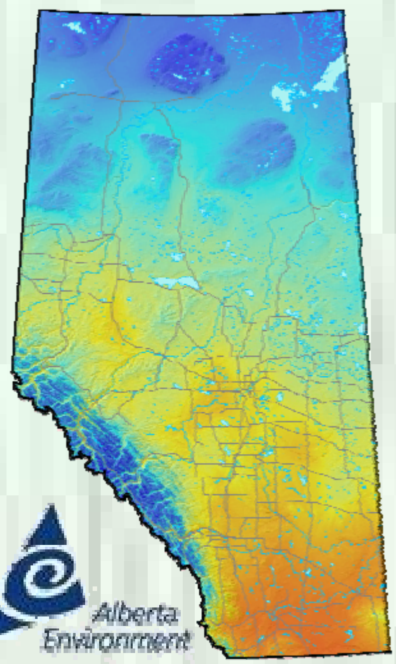
Alberta Climate Model (ACM) to Provide Climate Estimates (1961-1990) for Any Location in Alberta from its Geographic Coordinates



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Alberta Climate Model (ACM) to Provide Climate Estimates (1961-1990) for Any Location in Alberta from its Geographic Coordinates

Prepared for Alberta Environment
and
Alberta Sustainable Resource Development

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Alberta Environment

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Executive Summary

The relationship between climate and the distribution of plants and animals has been recognized for centuries. Most recently, concerns that climate is changing in ways that are having significant impacts on the Earth have stimulated interest in description and prediction of climate. Beyond that interest in climate lies questions of what associated changes may occur in aquatic and terrestrial ecosystems.

In a preliminary step to addressing questions of climatic change, an interdisciplinary group has expanded the database on Alberta climate. As in most jurisdictions, climatic stations in Alberta are concentrated in urban and agricultural areas with under representation of forests and poorly settled areas. Largely through interpolation, with some extrapolation, we have approximately tripled the number of geographic points for which consistent data are available. An archive containing data for monthly mean daily temperature, monthly mean daily maximum temperature, monthly mean daily minimum temperature and monthly mean precipitation has been produced. Data for each of the four variables are now easily accessible as monthly normals in the data archive.

Using data from the archive, values for 13 variables expected to be important in the distribution and responses of trees to climate have been derived. Mean temperature of the coldest month, degree-days above 5°C. and annual moisture index are examples. These variables will be used in on-going research on climate-forest tree relationships.

In addition, using the modern mathematical technique known as thin-plate splining, the pattern of fixed-point climate stations has been transformed into continuous surfaces that allow the estimation of climatic variables at any point in Alberta. This will be especially useful in addressing questions of climate-tree relationships at locations of experiments far removed from climatic stations. Splining also facilitates the production of maps at a scale of resolution of 500 meters. Examples of both point estimates and mapping are included.

The Alberta Climate Model is being used in a variety of research projects. These include studies of relationships between climate and forest productivity, distribution of peat lands, delineation of ecological regions and genetic responses of trees. Interest has been expressed in using the Model to assist in understanding habitat requirements for grizzly bears.

It should be noted that the Alberta Climate Model is based on records from Environment Canada for the period 1961-1990. The model is not a tool for predicting future climates.

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1. Background

Climate long has been recognized as a major factor in the distribution of plants and most animals. In a detailed exploration of the relationship between climate and plant distribution, Woodward (1987) indicates that recognition of the relationship was apparent at least twenty-five centuries ago. More recently, it has been recognized that the gene pool of populations of wild organisms is organized, by natural selection, to accommodate a climate in which those organisms are expected to live. Similarly, gene pools of domesticated plants and animals are organized, through breeding, to fit within specific climates. For both wild and domesticated populations, present climates are the standard although genetic variation allows flexibility for some degree of change.

The prediction of future climates has, in the last few decades, become of great interest both to the general public and to the scientific community. This interest is prompted by the possibility that climates may change significantly as a consequence of atmospheric changes caused by human activities. Any recognition of change would seem to require measurement from a more or less well–defined baseline, a requirement that is very difficult to achieve given the variability of climate.

The objective of the Alberta Climate Model is to provide a process for detailed description of Alberta climate, both for current use, and as a baseline from which to estimate impacts of changes suggested for future climates. The Model combines long-term records from weather stations with physiographic descriptors of station locations to allow the interpolation and extrapolation of values for climatic variables along gradients. Although built on a base of climatic data collected largely in agricultural environments, the Model facilitates estimation of values for climatic variables in areas poorly represented by climatic stations. This provides a much more complete picture of climate for the whole province.

2. Climate Data and Normalization

2.1 Variables

To describe aspects of current climate, climatic variables were divided into two groups. The first group, called “primary” variables, includes 48 variables provided by the national weather services of Canada and the United States. They are:

- monthly mean daily temperature
- monthly mean daily maximum temperature
- monthly mean daily minimum temperature
- monthly mean precipitation

An additional 13 variables, called “derived” variables, were calculated from the primary climatic data. Derived variables were chosen for their potential relationship to biological responses to climate. The choices represent a combination of personal experience and relationships demonstrated in literature. The variables are:

- mean annual temperature
- mean temperature of the warmest month

- mean temperature of the coldest month
- degree-days above 5° C.[1]
- degree-days less than 0° C.[1]
- mean Julian day on which degree-day sum reaches 100[1]
- mean maximum daily temperature of warmest month
- mean minimum daily temperature of coldest month
- summer-winter temperature differential[2]
- mean annual precipitation
- mean sum of summer precipitation (April to September)
- annual moisture index[3]
- annual summer moisture index[3]

1 Procedures for estimation are in Appendices.

2 Calculated from mean temperature warmest month – mean temperature coldest.

3 Annual moisture index is degree-days >5° C. /mean annual precipitation; Summer moisture index is degree-days >5° C/mean summer precipitation.

2.2 Data

The most common source of climatological records is national meteorological agencies. For Canada, arithmetic averages of 30-year records were first produced in 1930 and have been published every 10 years since. Records covering periods of 30 years originally were considered to be long enough to eliminate year-to-year variations (Environment Canada 1993). For the Alberta Climate Model, records for the period 1961 to 1990 were chosen to provide the highest sampling intensity and the possibility that the latest available data would be the most accurate. This choice follows the recommendation of the Intergovernmental Panel on Climate Change (IPCC 1999). Data were available for 32 variables but not all were represented at all stations or in all periods.

Records for periods of at least 20 years are now regarded as reliable for the national database (Environment Canada 1993). To increase the intensity and distribution of climatic stations providing data for the ACM, stations with temperature records for at least 5 years, and precipitation records for at least 7 years were included. The assumption here is that (within limits), records for periods of less than 20 years are more useful than no records, particularly in northern Alberta and at high elevations where there are few stations with many years of complete records. The adjustment of shorter-term records based on records of at least 20 years is discussed in Section 2.2.2.

Observations from climatic stations in Canada were provided on a compact disk purchased from Environment Canada (1993). For the U.S., climatic data were taken from compact disks purchased from the U.S. Department of Commerce (1994) and Earthinfo (1994).

2.2.1 Geographic representation - In addition to climate data from Alberta, data from portions of 6 adjacent jurisdictions were used to more accurately represent areas of Alberta near its borders. The area from 47° to 62° N. Latitude and 108° to 122° W. Longitude was included. For the target area, Table 1 summarizes the number of climatic stations available in records from national weather services. From a total of 2041 stations, data from between 1260 and 1433 met restrictions on number of years of observations. Observations on precipitation were more numerous than those for temperature. Not all of these, however, had records for all months.

Table 1. Number of climatic stations for the target area in data from the national climatic services of Canada and the U.S.

	Total Number of Stations	Mean Monthly Maximum Temperature	Mean Monthly Minimum Temperature	Mean Monthly Temperature	Mean Monthly Precipitation
Alberta	1089	593	593	590	725
Saskatchewan	148	98	98	98	118
British Columbia	564	354	355	353	359
Yukon	23	14	14	14	14
Canadian Totals	1824	1059	1060	1055	1216
Idaho	19	19	19	19	19
Montana	116	106	106	106	116
Washington	82	80	80	80	82
U.S. Totals	217	205	205	205	217
Totals for Study Area	2041	1264	1265	1260	1433

As a consequence of patterns of topography and human settlement, there is a concentration of data from 500 to 1200 m. and from 49° to 57° North Latitude. The operation of seasonal stations at higher elevations and higher latitudes resulted in a shortage of observations for those areas (Figure 1).

2.2.2 Normalization procedure – Climatic data for the period 1887 to 1993 were obtained from Environment Canada as monthly mean values. Although interest was mainly in data from the 1961 to 1990 period, use of data from earlier periods allowed a greater number of observations to be used. For the 1961 to 1990 records, monthly means by year for temperature were omitted if observations were missing for more than 3 consecutive days or more than a total of 5 days. For precipitation, monthly means by year were omitted if observations for one or more days were missing. Months for which at least the minimum data are available are termed “valid months” (Environment Canada 1993).

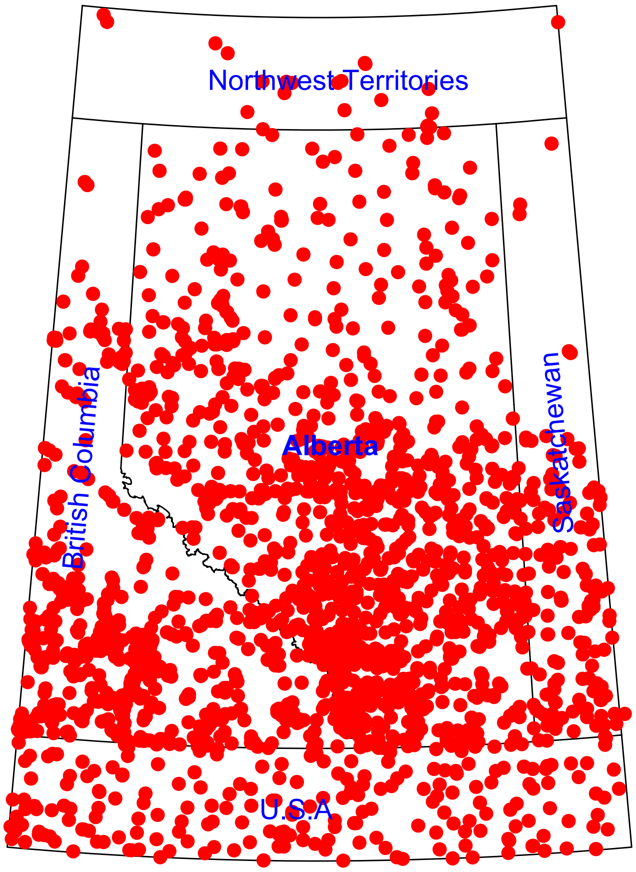

Figure 1. Distribution of normalized climatic stations in the target area.

Climate data typically are provided as “normals” to represent an average value over a period of time. In the simplest case, where substantial numbers of observations are available for a temperature variable, the arithmetic average was used. For precipitation, the sum was used. Data obtained from Environment Canada are described as monthly “normals”. For the ACM, these values provide the starting point and are considered to be “raw” data since they have received no adjustment except averaging.

To ensure that records for stations with less than 20 observations were credible, values were adjusted by reference to stations with records for at least 20 years (standard stations). Two protocols were considered. The first, used by Environment Canada for production of 1951 to 1980 normals (Environment Canada undated), was to select one standard station for a district with “… similar climate and physiographic characteristics.” and observations over at least 28 years. For stations with at least 5 years of observations, values were paired with comparable values for the standard station and a simple correlation was calculated. Pairs of stations with the highest correlation were chosen and adjustments were made to data from the station with the shorter record. The normal for the station with the shorter record was the normal for the standard station plus the average difference between records for the paired stations. This procedure was tested with data for the ACM and was rejected due to the small number of observations available for estimation of the correlation coefficient.

For the ACM, the procedure chosen for normalization of stations with less than 20 years of records was a modification of the current approach by Environment Canada. The method is described in Alisov, *et al.* (1952). For each raw station, all standard stations within certain horizontal and vertical distances were identified. About 500 standard stations were available within the target polygon. Distance limits for sequential screening of standard stations are in Table 2. Where available within the distance limits, the 3 closest standard stations were chosen and climatic data from each were used to produce a normal for the raw station. Where 3 standard stations were not available at the first screening level, restrictions were sequentially relaxed until the best available data from standard stations were identified. For the great majority of raw stations, three standard stations were located within 100 kilometers of horizontal distance and 300 meters of vertical distance (Table 2).

