7	3610	1222.0	0.34	77.230	27.16	11.40	5.38
8	3594	956.3	0.27	74.070	27.90	11.40	5.03
9	3520	1398.2	0.40	72.230	37.84	12.20	5.96
10	3362	1909.5	0.57	77.450	68.93	13.20	6.51
11	3283	1777.0	0.54	86.930	89.80	16.30	8.09
12	3256	1581.2	0.49	85.230	83.08	16.20	8.11

Table 4. Surface Diagnostics for North American models

Maximum Temperature

Month	Points	Signal	Ratio	Mean	Stdev	rtgcv	Rtmse
1	8034	1783.7	0.69	1.20	8.83	0.83	0.34
2	8034	1559.2	0.60	3.92	8.65	0.79	0.31
3	8034	1503.8	0.58	8.90	7.88	0.75	0.29
4	8034	1645.8	0.63	14.94	6.56	0.76	0.31
5	8034	1864.1	0.72	20.67	5.46	0.77	0.32
6	8034	1973.4	0.76	25.23	5.19	0.77	0.33
7	8034	2076.1	0.80	27.94	4.89	0.77	0.34
8	8034	2070.7	0.80	27.23	4.94	0.74	0.32
9	8034	1972.2	0.76	22.82	5.61	0.71	0.31
10	8034	1884.1	0.72	16.49	6.35	0.61	0.26
11	8034	1918.6	0.74	8.57	7.49	0.59	0.25
12	8034	1959.4	0.75	2.95	8.26	0.69	0.30

Minimum Temperature

Month	Points	Signal	Ratio	Mean	Stdev	rtgcv	Rtmse
1	8035	1925.3	0.74	-9.72	8.48	1.23	0.52
2	8035	1825.8	0.70	-7.76	8.08	1.22	0.51
3	8035	1760.6	0.68	-3.28	7.04	1.04	0.43
4	8035	1849.5	0.71	1.91	5.58	0.92	0.39
5	8035	1916.5	0.74	7.27	5.02	0.91	0.39
6	8035	2077.1	0.80	11.82	4.86	0.93	0.41
7	8035	2072.8	0.80	14.40	4.66	0.97	0.43
8	8035	2032.0	0.78	13.64	4.69	1.03	0.45
9	8035	2000.0	0.77	9.45	5.19	1.08	0.47
10	8035	1953.1	0.75	3.73	5.19	1.11	0.48
11	8035	1980.3	0.76	-2.09	6.29	1.03	0.44
12	8035	2012.5	0.77	-7.52	7.63	1.12	0.49

Precipitation

Month	Points	Signal	Ratio	Mean	Stdev	rtgcv	Rtmse
1	10646	2670	0.86	70.54	64.41	10.20	4.41
2	10646	2682	0.87	60.54	54.12	8.69	3.77
3	10646	2665	0.86	73.07	51.22	9.37	4.06
4	10646	2589	0.84	68.51	39.40	8.07	3.46
5	10646	2448	0.79	81.58	37.85	8.37	3.52
6	10646	2129	0.69	81.91	36.94	8.69	3.47
7	10646	1932	0.62	77.83	38.07	8.83	3.40
8	10646	1977	0.64	74.30	36.63	8.54	3.32
9	10646	2373	0.77	74.15	40.07	8.51	3.54
10	10646	2646	0.85	70.18	49.66	8.18	3.53
11	10646	2750	0.89	77.13	65.58	9.60	4.20
12	10646	2670	0.86	72.86	66.19	10.20	4.42

Note: Because of the large number of stations the Splinb version of ANUSPLIN was required for the North American models. In this case "knots" must be selected. A higher signal to error ratio is generally expected in these cases and is evident but they remain within recommended levels (see Hutchinson and Gessler 1994).

the zoom function. The individual monthly grids can be turned on or off, stacked, zoomed and queried. A particularly useful aspect of the web site is the capacity to overlay the station data. The observed value, estimated value (at that specific location), difference and Bayesian standard error estimate can be returned as well as the nearest grid point estimate. Where residuals seem higher they are often explained by apparently contradictory values at nearby stations. It also should be remembered that some regions have inherently more variable mean conditions.

