Climate trends of the North American prairie pothole region 1906–2000

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Abstract The Prairie Pothole Region (PPR) is unique to North America. Its millions
of wetlands and abundant ecosystem goods and services are highly sensitive to wide
variations of temperature and precipitation in time and space characteristic of a
strongly continental climate. Precipitation and temperature gradients across the PPR
are orthogonal to each other. Precipitation nearly triples from west to east from
approximately 300 mm/year to 900 mm/year, while mean annual temperature ranges
from approximately 1°C in the north to nearly 10°C in the south. Twentieth-century
weather records for 18 PPR weather stations representing 6 ecoregions revealed
several trends. The climate generally has been getting warmer and wetter and the
diurnal temperature range has decreased. Minimum daily temperatures warmed by
1.0°C, while maximum daily temperatures cooled by 0.15°C. Minimum temperature
warmed more in winter than in summer, while maximum temperature cooled in
summer and warmed in winter. Average annual precipitation increased by 49 mm
or 9%. Palmer Drought Severity Index (PDSI) trends reflected increasing moisture
availability for most weather stations; however, several stations in the western Cana-
dian Prairies recorded effectively drier conditions. The east-west moisture gradient
steepened during the twentieth century with stations in the west becoming drier and
stations in the east becoming wetter. If the moisture gradient continues to steepen,

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the area of productive wetland ecosystems will shrink. Consequences for wetlands would be especially severe if the future climate does not provide supplemental moisture to offset higher evaporative demand.

1 Introduction

Weather records for North America show a general trend of increasing temperature and precipitation during the twentieth century (Gullett and Skinner 1992; Karl et al. 1993; Nkemdirim and Weber 1999; National Assessment Synthesis Team 2001; IPCC 2007; Sauchyn et al. 2003). However, these trends are not uniform across the continent. Significant regional differences exist and complicate efforts to generalize the response of specific natural ecosystems to altered climate.

Our analysis focused on the Prairie Pothole Region (PPR), which includes 5–8 million glacially formed wetlands that are highly sensitive to climate variability (Poiani and Johnson 1991; Larson 1995; Sorenson et al. 1998; Johnson et al. 2005). This paper provides an overview of recent climatic trends across the PPR. Most relevant published information is for the larger Great Plains region (Borchert 1950; Bryson and Hare 1974; Woodhouse and Overpeck 1998). We use daily precipitation and daily maximum and minimum temperature data from January 1906 to December 2000 to characterize historic temporal and spatial climate patterns for the PPR and the implications of these patterns for the future of wetland biodiversity.

The PPR occupies approximately 750,000 km^2 in the center of the continent in both the United States and Canada (Fig. 1) (van der Valk 1989; Millett 2004). It is bounded on the south by the limits of the Laurentide ice sheet of the Wisconsinan glaciation and on the west by the Missouri River in the United States that occupied an ice marginal position during full glacial times and by the Rocky Mountain foothills in Canada. The northern limit of the PPR is the southern boundary of the Canadian boreal forests of Alberta, Saskatchewan, and Manitoba (Bird 1961), and the eastern limit is the prairie-deciduous forest transition zone (Buell and Facey 1960).

The climate of the PPR and of the larger northern Great Plains region is influenced by three air masses: Continental Polar, Maritime Tropical, and Maritime Polar (Bryson and Hare 1974). The complex interactions among these air masses in the middle of a large continent create one of the most extreme and dynamic climates on Earth (Winter 1989; Ahrens 2007; Woodhouse and Overpeck 1998). Temperatures can exceed 40°C in summer and drop below −40°C in winter. High summer temperatures and low humidity cause high evapotranspiration rates that can quickly dry shallow wetlands. The PPR has a strong precipitation gradient, with areas to the north and west receiving less precipitation than locations to the south and east. Evaporation exceeds precipitation by 60 cm in southwestern Saskatchewan and in eastern Montana but only by 10 cm in Iowa (Winter 1989).

The PPR also exhibits considerable spatial and temporal variability in rainfall (Johnson et al. 2004). The 1930s drought was particularly notable, comprising at least four distinct drought episodes: 1930–1931, 1934, 1936, and 1939–1940 (Riebsame et al. 1991). During severe droughts, most wetlands go dry during the summer and may remain dry for multiple years. In wet periods, wetlands and lakes can expand to the point of overflowing and may form surface connections between otherwise geographically isolated wetland depressions (Tiner 2003; Shapley et al. 2005).