Table 2. Distance limits, number of stations required, and percentage of cases at each of four levels of screening to identify standard stations used in normalization.

SCREENING	HORIZONTAL DISTANCE (km)	VERTICAL DISTANCE (m)	NUMBER OF STATIONS	PERCENT OF CASES (all primary variables)
LEVEL 1	100	300	3	86.3-87.4
LEVEL 2	100	500	1-3	5.1-5.9
LEVEL 3	300	500	1-3	6.8-7.4
LEVEL 4	300+	500+	3	0.1-0.5

The normalization procedure is illustrated in Table 3 for January mean temperature for the raw station at Anthracite. The deviation of a raw station from a standard station for years of common record is calculated and added to the normal for the standard station for 1960 to 1990 period. The resulting normals are then averaged to produce a normal for the raw station.

Table 3. An example of the normalization protocol for January mean temperature at Anthracite.

Year	Raw Station Anthracite	Standard Station 1 Banff	Standard Station 2 Kananaskis	Standard Station 3 Lake Louise
1930	-19.4	-19.7		-24.1
1931	- 3.9	- 3.8		- 9.2
1932				
1933	- 8.6	- 8.5		-12.1
1934	- 4.9	- 5.0		- 9.2
1935	-12.6	-12.6		-14.3
1936	-10.2			
1937	-19.0	-20.1		-23.9
1938	- 8.1	- 8.4		-13.3
1939	- 5.4	- 5.2		- 8.7
1940	- 11.0	-12.1	- 9.1	-15.5
1941	- 6.9	- 6.6	- 5.5	- 9.3
1942	- 9.2	- 9.5	- 3.7	-13.8
1943	-15.8	-16.0	-15.5	-18.4
1944	- 5.9	- 6.3	- 3.1	-10.5
1945	- 6.8	- 7.1	- 4.7	-10.7
1946	- 5.7	- 6.2	- 4.1	-10.0
1947	- 9.0	- 9.5	- 6.9	-12.7
1948	- 6.3	- 6.1	- 3.6	-10.5
1949	-14.7	-15.5	-11.2	-19.1
1950	-25.4	-26.5	-28.4	-28.4
1951	-12.7	-14.4	-11.8	-16.6
1952	-11.9	-12.8	-13.3	-15.7
1953	- 8.0	- 8.9	- 6.9	-10.3
1954	-15.5	-15.7	-15.8	-17.9
1955	- 7.9	- 8.8	- 6.2	-13.2
1956	-11.3	-11.1	- 9.8	-14.1
1957	-15.9	-16.4	-15.8	-20.7
1958	- 4.0	- 4.5	- 1.3	- 8.9
1959	- 9.9	-10.9	-10.3	-14.2
1960	-10.3	-10.4	- 8.2	-15.0
1961	- 5.6	- 5.4	- 4.3	-10.3
1962	-11.5	-10.9	- 7.7	-14.3
1963		-14.3	-12.0	-18.7
1964-1990		-10.02	- 8.32[1]	-14.38

[1]Obervations for 1961 to 1990 are complete except for 1970 and 1971 at Kananaskis

Anthracite with Banff	-10.4226	(31)	Banff with Anthracite	- 10.8032 (31)
Anthracite with Kananaskis	-10.4870	(23)	Kananaskis with Anthracite	- 9.0087 (23)
Anthracite with Lake Louise	-10.4226	(31)	Lake Louise with Anthracite	- 14.3800 (31)

Estimate 1 = Anthracite (1930 to 1962)	- Banff (1930 to 1962)	+ Banff (1961 to 1990)	= - 9.6360
Estimate 2 = Anthracite (1940 to 1962)	- Kananaskis (1940 to 1962)	+ Kananaskis (1961 to 1990)	= - 9.7961
Estimate 3 = Anthracite (1930 to 1962)	- Lake Louise (1930 to 1962)	+ Lake Louise (1961 to 1990)	= - 10.4510

Normal for Anthracite is ((-9.6390) + (-9.7961) + (-10.4510))/3 = -9.9610

2.2.3 Verification of normalization procedure – To check on how consistent were the results of the normalization procedure, pairs of observations involving 19 stations were compared. The stations, all with more than 20 years of observations, were chosen to represent all of the climatic zones of Alberta. Some remote and/or high elevation stations that might be difficult to normalize due to lack of standard stations in close proximity also were included. For each station, every second observation was removed thereby creating a "dummy" set of observations that required application of the normalizing procedure described above. After normalization, values from the "dummy" station were regressed on values from the standard station. Figure 2 shows results for four variables spanning the range from most consistent (maximum temperature) to least consistent (annual precipitation, r^2=0.98). These plots suggest that the normalization gave very consistent results.

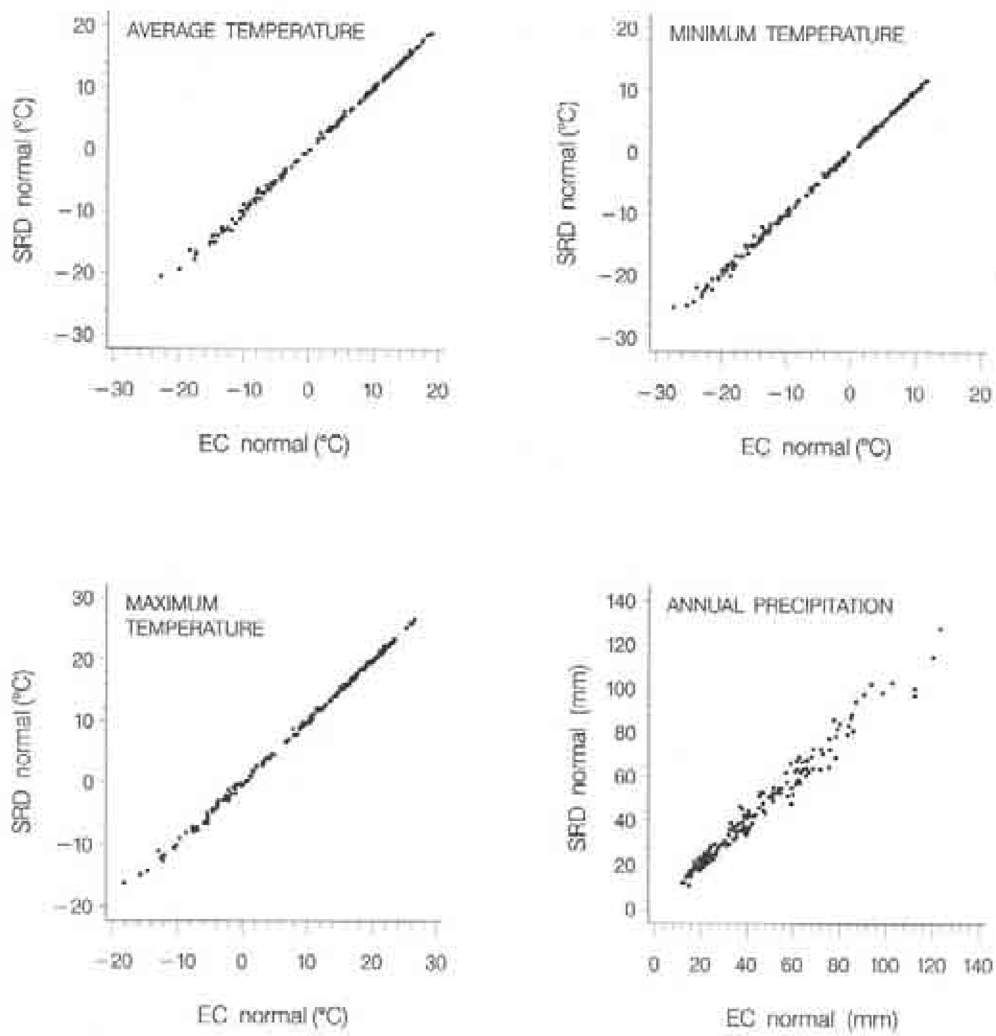

Figure 2. Plots of normals from national climatic services (EC normal) and values developed from the normalization protocol described in the text (SRD normal). Monthly values for 19 stations were compared.

2.3 The archive

The number of climatic stations represented in normalized data from the national weather services varied by primary variable. The range was from 480 (monthly mean minimum temperature) to 538 (monthly mean precipitation). After completing the normalization procedure, the number of stations ranged from 1264 (monthly mean maximum temperature) to 1433 (monthly mean precipitation). Because all primary variables were not reported for all stations (data at some stations were not recorded during the winter), the range in number of observations in the data archive is 1016 to 1133 for data from January and 1193 to 1359 for data from July. The minimum number of observations is in January and the maximum is in July.

The archive is a 23 by 5222 matrix with 10 coding variables and 13 columns of data variables. A sample is in Table 4. The archived data can be accessed using the READ.ME statement in Appendix 3.

3. Models

Although the approach taken in Section 2 provided many more estimates for climatic variables, some geographic areas are necessarily poorly sampled. Moreover, geographic locations for which estimates may be needed, such as field experiments and locations for proposed facilities, often are not near climatic stations. At the most elementary level, arithmetic interpolation with data among existing stations has been used but it is difficult or impossible to incorporate local topographic effects with this approach. Recently, techniques have been developed which allow the incorporation of geographic variables and which produce mathematical functions that allow point or area estimates along a geographic continuum. The functions follow the general form of polynomial regression.

3.1 Choice of model

An original technique for fitting noisy multi-variate data to a smoothed continuous surface is called thin plate splining. It was developed by Wahba (1990) and has progressed through modifications that allow application to large data sets and the inclusion of covariates. At the start of development of the Alberta Climate Model, a routine for fitting noisy multi-variate data named ANUSPLIN was the only one available. Subsequently, a different method, named PRISM, became available. ANUSPLIN, however, is considered to be the better choice for this project for three reasons: the model can be operated locally rather than sending input to a central location for analysis, output can accommodate several climatic variables in a way that they can be overlaid to produce multivariate views of climate, and point estimates from ANUSPLIN match adiabatic lapse rates.

3.2 The ANUSPLIN Model

ANUSPLIN is described as a package of "…FORTRAN programs for fitting surfaces to noisy data as functions of one or more independent variables…" (Hutchinson 2000). There are nine individual programs, which can accept up to 10,000 data points to produce fitted surfaces. A substantial advantage of the package is the production of statistics, which estimate the degree of fit between the spline and the input dependent variable.

Table 4. A sample of the data archive.