The North American monthly and bioclimate model results can be accessed at the same URL noted above. The North American models have been useful for international collaborative efforts for a number of species modelling efforts (see for example www.planthardiness.gc.ca).

Conclusions

There appears a growing demand for spatially reliable climate models at various time and spatial resolutions for numerous economic sectors. This note provides some details about 1971/2000 models for both Canada and North America. Results indicate that these are robust and reliable models. We note that assessments of model quality are challenging tasks. The model diagnostics in combination with the Internet accessibility of the

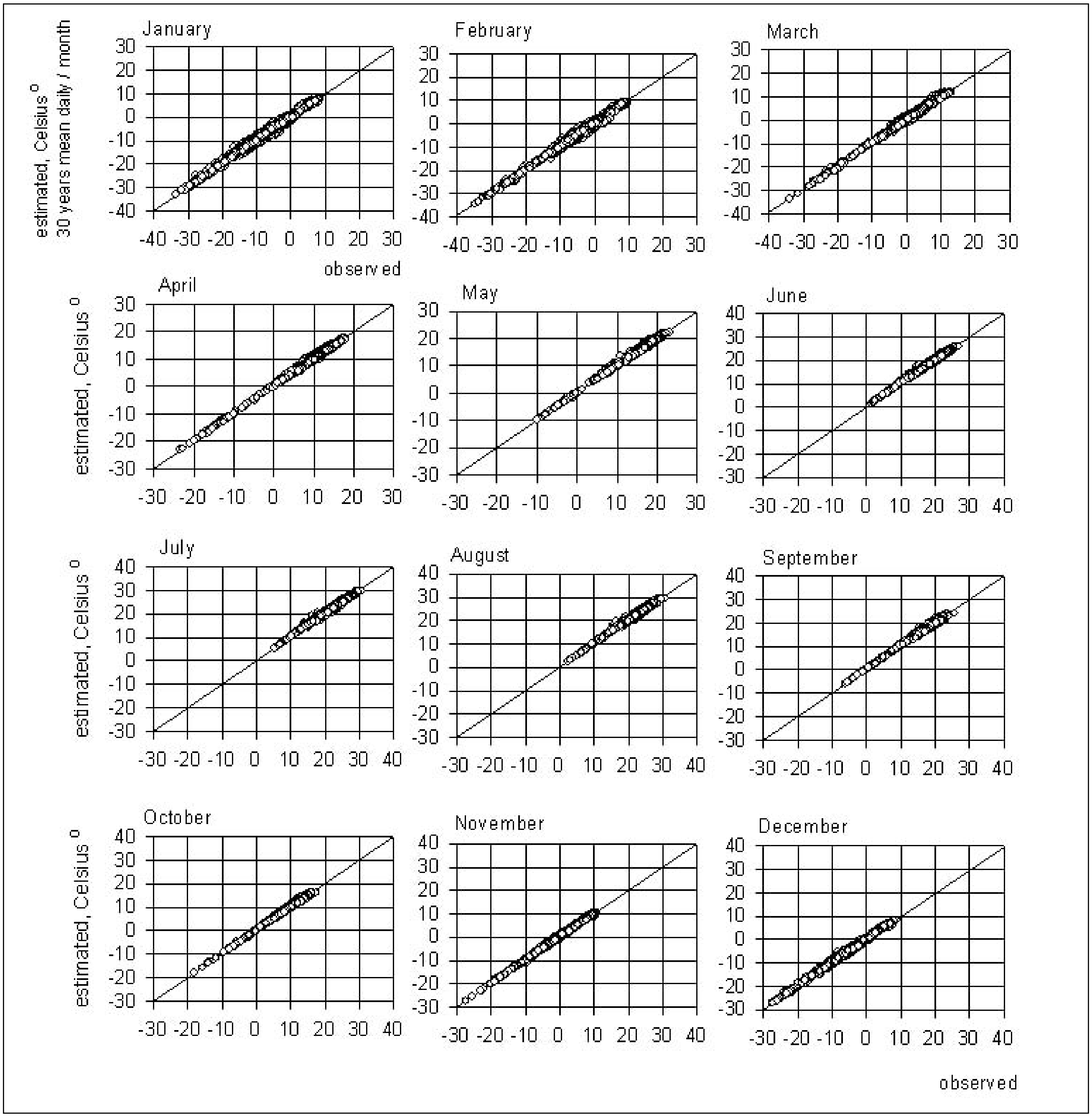

Figure 3. Maximum Temperature estimated vs. observed, Model 1, all stations

maps and the source data are intended to help users assess the quality and utility of the models for their own applications. All models presented here can be used to generate both point estimates (e.g., at field survey locations) and regular grids of the climate variables of interest. Contact the senior author for further details on how to obtain point estimates or grids for your region.