0100525	AVERY RANGER STN	47	15	115	48	759	PRCP	034	5	115	83	73	63	70	61	32	42	44	55	101	96	836
0100528	AVERY RANGER STN 2	47	15	115	55	729	PRCP	034	4	136	92	82	65	71	59	33	40	52	67	107	115	919
0100667	BAYVIEW MODEL BASIN	47	59	116	33	633	PRCP	034	4	77	61	52	45	53	49	25	31	35	46	79	86	638
0101079	BONNERS FERRY 1 SW	48	41	116	19	567	PRCP	034	4	81	50	41	37	42	41	24	29	36	45	90	87	602
0101272	BURKE 2 ENE	47	32	115	48	1247	PRCP	034	5	175	133	123	82	82	85	33	44	66	89	143	156	1211
0101363	CABINET GORGE	48	5	116	4	689	PRCP	034	4	109	81	66	53	56	59	26	41	42	55	110	113	812
0101831	CLARKIA RANGER STATI	47	1	116	15	865	PRCP	034	5	148	95	79	61	72	56	35	38	45	67	98	131	924
0101956	COEUR D'ALENE RS	47	41	116	45	658	PRCP	034	4	88	63	58	43	52	50	23	33	30	41	84	93	659
0104831	KELLOGG	47	32	116	7	707	PRCP	034	4	107	74	71	59	63	55	27	36	45	51	95	104	787
0106230	MULLAN	47	28	115	48	1011	PRCP	034	5	122	106	95	66	68	63	32	40	49	74	112	119	945
0106235	MULLAN AIRPORT	47	28	115	46	1093	PRCP	034	5	159	105	92	68	64	67	32	40	60	83	135	138	1042
0106237	MULLAN PASS CAA AIRP	47	27	115	40	1826	PRCP	034	5	154	104	102	53	58	69	28	51	54	71	108	144	994
0107264	PORTHILL	49	0	116	30	541	PRCP	034	4	57	40	38	35	44	46	27	32	36	35	70	64	524
0107386	PRIEST RIVER EXP STN	48	21	116	50	726	PRCP	034	4	101	79	70	53	62	52	31	37	39	51	110	113	798
0108062	SAINT MARIES	47	19	116	34	677	PRCP	034	4	105	75	70	55	57	51	25	34	36	47	91	99	746
0108137	SANDPOINT EXP STATION	48	17	116	34	640	PRCP	034	4	103	84	72	54	64	57	32	41	43	60	120	119	851
0109029	DESMET 1 S	47	10	116	55	780	PRCP	034	5	93	67	62	45	53	42	25	24	32	38	77	85	640
0109493	WALLACE	47	28	115	56	845	PRCP	034	5	168	130	107	83	68	69	44	46	61	84	157	153	1168
0109498	WALLACE WOODLAND PARK	47	30	115	53	896	PRCP	034	4	140	103	95	71	72	66	33	38	50	70	127	133	997
0240075	ALBERTON	47	0	114	29	932	PRCP	034	5	53	35	37	40	52	52	30	36	37	36	44	40	490
0240364	AUGUSTA	47	29	112	23	1241	PRCP	034	4	13	11	17	27	59	61	32	36	33	17	12	14	332
0240392	BABB 6 NE	48	56	113	22	1311	PRCP	034	4	20	16	23	31	69	79	42	48	50	22	19	20	437
0240755	BIGFORK 13 S	47	53	114	2	887	PRCP	034	4	49	32	38	38	69	74	38	47	51	37	42	54	569
0240770	BIG SANDY	48	10	110	7	823	PRCP	034	4	16	10	15	27	69	59	38	36	38	19	11	15	353
0240877	BLACKLEAF	48	1	112	26	1291	PRCP	034	4	14	13	18	30	61	62	34	41	31	13	12	14	343
0241080	BRADY AZNOE	47	58	111	21	1024	PRCP	034	5	7	5	15	23	59	56	32	37	27	13	8	7	286
0241202	BROWNING	48	34	113	1	1328	PRCP	034	4	28	20	23	31	56	62	37	37	34	23	24	22	397
0241525	CARTER 14 W	47	47	111	13	1052	PRCP	034	5	15	11	20	27	61	56	29	37	31	17	13	13	328
0241552	CASCADE 5 S	47	13	111	43	1034	PRCP	034	4	16	12	28	39	75	62	36	40	41	23	16	17	405
0241557	CASCADE 20 SSE	47	0	111	35	1402	PRCP	034	4	15	10	20	31	72	67	35	36	43	23	13	15	378
0241692	CHESTER	48	31	110	57	965	PRCP	034	4	11	7	14	20	45	55	37	31	21	10	9	12	270
0241695	CHESTER 31 N	48	58	110	58	1036	PRCP	034	5	10	7	11	21	43	53	24	29	33	9	6	7	253
0241722	CHINOOK	48	35	109	14	713	PRCP	034	4	14	7	12	28	54	51	39	34	38	14	9	14	315
0241737	CHOTEAU AIRPORT	47	49	112	10	1203	PRCP	034	4	7	5	10	20	51	55	33	33	26	11	8	9	269
0241824	CLEVELAND 5 ENE	48	19	109	4	1015	PRCP	034	4	20	13	26	39	68	67	40	35	39	22	18	17	404
0241974	CONRAD AIRPORT	48	10	111	58	1078	PRCP	034	4	13	8	17	24	54	57	31	35	27	12	12	12	302
0242104	CRESTON	48	11	114	8	896	PRCP	034	4	37	29	32	37	62	70	42	41	45	32	37	43	507
0242173	CUT BANK FAA AP	48	36	112	22	1170	PRCP	034	4	10	7	14	21	56	62	33	40	28	11	9	8	300
0242301	DEL BONITA	49	0	112	47	1322	PRCP	034	4	14	10	20	31	64	81	33	45	39	13	12	11	372
0242347	DENTON 1 NNE	47	20	109	57	1104	PRCP	034	4	15	10	16	26	77	67	44	41	37	23	12	16	383
0242438	DODSON	48	24	108	15	695	PRCP	034	4	10	7	11	20	52	49	39	30	27	12	8	10	274
0242550	DUNKIRK 15 NNE	48	41	111	35	1027	PRCP	034	5	11	8	15	17	51	49	36	34	23	13	11	11	280
0242576	DUPUYER 7 WNW	48	15	112	38	1251	PRCP	034	5	11	9	14	19	49	61	44	41	32	14	9	9	311
0242629	EAST GLACIER	48	27	113	13	1466	PRCP	034	4	92	67	62	54	68	74	35	44	49	48	79	80	750
0242629	EAST GLACIER	48	27	113	13	1465	PRCP	034	4	87	61	57	51	64	72	36	47	51	49	74	77	725
0242812	ESSEX	48	17	113	37	1177	PRCP	034	5	126	94	80	72	77	78	47	44	76	72	125	113	1003
0242820	ETHRIDGE	48	34	112	8	1080	PRCP	034	4	8	6	13	22	50	58	31	36	26	11	7	6	275
0242827	EUREKA RANGER STATION	48	54	115	4	772	PRCP	034	4	33	21	21	23	42	52	32	31	30	23	29	32	368
0242857	FAIRFIELD	47	37	111	59	1214	PRCP	034	4	11	7	17	27	61	57	35	39	31	14	9	10	317
0243110	FORT ASSINNIBOINE	48	30	109	48	797	PRCP	034	4	13	9	16	25	51	48	36	35	34	15	10	14	306
0243113	FORT BENTON	47	49	110	40	804	PRCP	034	4	18	12	23	31	64	64	33	37	33	20	15	17	365

There are two principal outputs from the ANUSPLIN Model. The several output statistics allow assessment of how well the model is fitting the data. Poor fits may prompt an exploration of causes. Once the Model is accepted, interest may focus on one or both of two types of estimates for climatic variables. Since output from the spline is continuous, an estimate for a climatic variable can be obtained at any point. This capability is useful for characterizing climate at points that are distant from climatic stations.

A second type of estimate is the assignment of a point estimate to a grid in order to allow mapping. Although the distribution of values along a spline is continuous, limitations in mapping by computer require an area estimate to reduce the volume of data. For Alberta, a point estimate from the spline is assigned to a grid composed on one-kilometer polygons. The value for a climatic value is assigned as if it was in the center of the square although it is only certain that the value falls somewhere within the square. In the early stages of Model development, maps can provide an effective way to identify anomalies in the pattern of climate that may indicate invalid data.

3.2.1 Output statistics and their interpretation – Several statistics that measure the fit of splines to data are produced by ANUSPLIN. They are discussed and illustrated by McKenney *et al.* (2001). These are:

signal which indicates the degrees of error associated with each spline

square root of the generalized cross-validation statistic (RTGCV) that is similar to a spatially-averaged standard error where twice the statistic gives an approximation of the 95% confidence interval for the value of any point prediction

root mean square error (RTMSE) which estimates the standard error after estimated data error has been removed

residuals for stations with the poorest fit as an indication of possible data errors or very localized topographic effects.

4. Modeling and Model Output

4.1. The initial model (Climate Model I)

4.1.1 Procedural flow with ANUSPLIN – The initial steps in developing and validating a preliminary model, are indicated in Figure 3.

4.1.2 Sample size – From the normalized data in the archive, 270 to 300 observations per variable were withdrawn to provide a sample for verification. These data included 170 to 200 observations withdrawn from geographic areas where there were clusters of data and 100 observations withdrawn to improve geographic representation. They represented about 30% of the total observations. The remaining data formed the basis for development of the initial splines and included from 772 to 1062 observations per variable.

4.1.3 Output statistics – Output statistics from the preliminary model were reviewed and found to be within acceptable limits. Since they do not represent the full data set, results of the verification procedure received most attention. A scan of residuals, however, was valuable for locating data errors, the presence of stations whose data do not fit general trends, and identifying geographic sub-regions where errors of prediction may be the greatest, or locating other anomalies in the spline surfaces. To this end, output from the first spline fitting produced a root mean square error for temperature variables at one weather station that was approximately 0.4 units larger than for any other station. This station was from Coalspur, Alberta (number 3061674, latitude 53.18, longitude 117.00, elevation 1174m) and was eliminated from the final splines.

4.1.4 Verifying the model - Testing of any mathematical model involves verification of estimates made by the model with observed values that were not used to develop the model. A comparison of estimated values with observed then provides an assessment of the capabilities of the model and the confidence one can have in using it. Model testing procedures used here required (1) withdrawing and setting aside a sample of data from the data base (Verification Data Set (Fig. 3)), (2) developing a prototype of the model from data remaining in the data base (Climate Model I (Fig. 3)), (3) using the prototype to make estimates for locations represented in the withdrawn data, and (4) regressing observed values on the estimated. In judging the quality of the model (Verification Statistics (Fig. 3)), one customarily focuses on three statistics from the regression obtained in step 4: the goodness of fit (r^2), the value of the intercept, and the slope of the regression line. Ideally, the relationship should be statistically significant with estimated values accounting for a high proportion of the variance in the observed values; the intercept should not differ from zero; and the slope should not differ from 1.0 (Draper and Smith 1981).

Results of testing for the Alberta Model indicate an excellent fit. All regression equations were statistically significant at a probability less than 0.01. Degrees of freedom for the 48 equations were between 231 and 294. Intercepts for each of the four climatic variables included small negative and small positive figures for different months indicating an approximation of zero. Regression coefficients ranged from 0.95 to 1.06. Figure 4 illustrates results for four climatic variables that span the range of fit from closest to least close. Clearly, the slope of each regression is about 1 and the intercept is about 0. August minimum temperature had the poorest fit ($r^2 = 0.77$) and February average temperature had the closest fit ($r^2=0.98$). Note that the scales are different for each graph. In addition, maps were produced using data from the Model and were reviewed for anomalies (spikes and voids). Where anomalies were noted, observations from the geographically nearest stations were compared with data from the Model, programming errors in the archived data set were identified and corrected and the Model was re-run with corrected data.

4.2 The final model (Climate Model II)

After verifying the initial splines, the 100 independent observations that had been withdrawn from the archive were returned and splines were developed using the augmented data set. Observations withdrawn to reduce clusters of data points were not included to lessen possible over-representation of geographic areas where several stations were clustered.

4.2.1 Output statistics - Output statistics in Table 5 are from the second fitting of thin-plate splines (CLIMATE MODEL II) which included all valid data. In general, the splines fit as well as can be expected given the original distribution of the weather stations. No statistical procedures exist for accurate extrapolation to regions where stations do not exist. Because weather stations tend to be concentrated in valleys and in agricultural areas, it is perhaps surprising that the fit of the splines is as good as indicated by these results.

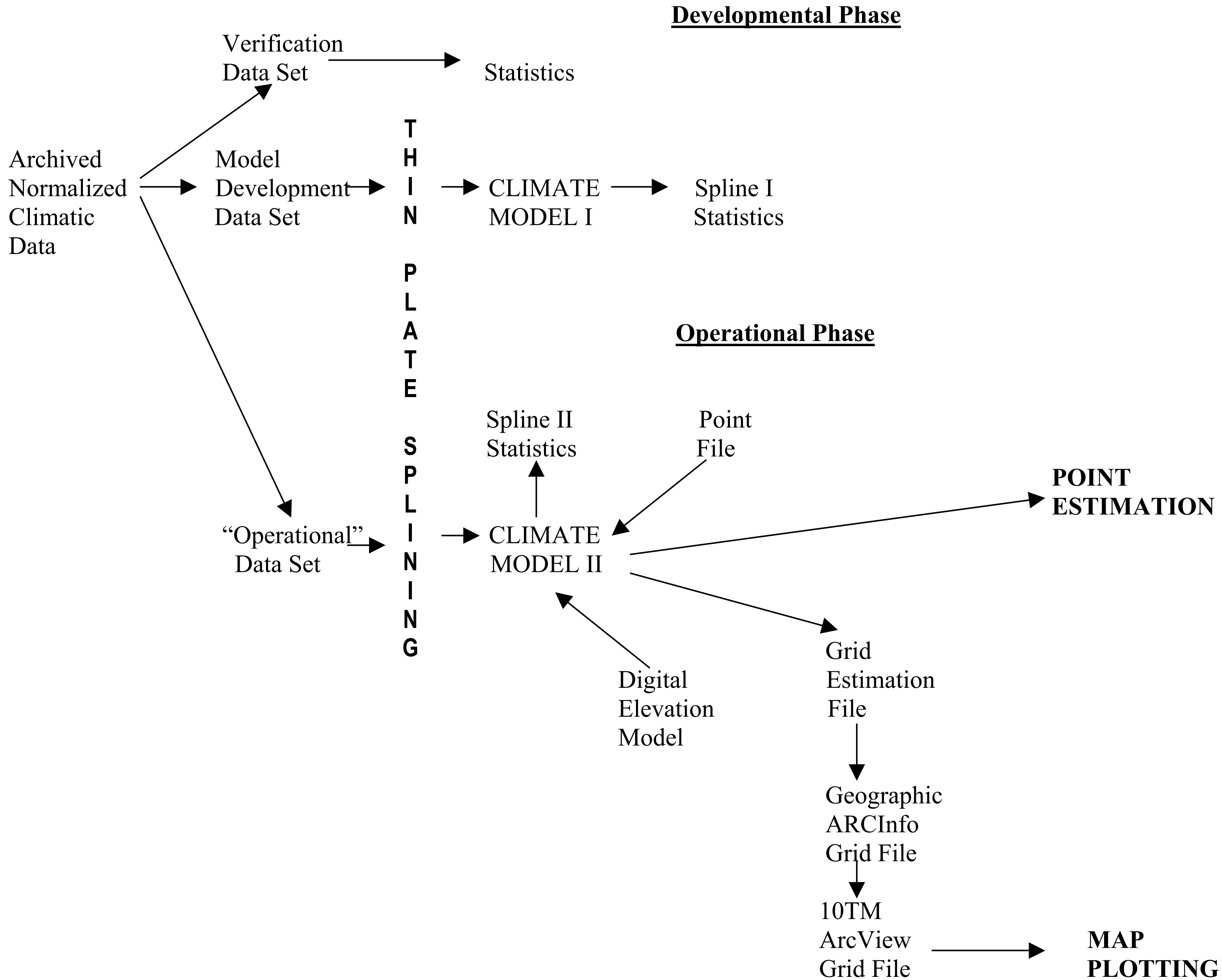

Figure 3. Flow diagram of data processing, analysis and validation from archival data to point estimates of climatic variables and to maps

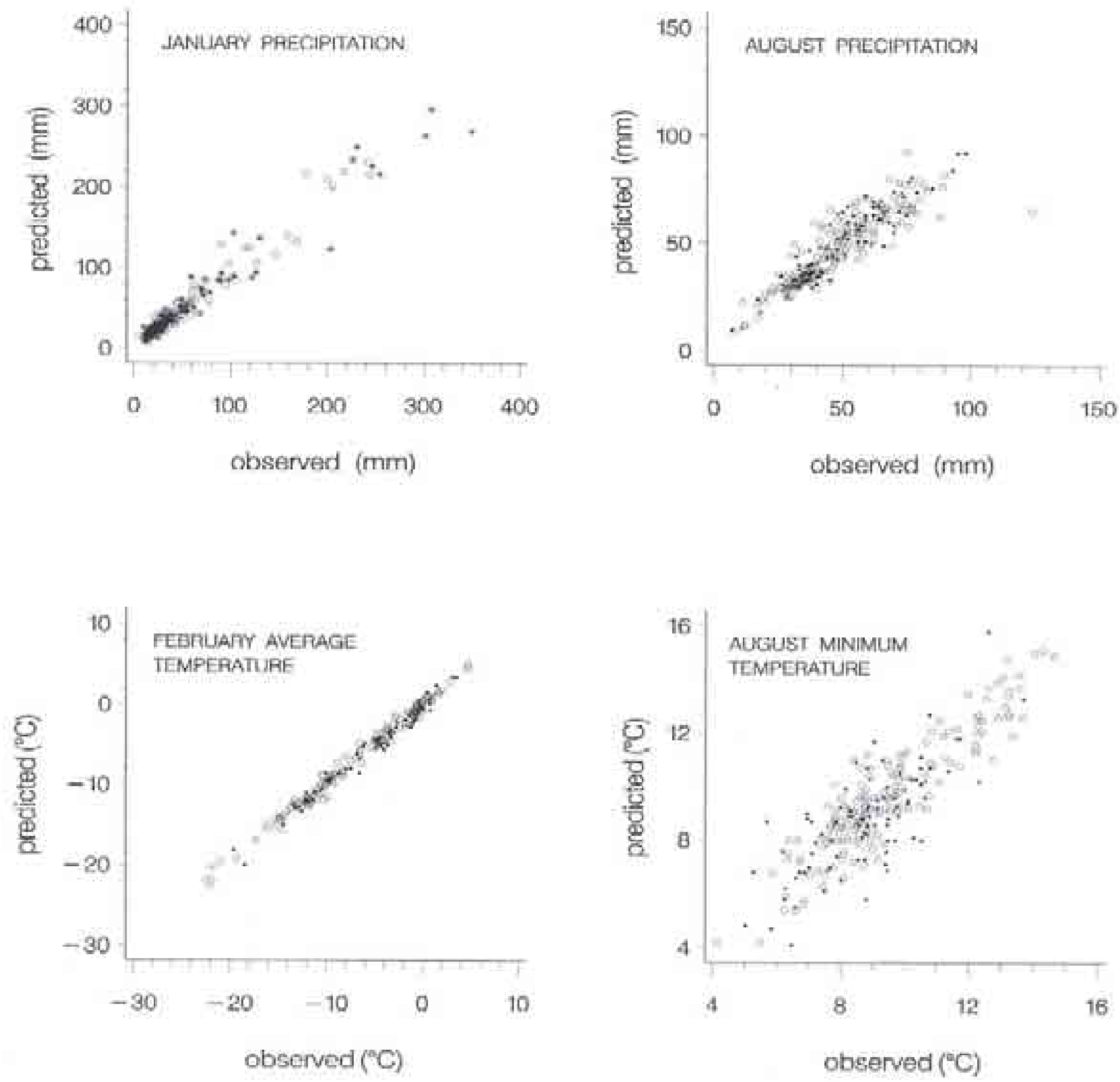

Figure 4. Examples of fit between observations and estimates for verification of Climate Model I for four variables, o – duplicated (or nearly duplicated) locations, • - stations independent of modeling procedures

As recommended by Hutchinson (2000), the signal in general should not be larger than one-half of the number of observations. Table 5 shows that for most of the 36 temperature splines, the ratio of the signal to the total number of observations was below 0.5. For only two of the temperature splines did the signal exceed 70 % of the number of observations. Nearly all of the ratios of signal to number of observations for precipitation, however, were greater than 0.5.

These values, including those for the splines of monthly precipitation, generally are below those of McKenney *et al.* (2001) for the same variables. The causes of high signals can be due to either data with excessive noise (inherent variability) or a lack of adequate data. The applicability of either of these causes can be judged from the statistics presented below.

Table 5. Summary statistics from Climate Model II showing the signal, the ratio of the signal to the total number of observations, surface means and their standard deviations, the root generalized cross validation (RTGCV) and root mean square error (RTMSE) for each of the 48 surfaces used for the Alberta Climate Model.

Month	Signal	Ratio of signal to observations	Mean	Standard deviation	RTGCV	RTMSE
monthly mean average temperature (C°)						
January	596	0.702	-9.8	5.52	0.88	0.40
February	455	0.536	-6.3	5.23	0.78	0.39
March	384	0.451	-1.7	4.24	0.66	0.33
April	326	0.382	4.8	2.45	0.55	0.27
May	438	0.441	10.0	2.15	0.55	0.28
June	407	0.402	14.1	2.28	0.56	0.28
July	410	0.403	16.6	2.40	0.63	0.31
August	394	0.389	15.9	2.55	0.66	0.32
September	379	0.385	10.9	2.40	0.62	0.30
October	393	0.448	5.6	2.15	0.61	0.31
November	433	0.505	-2.7	3.76	0.67	0.34
December	622	0.727	-8.3	4.93	0.81	0.36
monthly mean minimum temperature (C°)						
January	501	0.587	-15.0	6.37	1.32	0.65
February	410	0.477	-12.0	5.97	1.27	0.64
March	346	0.403	-7.5	4.55	1.06	0.52
April	392	0.457	-1.7	2.39	0.86	0.43
May	434	0.434	3.1	1.90	0.92	0.46
June	514	0.503	7.2	2.00	0.94	0.47
July	518	0.505	9.3	2.04	1.10	0.55
August	505	0.495	8.6	2.09	1.19	0.60
September	496	0.497	4.0	2.10	1.14	0.57
October	480	0.542	-0.5	2.26	1.13	0.56
November	402	0.467	-7.3	4.34	1.04	0.52
December	525	0.610	-13.0	5.77	1.21	0.59
monthly mean maximum temperature (C°)						
January	515	0.603	-5.0	4.97	0.81	0.39
February	474	0.550	-0.9	4.71	0.69	0.34
March	439	0.511	4.1	4.11	0.65	0.32
April	418	0.486	11.3	2.77	0.62	0.31
May	504	0.501	16.8	2.78	0.62	0.31
June	413	0.403	20.9	2.94	0.63	0.31
July	443	0.428	23.8	3.39	0.66	0.33
August	440	0.429	23.3	3.60	0.65	0.32
September	481	0.483	17.6	3.30	0.62	0.31
October	456	0.513	11.8	2.71	0.59	0.30
November	478	0.554	1.9	3.55	0.64	0.32
December	561	0.652	-3.8	4.33	0.72	0.34
monthly mean precipitation (mm)						
January	663	0.697	51.0	58.92	11.90	5.45
February	729	0.767	36.0	41.55	8.59	3.62
March	723	0.753	35.8	35.52	8.15	3.51
April	638	0.643	35.3	26.17	7.36	3.49
May	699	0.624	51.3	18.77	7.32	3.54
June	672	0.585	68.4	21.51	8.81	4.34
July	599	0.518	61.2	27.82	7.88	3.93
August	479	0.418	52.1	18.54	6.89	3.40
September	677	0.610	45.5	17.84	6.68	3.25
October	811	0.736	33.7	33.87	6.71	2.67
November	736	0.750	46.2	55.99	9.64	4.17
December	715	0.740	52.6	59.67	11.30	4.94

The square root of the generalized cross validation statistic (RTGCV) is presented in Table 5. A confidence interval ($\alpha \cong 0.05$) of about ±1.25 °C would surround an estimated value of average daily temperature regardless of month; of about ±2 °C for minimum temperature; of about ±1.25 °C for maximum temperature; and of about 15 mm for precipitation. Notice in the table, however, that confidence intervals for any estimate tend to be the smallest for summer months and largest for winter months, particularly December and January. This result undoubtedly stems from the fact that many secondary weather stations are abandoned during the winter which meant that in our analyses, the summer months contained as many as 200 more observations than the winter months. Nonetheless, these values of RTGCV for temperature variables are generally lower than those reported by McKenney *et al*. (2001); the RTGCV values for precipitation tend to be less by one-half.

In the analyses reported here, the RTMSE is approximately one-half of the RTGCV (Table 5). The size of this reduction suggests that the fitting of thin-plate splines overcame a substantial amount of noise that was inherent in the normals that were used in the present analyses. It is quite likely that much of this noise was introduced by accepting data from stations with a limited record interval (5 years for temperature and 7 years for precipitation). Detection of the noise was made possible by the large number of weather stations that were added to the standard stations of the respective weather services of Canada and the United States.

Table 6 lists the 10 stations with the largest RTMSE calculated as a composite for the 12 splines for each of the four variables. The table shows that for temperature estimates, the worst fitting stations seem to be dispersed randomly with respect to geography. However, nearly half (12) of these stations were established early in the 20th Century and abandoned in mid-century. In all cases, the data were normalized by the procedures used in this report. It seems reasonable, therefore, that in the case of these stations, anomalies in the original data have contributed disproportionately to errors in estimates from the Models.

It is important to note that the Alberta Climate Model was not tested outside of the target area that provided data for model development. While the principles on which splining are based have been shown to have general applicability, the formulae used to generate values for some derived variables may be appropriate only for the data to which they were applied.

The 10 locations with the largest residuals for monthly annual precipitation tended to come from areas where precipitation is high. Thus, 7 of the 10 are stations in either the northern tip of the Cascade Range in British Columbia and Washington or in the Waterton Region in the Alberta Rockies.