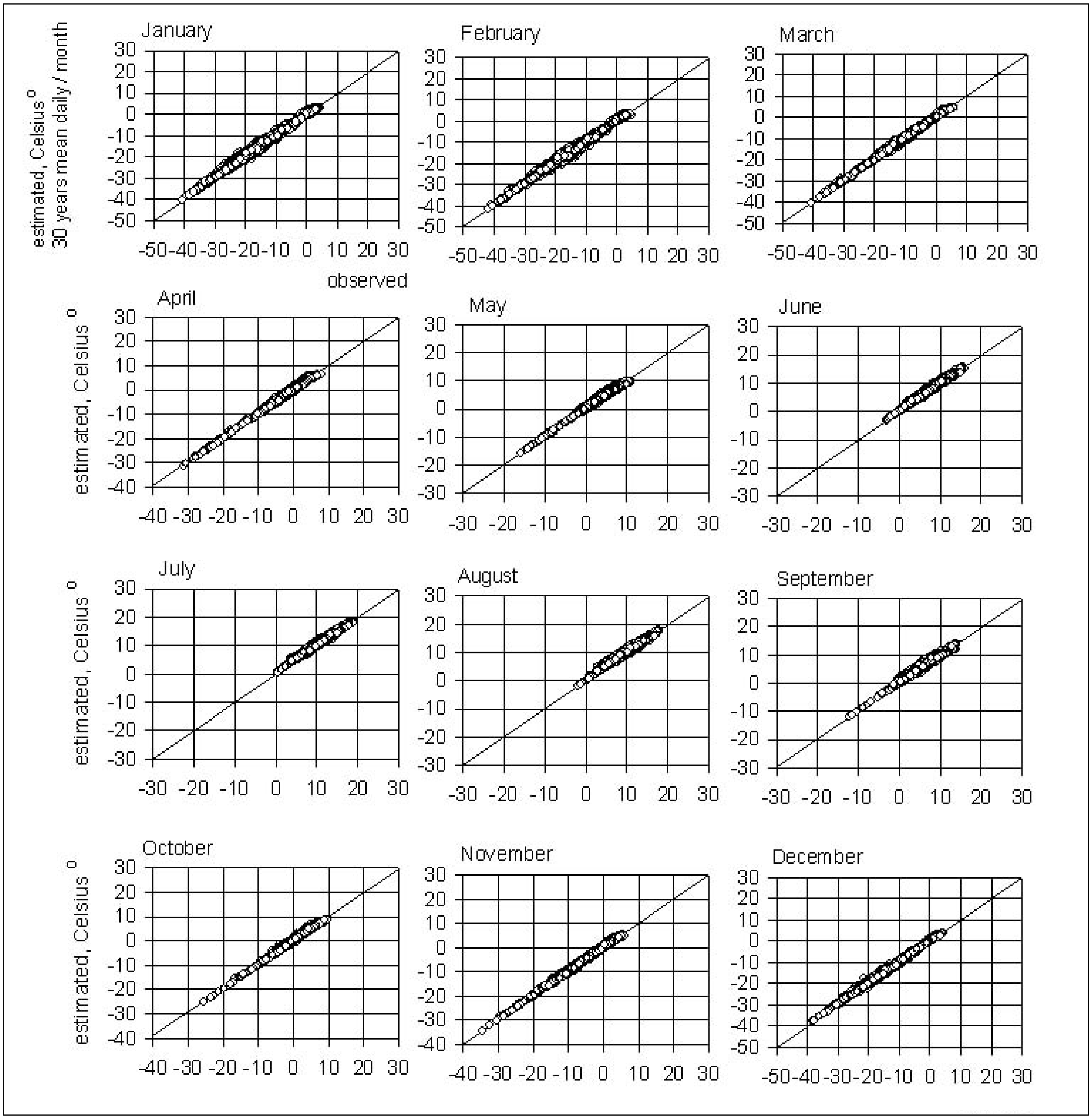

Figure 4. Minimum temperature estimated vs. observed, Model 1, all data

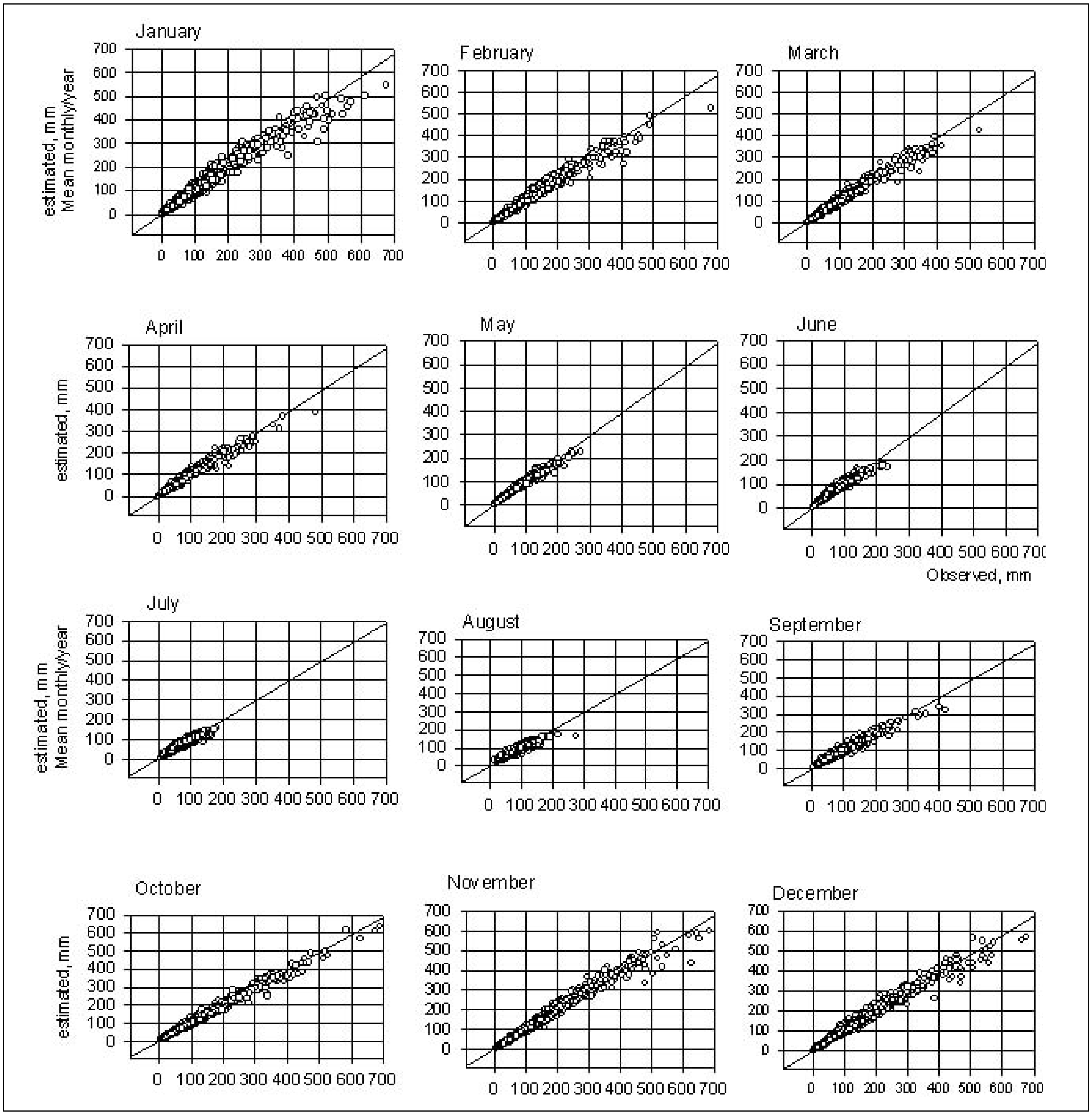

Figure 5. Precipitation estimated vs. observed, Model 1, all data

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