5. Using Data from Climate Model II

ANUSPLIN produces climatic data that can be used in two ways; point estimates can be made for any geographic point within the target region and grid estimates can be assigned to the polygons that are required for mapping algorithms.

Table 6. Ten stations and their locations with the highest aggregate root mean square error (RTMSE) across the 12 monthly surfaces for mean average temperature, mean minimum temperature, mean maximum temperature, and mean annual precipitation. Units for the annual mean are °C for temperature variables and mm for precipitation.

STATION	NAME	LATITUDE	LONGITUDE	ELEVATION	ANNUAL MEAN	RTMSE
Mean annual temperature						
3012620	FIVE LAKES	53.95	114.22	722	3.8	1.040
3036235	SUFFIELD	50.22	111.15	748	3.4	1.040
3035233	POKAPPINI	50.42	113.63	744	3.2	0.999
3064400	MEANOOK	54.62	113.35	684	2.7	0.964
3076071	SPIRIT RIVER RS	55.78	118.83	630	2.7	0.961
3040223	ALTAWAN	49.23	110.02	945	2.6	0.945
1157380	SINCLAIR PASS	50.67	115.97	1170	2.1	0.900
0100667	BAYVIEW MODEL BASIN	47.98	116.55	633	6.9	0.894
1158990	WYCLIFFE	49.58	115.88	914	4.2	0.889
3015295	PRAIRIE CREEK RS	52.25	115.30	1174	1.7	0.885
Mean minimum temperature						
1158990	WYCLIFFE	49.58	115.88	914	-3.4	1.85
3015295	PRAIRIE CREEK RS	52.25	115.30	1174	-7.6	1.72
3064400	MEANOOK	54.62	113.35	684	-2.2	1.71
3053760	LAKE LOUISE	51.43	116.22	1524	-7.8	1.62
0246615	POLEBRIDGE	48.77	114.27	1073	-4.3	1.60
1163340	HAT CREEK	50.75	121.58	923	-3.7	1.58
1125060	MEADOWGREEN	50.47	120.68	1207	-5.0	1.55
3074743	MUSKEG RS	53.92	118.65	1227	-7.6	1.54
3076071	SPIRIT RIVER RS	55.78	118.83	630	-2.6	1.54
3052508	EXSHAW	51.07	115.20	1298	-1.4	1.53
Mean maximum temperature						
3010704	BITTERN LAKE	53.07	113.00	745	6.3	1.120
0100667	BAYVIEW MODEL BASIN	47.98	116.55	633	12.9	1.070
1117410	SKAGIT RIVER	49.08	121.17	515	13.5	1.050
3075047	PEACE RIVER CROSSING	56.25	117.25	373	9.0	1.030
3012620	FIVE LAKES	53.95	114.22	722	9.4	1.010
1157380	SINCLAIR PASS	50.67	115.97	1170	7.8	0.992
3015530	ROCKY MOUNTAIN HOUSE	52.38	114.92	969	7.8	0.971
3020120	ALIX	52.38	113.17	788	10.6	0.930
1114620	LILLOOET	50.70	121.93	290	16.3	0.896
3042041	DEL BONITA	49.13	112.82	1293	11.0	0.845
Mean annual precipitation						
1114474	LADNER CREEK	49.50	121.25	807	1979	1.410
1152850	FERNIE	49.50	115.07	1001	1175	0.872
0456295	PALMER 3 ESE	47.30	121.85	280	2242	0.851
3056067	SPIONKOP CREEK	49.22	114.08	1861	1344	0.727
1102650	ELBOW LAKE	49.28	121.97	218	1991	0.719
3041908	COUTTS	49.00	111.95	1036	431	0.704
3057242	WATERTON RED ROCK	49.13	114.03	1524	814	0.695
0450456	BARING	47.77	121.48	235	2782	0.652
1113581	HOPE SLIDE	49.28	121.23	674	1168	0.638
1158200	TOBACCO PLAINS	49.02	115.08	701	556	0.624

5.1 Point estimates

Estimates for climatic data at specified points can be obtained from entering coordinates for the point of interest into Climatic Model II (Fig. 3). Values for derived variables are calculated using splined output from primary variables. For example, to estimate Mean Annual Temperature (MAT) for a given point, splined monthly mean daily temperatures are generated for that point and MAT is then calculated by summing the monthly temperatures and dividing by twelve. Table 7 provides an example in which climatic variables are estimated for 51 locations where seed of white spruce was collected ("Provenances") and for the 9 locations where the collections are being tested.

5.2 Grid estimates

As noted in Section 3.2, the splining algorithm allows output of an ASCII grid file in which point estimates are assigned to grids of specified dimensions to facilitate mapping. The ACM uses a 1 km (0.00833333 degrees) grid supplied as a digital elevation model from NOAA (2003). Although different grid sizes can be used to achieve different degrees of resolution, it should be kept in mind that regardless of the chosen level of resolution, all data are drawn from the same spline and thus reflect the accuracy of the same underlying model.

5.3 Mapping

For this report, ASCII grid output from Climate Model II was processed by a GIS software known as ArcInfo (Environmental Systems Research Institute 2004) to create a GIS raster data set in geographic coordinates. ArcInfo was also used to re-project the data with geographic coordinates to the modified 10-degree Transverse Mercator projection used for the mapping of Alberta.

Using output from Climate Model II, 48 maps could be produced using monthly means for each of the four primary variables. In addition, data from each of the 13 derived variables (Section 2.1) could be mapped. Moreover, additional variables could be derived from the archived data, processed through Climate Model II and plotted.

ASCII grid files for derived variables are calculated in one of two ways. For variables such as Mean Annual Temperature (MAT), the method is as described in Section 5.1. Limitations in the data processing capability of ArcInfo, however, require another approach to produce input for mapping where calculations are more complicated. For variables such as degree-days >5 °C, the derived variable is calculated from values for splined primary variables, then fitted by splining to generate the grid file required for mapping. For the data produced by the ACM, grid files for eight derived variables were produced by the method in Section 5.1, three were produced by the method for complex variables and two (ratios) were produced by using each method for one variable.

For purposes of illustration, values for five variables were mapped as shown in Figures 5 to 9. These variables include some of those found to be important in describing tree responses to climate in reports by Rehfeldt, *et al.* (1999) and Rehfeldt *et al.* (2002). Many studies have reported substantial relationships between a variety of climatic variables and plant distributions. Different species and different geographic ranges may be expected to show somewhat different relationships. A comprehensive review of the links between climatic variables and physiological responses of trees was presented by Saxe *et al.* (2001).

Table 7. Point estimates for five climatic variables for white spruce provenances and the nine test locations on which provenances are being tested by ABSRD. Note: MAT = mean annual temperature, MAP = mean annual precipitation, DD5 = degree-days > 5 °C, NDD = degree-days < 0°C, AMI = annual moisture index.

Number/Region	LAT °N	LONG °W	ELEV m	MAT °C	MAP mm	DD5 °C	NDD °C	AMI
Provenances								
0002 Footner Lake	58.73	117.25	335	-1.6	408	1190	2668	2.9
0003 Footner Lake	57.92	117.07	305	-0.3	401	1303	2371	3.2
0004 Footner Lake	57.92	115.50	360	-0.4	428	1275	2353	3.0
0005 Footner Lake	58.55	114.23	235	-1.0	370	1239	2502	3.3
0006 Athabasca	58.73	111.25	235	-1.7	386	1242	2759	3.2
0007 Athabasca	58.20	111.38	229	-0.9	417	1330	2554	3.2
0008 Athabasca	57.13	111.63	274	-0.2	439	1340	2351	3.1
0009 Athabasca	56.63	111.17	370	0.2	473	1320	2203	2.8
0010 Athabasca	59.88	111.72	183	-2.6	331	1174	2984	3.5
0011 Lac La Biche	54.37	110.75	550	0.8	418	1351	2035	3.2
0012 Lac La Biche	54.63	110.22	610	0.6	462	1300	2039	2.8
0013 Lac La Biche	54.97	112.17	551	1.3	503	1310	1835	2.6
0014 Lac La Biche	55.22	113.20	610	1.0	482	1261	1889	2.6
0015 Slave Lake	56.63	114.58	731	-0.1	539	1083	2054	2.0
0016 Slave Lake	54.80	116.98	731	2.5	553	1294	1432	2.3
0017 Slave Lake	55.23	114.77	610	1.5	520	1259	1701	2.4
0018 Slave Lake	54.53	114.08	640	1.6	509	1291	1725	2.5
0019 Slave Lake	55.48	116.08	610	1.4	481	1287	1794	2.7
0020 Slave Lake	55.77	113.30	579	0.8	509	1263	1946	2.5
0021 Peace River	57.60	117.52	460	-0.5	443	1223	2340	2.8
0022 Peace River	56.98	117.83	610	-0.3	445	1174	2230	2.6
0023 Peace River	56.57	119.67	762	-0.2	454	1086	2101	2.4
0024 Peace River	56.47	118.08	823	-0.1	480	1114	2073	2.3
0025 Peace River	56.03	116.67	700	0.6	493	1218	1959	2.5
0026 GrandePrairie	55.58	119.58	838	0.8	522	1104	1771	2.1
0027 GrandePrairie	55.58	118.30	640	1.6	483	1320	1747	2.7
0028 GrandePrairie	55.13	117.28	667	2.4	490	1365	1528	2.8
0029 GrandePrairie	54.45	118.63	940	1.8	611	1112	1474	1.8
0030 GrandePrairie	54.63	118.95	990	1.6	614	1088	1507	1.8
0031 Edson	53.77	118.80	1402	0.7	627	773	1462	1.2
0032 Edson	53.23	117.47	1340	1.5	601	932	1372	1.6
0034 Edson	53.32	117.85	1067	2.4	566	1079	1232	1.9
0035 Whitecourt	53.65	115.70	838	1.7	568	1166	1547	2.1
0036 Whitecourt	54.27	115.30	762	1.8	535	1219	1574	2.3
0037 Whitecourt	54.18	116.62	945	2.3	591	1159	1341	2.0
0038 Whitecourt	54.37	114.67	610	1.9	480	1327	1647	2.8
0039 RockyClearwater	52.55	115.50	1067	2.4	610	1153	1304	1.9
0040 RockyClearwater	52.17	115.47	1341	1.4	620	911	1380	1.5
0041 RockyClearwater	52.00	115.25	1280	1.8	624	947	1294	1.5
0042 RockyClearwater	52.72	115.42	1036	2.5	614	1205	1328	2.0
0043 RockyClearwater	52.92	115.78	1067	2.2	618	1161	1367	1.9
0044 Bow/Crow	51.75	114.63	1128	2.5	499	1135	1272	2.3
0045 Bow/Crow	50.80	114.60	1463	2.0	599	921	1201	1.5
0046 Bow/Crow	51.40	115.22	1750	0.8	593	807	1466	1.4
0047 Bow/Crow	50.08	114.50	1830	0.8	689	780	1407	1.1
0048 Bow/Crow	49.65	114.62	1585	2.2	756	943	1168	1.2
0446 Cypress Hills	49.63	110.23	1310	2.4	484	1243	1375	2.6
0448 Bow/Crow	49.53	114.43	1981	0.8	956	765	1404	0.8
0782 Edson	53.05	117.47	1707	-0.1	662	695	1622	1.0
0783 Bow/Crow	50.78	115.33	1859	0.1	722	716	1589	1.0
0784 Footner Lake	59.53	117.22	305	-2.3	382	1171	2874	3.1
Test sites								
G103B Footner Lake	59.13	117.57	370	-2.3	410	1137	2862	2.8
G103C Slave Lake	55.55	114.83	670	1.2	551	1210	1765	2.2
G103D Grande Prairie	55.52	118.75	805	1.2	509	1199	1733	2.4
G103E Edson	53.38	116.50	990	2.1	580	1123	1380	1.9
G103F Rocky/Clearwater	52.25	115.35	1220	1.6	625	965	1376	1.5
G103G Peace River	57.83	118.20	470	-0.8	448	1188	2396	2.7
G103H Lac La Biche	55.28	113.15	625	0.9	488	1254	1901	2.6
G103I Whitecourt	54.47	115.85	1127	1.2	641	1009	1555	1.6
G103J Athabasca	56.38	111.43	550	0.2	534	1251	2112	2.3
G103RW Range wide	55.28	113.15	625	0.9	488	1254	1901	2.6

The maps presented in Figure 5 through 9 show some general trends. For mean annual degree-days > 5° C. (Figure 5), strong topographical and elevation relationships are apparent. This is true for summer temperature variables generally. In contrast, mean annual degree-days < 0° C. (Figure 6) indicate a relatively stronger influence by latitude over topography and elevation. This is illustrated by isotherms that form bands of lower temperature and higher negative degree-day sums extending from northwest to southeast and increasing with latitude. Mean annual temperature (Figure 7) is a composite of summer and winter degree-days. Temperatures showing the summer influence of elevation and topographical features embedded within general latitudinal bands representing winter climate.

The map of mean annual precipitation (Figure 8) once again illustrates the importance of increased elevations and topography associated with the Rocky Mountains and boreal hill systems as does the map of mean annual moisture index (Figure 9).

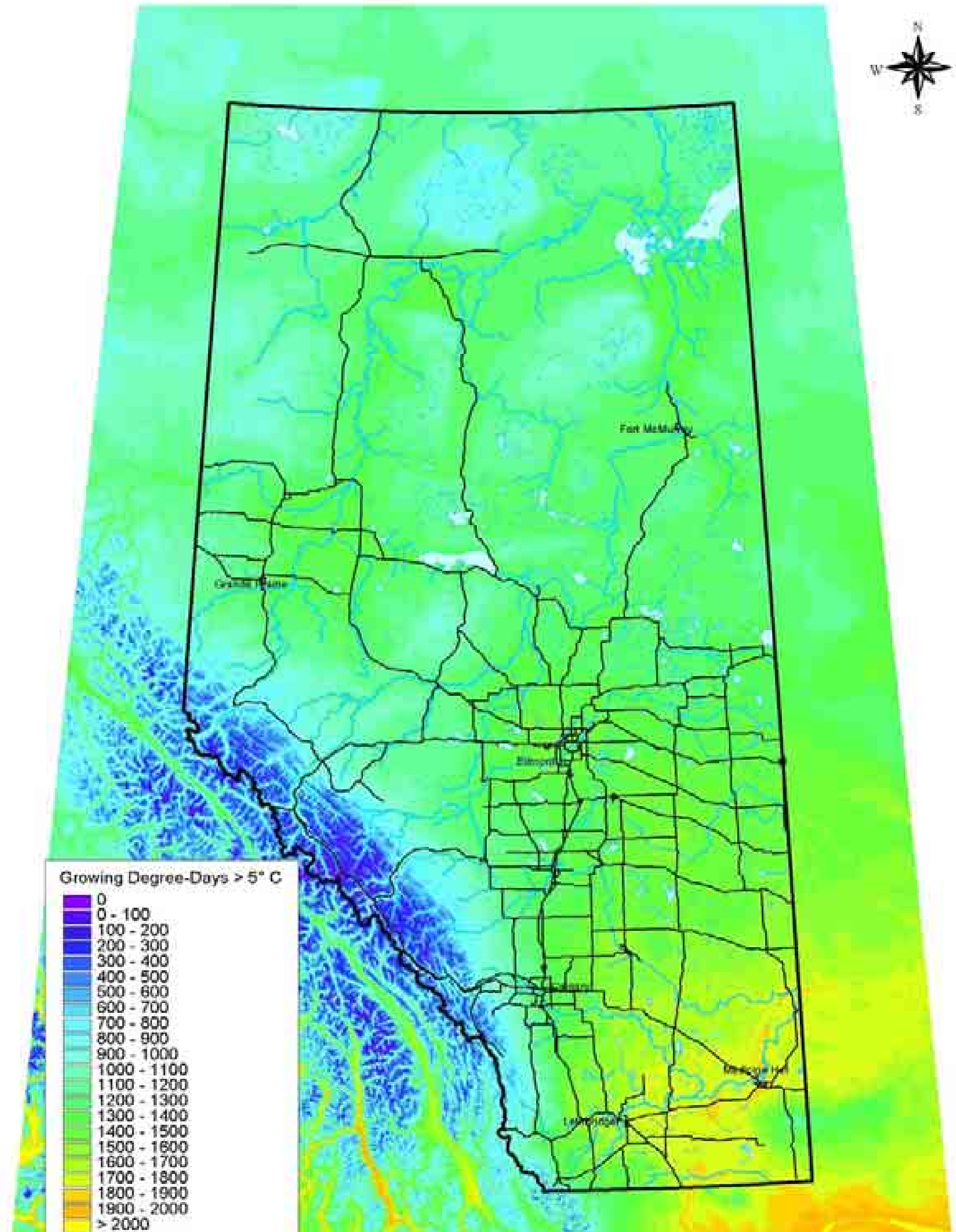

Figure 5. Mean annual degree-days over 5° C plotted from output from the Alberta Climate Model

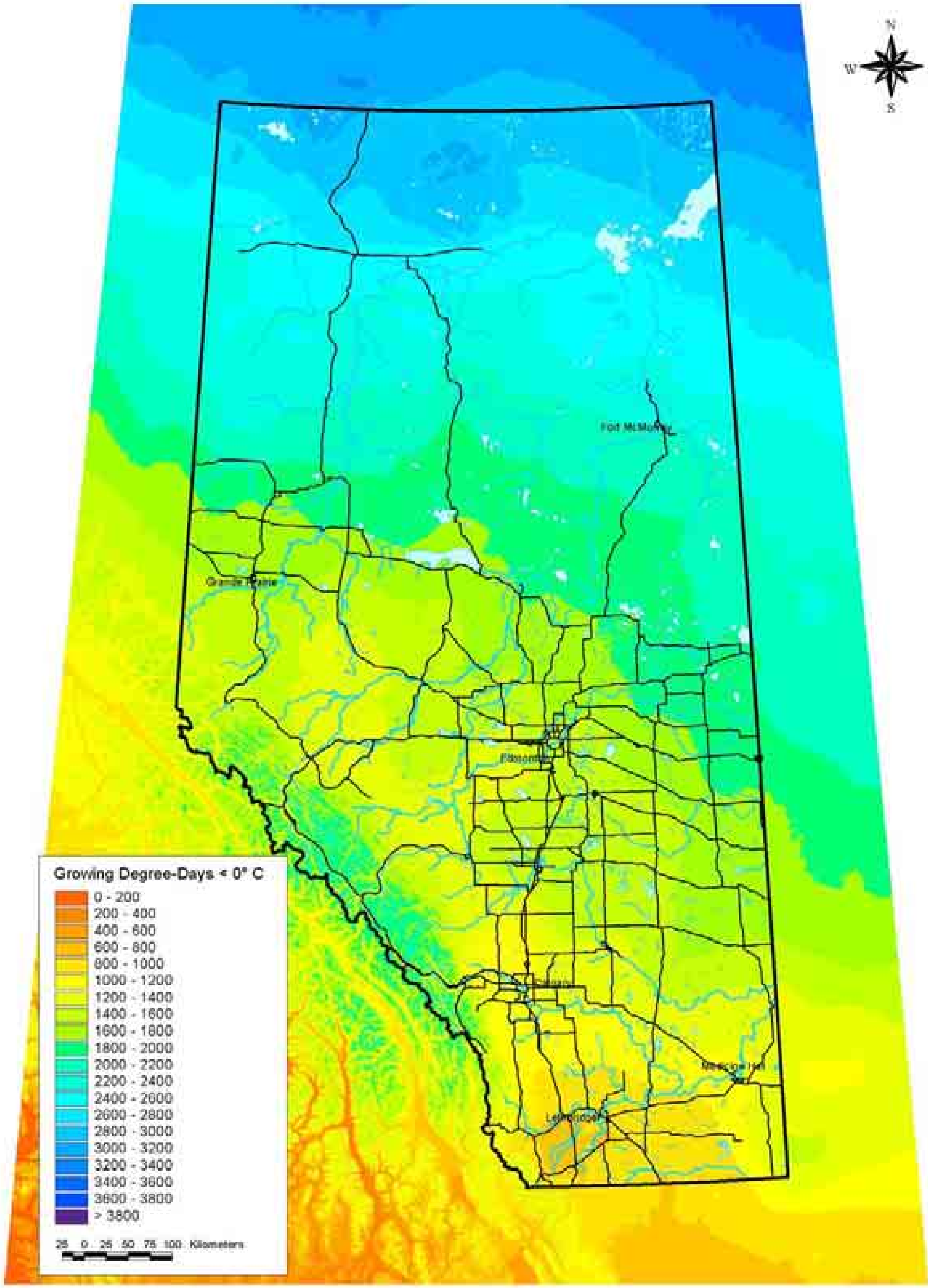

Figure 6. Mean annual degree-days less than 0° C plotted from output from the Alberta Climate Model

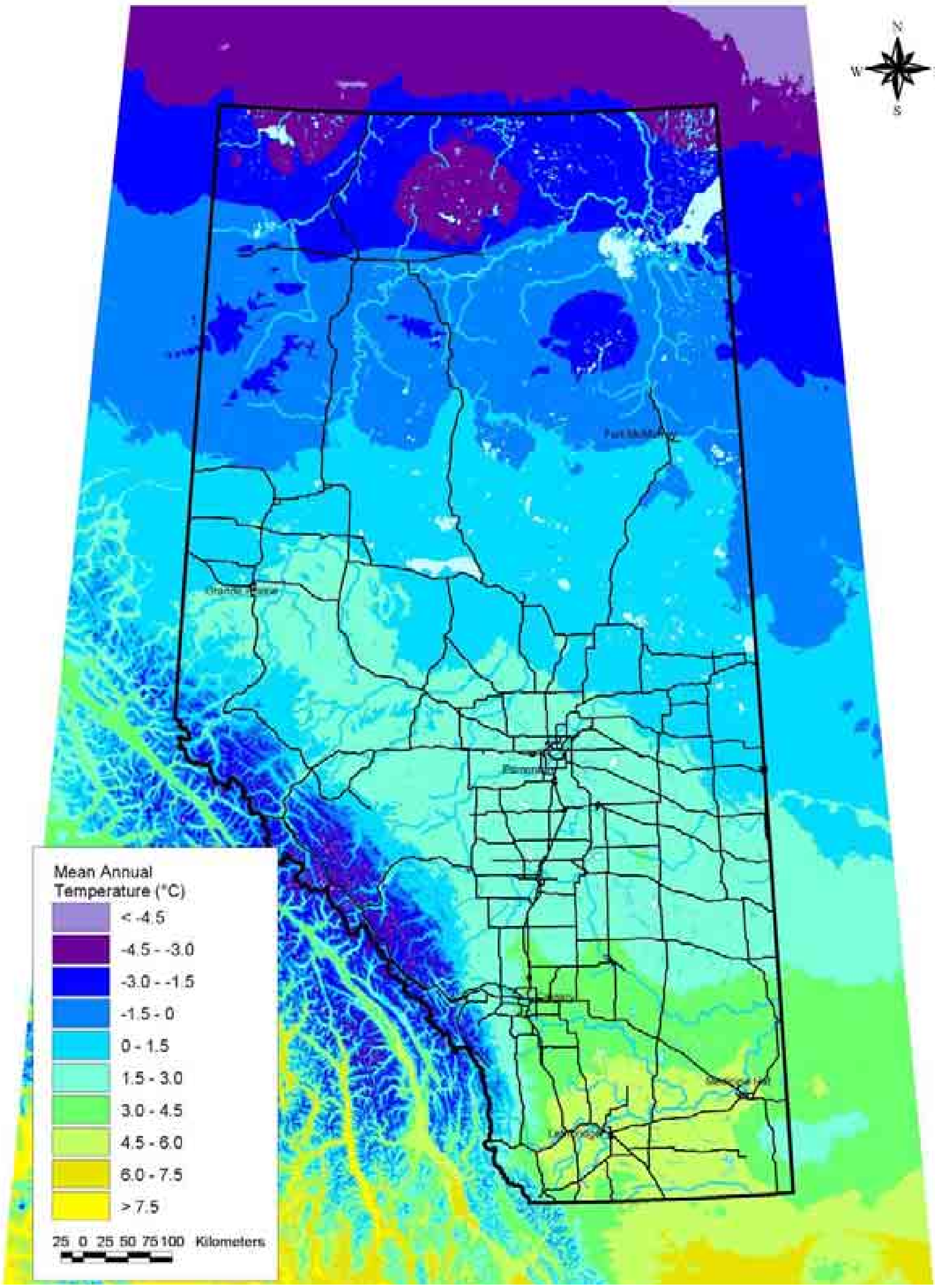

Figure 7. Mean annual temperature plotted from output from the Alberta Climate Model

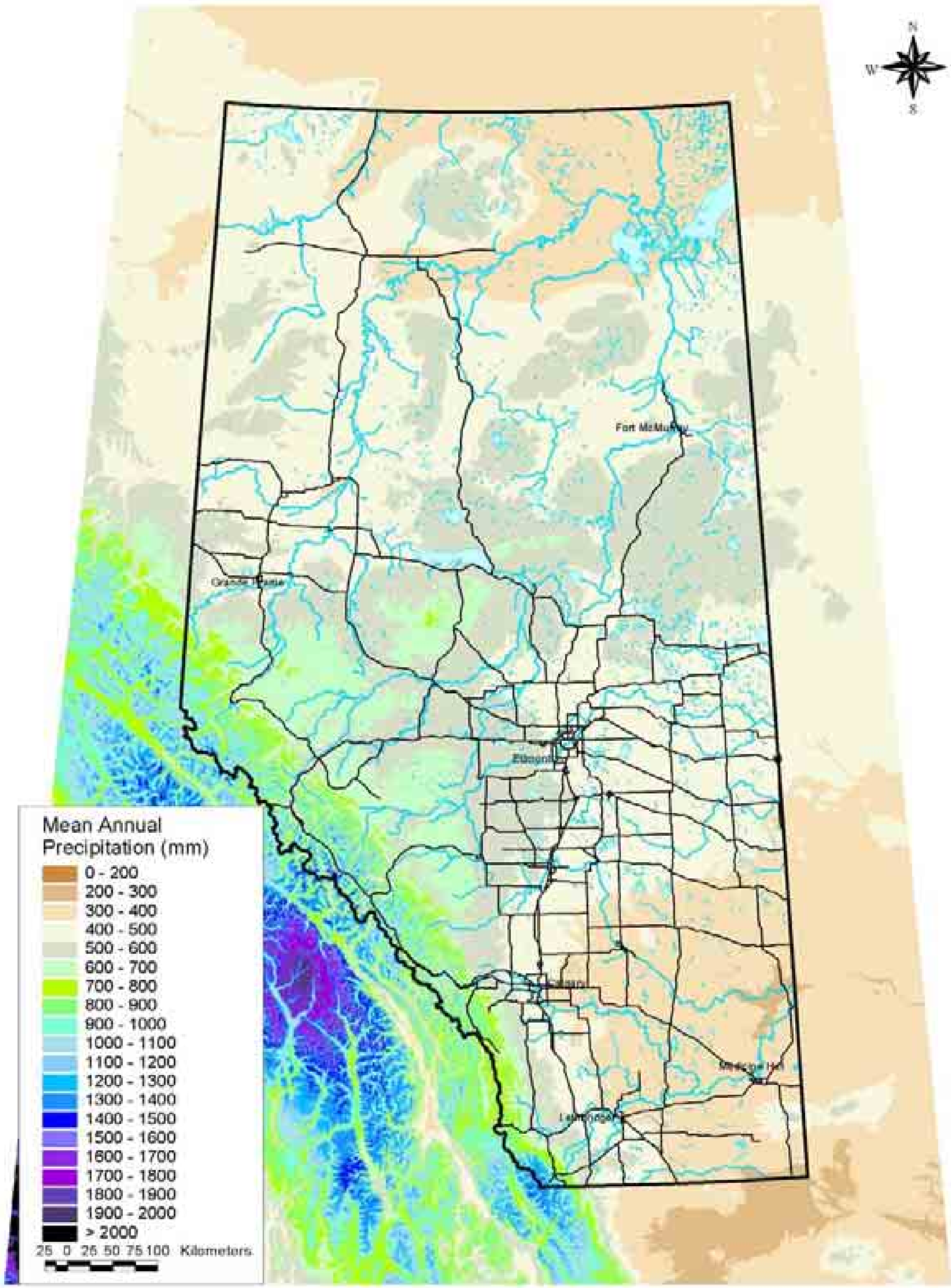

Figure 8. Mean annual precipitation plotted from output from the Alberta Climate Model

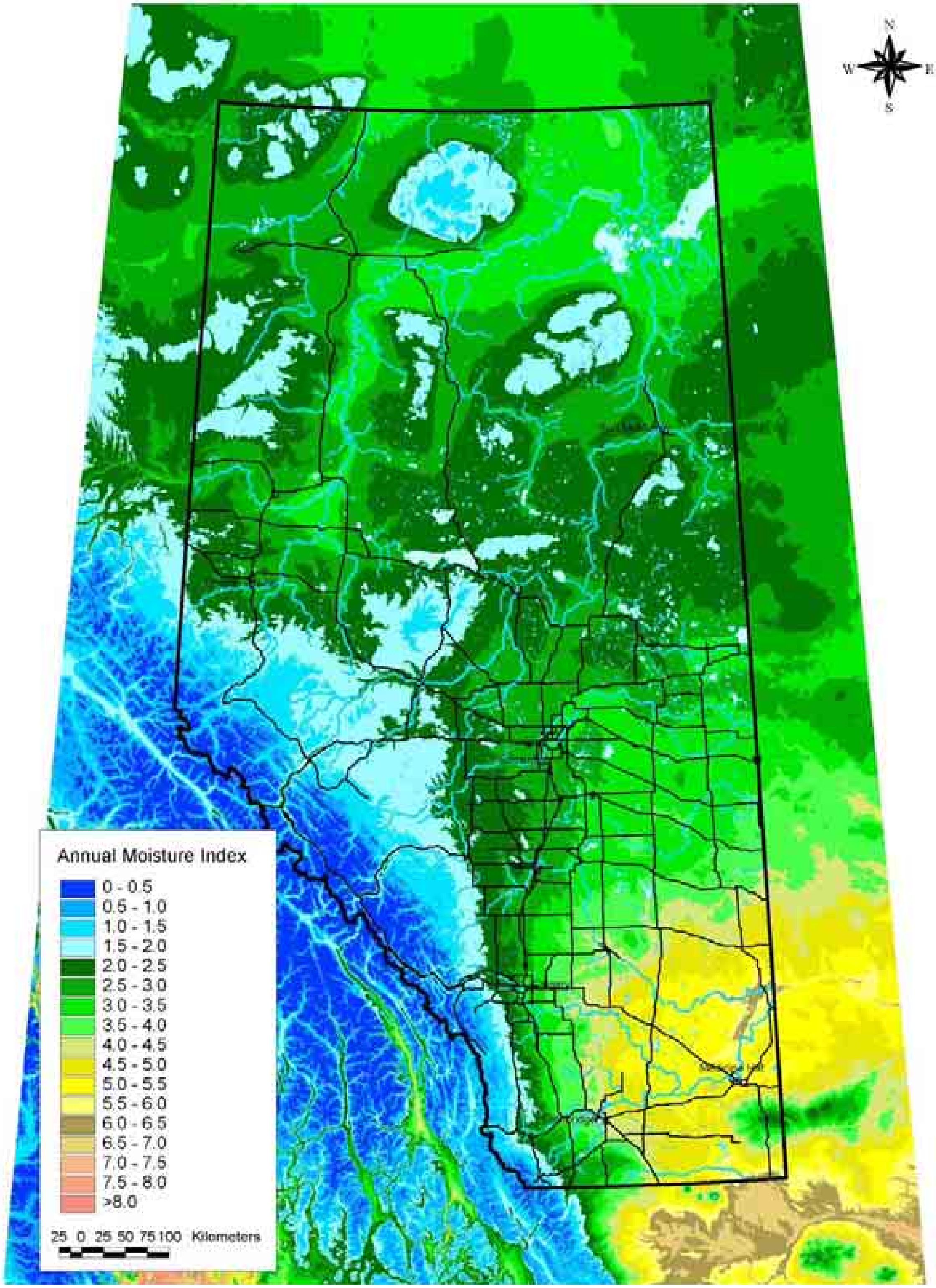

Figure 9. Mean annual moisture index plotted from output from the Alberta Climate Model

6. Acknowledgements

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8. Appendices

Appendix 1. Estimation of degree-days > 5 °C and degree-days < 0 °C

Degree-days are statistics of use in describing the general climate for a specified period of time (week, month, year). These statistics are most commonly presented as a sum of temperatures above or below a threshold temperature. Two annual degree-day sums have been calculated for the Alberta Climate Model (ACM): degree-days > 5 °C (DD5) and degree-days < 0 °C (DD0). The former is widely accepted among plant ecologists and physiologists as a general indication of the warmth of the growing season while the latter is viewed as an indicator of the coldness of the winter.

Degree-days are ordinarily calculated from daily temperatures in three steps.
1. Calculate the difference (T_{di}) between the mean temperature of the day (T_i) and the threshold temperature (T_t):

$$T_{di} = T_i - T_t$$

where i is the Julian date.

2. Apply a condition that is dependent on whether DD5 or DD0 is being summed:
   (a) if DD5 is the statistic of interest, all values of $T_{di} < 0$ are equated to zero.
   (b) if DD0 is the statistic of interest, all values of $T_{di} > 0$ are equated to zero.

3. Summing T_{di} across the period of interest. For an annual sum of DD5:

$$DD5 = \sum_{i=1}^{365} T_{di}$$

These steps use daily temperatures. The ACM, however, is based on monthly temperatures rather than daily. As a result, the customary approach needed modification in order to provide unbiased estimates of degree-days. Obviously, T_{di} could be calculated as above using monthly average temperatures and multiplying by the number of days in the month to estimate the degree-days that accumulated for that month. The problem, however, is that in doing so, one ignores daily variations about the monthly mean. This would mean that for the calculation of DD5, daily contributions to the sum would be ignored if the monthly mean was < 5 °C. The resulting sum, therefore, would underestimate the actual.

To provide an unbiased estimate of DD5 and DD0, regressions using normalized values of Environment Canada (1993) were developed for monthly average temperature on the monthly sum of degree-days. Because months have a different number of days, the latter statistic was expressed as an average daily value by dividing the monthly sum by the number of days in the month.

Estimation of DD5

A complete set of climate normals for average monthly temperature and DD5 were available for 275 stations from western Canada. The relationship between average monthly temperature and degree-days >5 °C, expressed as the average daily accumulation, is shown in Figure A1a. The figure illustrates a strong and non-linear relationship. It also shows that at temperatures > 10 °C, the daily accumulation equals the amount by which the average temperature exceeds 5 °C, and at mean daily temperatures below –13 °C, the daily contribution equals zero. The regression, therefore, needs to deal with the interval 10 °C > temperature >-13 °C. Temperatures beyond this range were removed from the Environment Canada normals. Truncation left 1804 observations with as few as 25 available for July and as many as 252 available for March, April, and October. The following regression model was fit for each month:

$$D_i = a + be^{(T_i')^c}$$

where *D* is daily degree-days > 5 °C for station *i*; *a, b,* and *c* are regression coefficients; *e* is the base of the Napierian logarithms; and *T′* is the average temperature for station *i* transformed to a value between zero and one:

$$T'_{\text{avg}} = (T_{\text{avg}} - 13)/24$$

where –13 is the minimum value and 24 is the range in values.

All regressions were statistically significant ($p < 0.0001$), accounting for an average of 96 % of the variance in the dependent variable, a minimum of 89 % (April), and a maximum of 96.5 % (November). The regression for December data is plotted against the observed data points in Figure A1b.

Regression coefficients for each month are:

	a	b	c
January	-5.54453	5.56791	6.10846
February	-7.82957	7.85383	7.24939
March	-8.48367	8.56278	7.98210
April	-3.38021	3.41188	3.17280
May	-3.90110	3.86835	3.63451
June	-4.20032	3.97762	3.67099
July	-7.51866	4.92424	1.84912
August	-4.75556	4.33553	3.84939
September	-4.37997	4.12294	3.41947
October	-3.84607	3.68301	2.88888
November	-5.35786	5.46167	5.72048
December	-5.48569	5.49894	5.82408

Calculation of DD5 per day for the month of May, for instance, is as follows:

If 10 °C > T_{avg} > -13 °C, then $D_i = -3.90110 + 3.86835e^{(T_i')^{3.63451}}$

where D is the estimate of degree-days > 5 °C that accumulate each day across the month at station i; and T' is the transformation of the average monthly temperature $[(T_{avg} - 13)/24]$; and e is the base of the Napierian logarithms. If T_{avg} >10 °C then $D_i = T_{avg} - 5$

If T_{avg} < -13 °C then $D_i = 0$

To obtain the number of degree-days expected to accumulate across the entire month, D_i is multiplied by 31, the number of days in May.

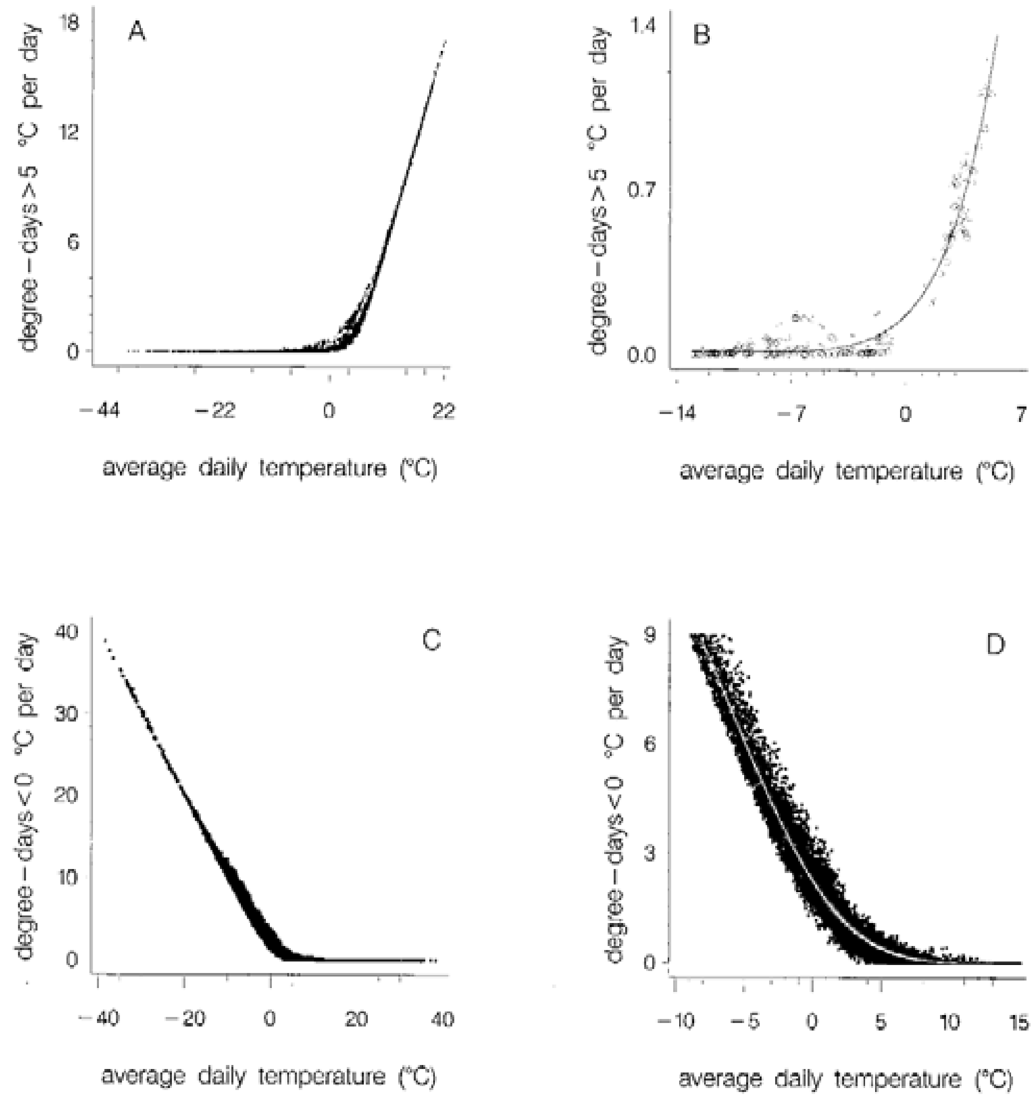

Figure A1. Plots of the relationships between degree-days per day and average daily temperature. (a) degree-days >5° C; (b) degree-days >5° C., o – observed, • - estimated; (c) degree-days <0° C.; (d) degree-days <0° C, • – observed, + - estimated

Estimation of DD0

The set of Environment Canada's climate normals contained 275 stations in western Canada for which average monthly temperature and DD0 were available. Few of these stations were of such warmth that DD0 approached zero. Because one of the future uses of ACM will be to assess the effects of global warming, data from 1786 weather stations in the USA (U.S. Department of Commerce, 1994) were added to the data base. The relationship between average temperature and degree-days < 0 °C expected to accumulate each day is shown in Figure A1c. The relationship is obviously strong and non-linear. The figure also shows that at average daily temperatures > 15 °C, the daily accumulation of negative degree-days is zero, and that at temperatures less than –10 °C, the daily accumulation of degree-days is essentially equal to the absolute value of the average temperature. This means that bias in estimating DD0 would accrue when 15 °C > T_{avg} > -10 °C. Initial analyses showed that months had no effect on the relationship between monthly temperature and degree-days per day. Therefore, in the first stage, a single regression model was fit for the range of values between -10 and 15°C:

$$D_i = e^{a+b(T_i')}$$

where D_i is degree-days per day < 0 °C for station *i*; *a* and *b* are regression coefficients; *e* is the base of the Napierian logarithms; and T' is the average temperature for station *i* transformed according to:

$$T'_{avg} = \left[(T_{\mathrm{avg}} - 78)/25\right]^{10}$$

This regression was based on 22,205 degrees of freedom, was statistically significant ($p <$ 0.0001), and accounted for 98 % of the variance in the dependent variable. Figure A1d shows the relationship between observed values of degree-days per day and average temperature along with those predicted for the first stage.

Calculation of DD0 per day (D_i) for any month, is as follows for 15°C > T_{avg} > -10 °C:

$$D_i = e^{2.8727 - 0.0000235 T_i'}$$

where D_i is the estimate of degree-days < 0 °C that accumulate each day across the month; and T' is the transformation of the average monthly temperature $[(T_{avg} - 78)/25]^{10}$; and *e* is the base of the Napierian logarithms.

The same result for 15°C > T_{avg} > -10 °C can be obtained from the SAS expression:

D_i = exp(2.8946+(-194E-21*(((T_{avg}+80))**10;

The second stage of the estimation process showed that if T_{avg} >15 °C then $D_i = 0$, and in the third stage, where T_{avg} < -10 °C, then $D_i = 0.64543 - (0.98035 T_{avg})$.

For all stages, obtaining the number of degree-days expected to accumulate across the entire month requires D_i to be multiplied by the number of days in the month.

Appendix 2. Estimation of the Julian date on which degree-days > 5 °C reaches 100

Experience in forestry research has led to the belief that the day on which the daily accumulation of degree-days > 5 °C reaches 100 ($DD5_{100}$) is important in plant development. This date can be estimated readily from monthly sums of DD5. Doing so requires, first, the conversion of monthly values of DD5 to the proportion of the annual DD5 that had accumulated by the end of each month. Such proportions can then be fit nearly perfectly with a modified logistic function:

$$P = \frac{1}{1 + e^{(b_0 + b_1 X + \frac{b_2}{X})}}$$

where P is the proportion of the annual sum of DD5 that had accumulated by Julian day X, and the b's are regression coefficients, and e is the base of the Napierian logarithms.

For the Alberta Climate Model, the logistic regressions were calculated for all stations for which spline output was available. The regressions fit the observed data nearly perfectly, accounting on average for at least 99.86 % of the variance in the monthly accumulations and at most 99.99 %. The fit of the regression model to the original data is shown in Figure A2 for three stations with very different climates.

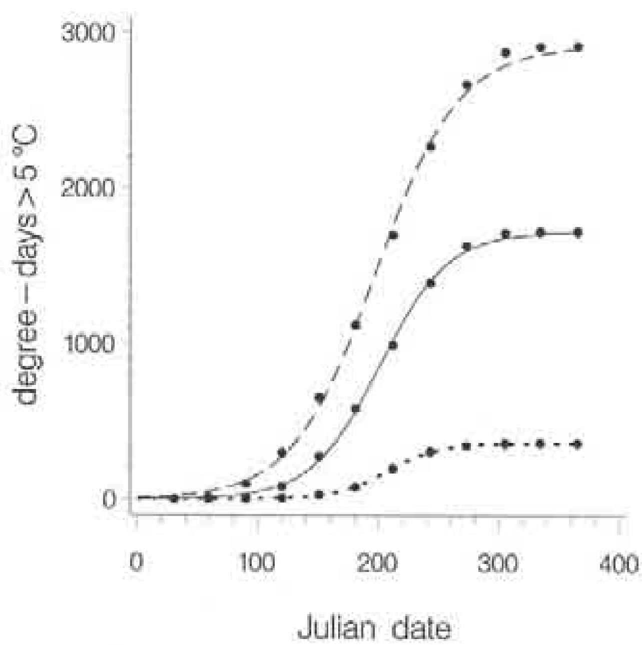

Figure A2. Plots of the relationship between cumulative degree-days >5° C. and Julian date (• - observed, lines – predicted) for three climatic stations.

DD5$_{100}$ can be estimated by solving the function for a value of X when the product of P and DD5 equals 100. Thus, from the equation above:

$$\frac{100}{DD5} \bullet \left[1 + e^{(b_0 + b_1 X + \frac{b_2}{X})}\right] = 1$$

then by rearranging,

$$e^{(b_0 + b_1 X + \frac{b_2}{X})} = \frac{DD5}{100}$$

taking the logarithm and again rearranging,

$$b_2 + b_0 X + b_1 X^2 = \left[\ln\left(\frac{DD5}{100}\right)\right] X$$

the expression becomes

$$0 = b_2 + \left[b_0 - \ln\left(\frac{DD5}{100}\right)\right] X + b_1 X^2$$

which is in a form suitable for solving for X using the solution to the quadratic equation. There will be two solutions, one of which is absurd and can be discarded.

For SAS users, the following programming statement will produce the estimate of DD5$_{100}$:

```
DD5100 =((LOG((DD5/100)-1)-B0)-(SQRT(((LOG((DD5/100)-1)-B0)**2)-
        (4*B1*B2))))/(2*B1);
```

Appendix 3. Description and a sample input statement for Archived 61-90 normals produced for the Alberta Climate Model.

The file ARCHIVE.DAT contains monthly and annual climate normals for average daily temperature, average daily precipitation, minimum daily temperature, and maximum daily temperature. The data were produced according to procedures described in the report "The Alberta Climate Model" available from Forest Management Division, Alberta Sustainable Resource Development. The data matrix is 23 columns by 5222 rows in READ ONLY format.

Description of variables:

1-7	Station number. Alphabetic data
9-31	Station name, 23 characters
33-34	Station location, degrees latitude
36-37	Station location, minutes of latitude
39-41	Station location, degrees longitude
43-44	Station location, minutes of longitude
46-49	Station location, meters elevation

51-54 Weather variable name
TMAX, average daily maximum temperature
TMIN, average daily minimum temperature
TAVG, average daily temperature
PRCP, sum of daily precipitation
56-58 Environment Canada parameter code
001, average maximum daily temperature
002, average minimum daily temperature
003, average daily temperature
034, sum of daily precipitation
60 Source of normalized data
1, Environment Canada standard station
2, Alberta Sustainable Resource Development
3, Combination of Environment Canada and Alberta Sustainable Resource Development
4, National Climate Data Center, U. S. Department of Commerce
5, Rocky Mountain Research Station
62-144 Monthly values in 6-column files.
146-151 Annual mean (temperature) or sum (precipitation).

Note: For data for stations from which normals were obtained from a combination of sources (#3 in column 60), an asterisk (*) marks those normals derived from Environment Canada. No codes mark normals produced by Alberta Sustainable Resource Development.

A sample SAS input statement for this file:

```
input station $ 1-7
name $char23.
latd 33-34
latm 36-37
longd 39-41
longm 43-44
elevation 46-49
vname $ 51-54
vcode $ 56-58
source 60
jan 62-66
feb 69-73
mar 76-80
apr 83-87
may 90-94
jun 97-101
jul 104-108
aug 111-115
sep 118-122
oct 125-129
nov 132-136
dec 139-143
ann 146-150
```