Fig. 1 Map of the Prairie Pothole Region (PPR) of North America based on ecoregion classification (Omernik 1987, 1995)

However, wetlands may be connected by groundwater even during droughts (Winter and LaBaugh 2003).

The Holocene climate of central North America has varied markedly (Wells 1970). Temperatures during the Hypsithermal (4,000–8,000 years B.P.) in the northern Central Plains were 1°C to 2°C (Bartlein et al. 1984, 1998) or 2°C to 3°C (Denton and Porter 1970) warmer than today. Bluemle et al. (1999) characterized this period as ten or more "little ice ages" separated by global warming events. Records during this period showed evidence of aridity, increased salinity, and higher than present temperatures, with grasslands spreading farther north (Lemmen et al. 1997). The prairie-forest border along the eastern margin of the PPR has moved in response to climate fluctuations, moving west during cool, wet periods and east during warm, dry periods (Anderson 1983; Clark et al. 2001).

Climate controls the many important ecosystem services provided by prairie wetlands. For example, climate largely determines the amount of water that enters, resides in, or leaves a wetland basin. Prairie wetlands stabilize local watershed budgets by buffering the effects of drought and inundation. Some wetlands provide focused groundwater recharge during wet periods, which may stabilize surface water levels during dry periods. During wet periods, they store large amounts of surface water reducing flooding in streams and rivers. Prairie wetlands also are habitat for

thousands of plant and animal species. The PPR is an important breeding ground for North American waterfowl (Batt et al. 1989).

Research has indicated that prairie wetlands and their biodiversity would be vulnerable to climate change. Larson (1995) used statistical modeling to project that a combined 3°C temperature increase and a 10% decrease in precipitation would reduce the number of wet basins by 74%, 31% and 56% for Canada Parkland, Canada Grassland and United States Grassland subdivisions, respectively. Another statistical analysis estimated that climatic warming could reduce the number of breeding ducks settling in the PPR by half (Sorenson et al. 1998). Johnson et al. (2005) used a climate-driven, wetland simulation model to show that a warmer future climate would shift optimal breeding conditions for waterfowl eastward in the PPR, toward where most wetlands have been drained, and away from areas of high wetland density and favorable nesting cover that produced most ducks during the twentieth century.

2 Data and methods

2.1 Weather stations and records

Ecoregions represent areas with similar biotic and abiotic phenomena (Wiken 1986; Omernik 1987, 1995; USEPA 1996) and were the strata from which weather stations were selected for this analysis. Three weather stations were selected from each of six modified Level III ecoregions (Fig. 2). These 18 stations were chosen based on their longevity and completeness of record and geographic location within each ecoregion. Within ecoregions weather stations were mostly selected from locations to represent the greatest environmental range. A different set of weather stations (340 stations with 30 year records) was used to create a map of historic temperature and precipitation across the PPR.

Data for U.S. weather stations were obtained from the National Climate Data Center (NCDC), while Canadian weather data were purchased from the Environment Canada (EC) Manitoba and Arctic Regional Office. There were 588 weather stations within the PPR, and of these, approximately 130 stations had collected some data prior to 1932. All stations had breaks in their period of record. For example, only partial weather data were collected at some stations in some years. At other stations data were collected only in certain seasons or collection was interrupted for several months or years. Each of the 18 climate data sets that we compiled had three variables: daily precipitation, maximum daily temperature, and minimum daily temperature. Climate data sets were either truncated or expanded to 95 years to be of equal length. The total number of records for each of these three variables was 34,699 for each station. Fewer Canadian weather stations were used than U.S. stations because there were fewer ecoregions in Canada.

Many techniques have been used to reconstruct missing weather data (Kemp et al. 1983; Karl and Williams 1987; Mott et al. 1994; DeGaetano et al. 1995; Eischeid et al. 2000). Eischeid et al. (2000) compared six different methods of spatial interpolation and found no systematic bias in any of the estimation procedures particularly where the terrain and the density of surrounding stations were relatively uniform. We reconstructed missing daily air temperature and precipitation data by averaging data
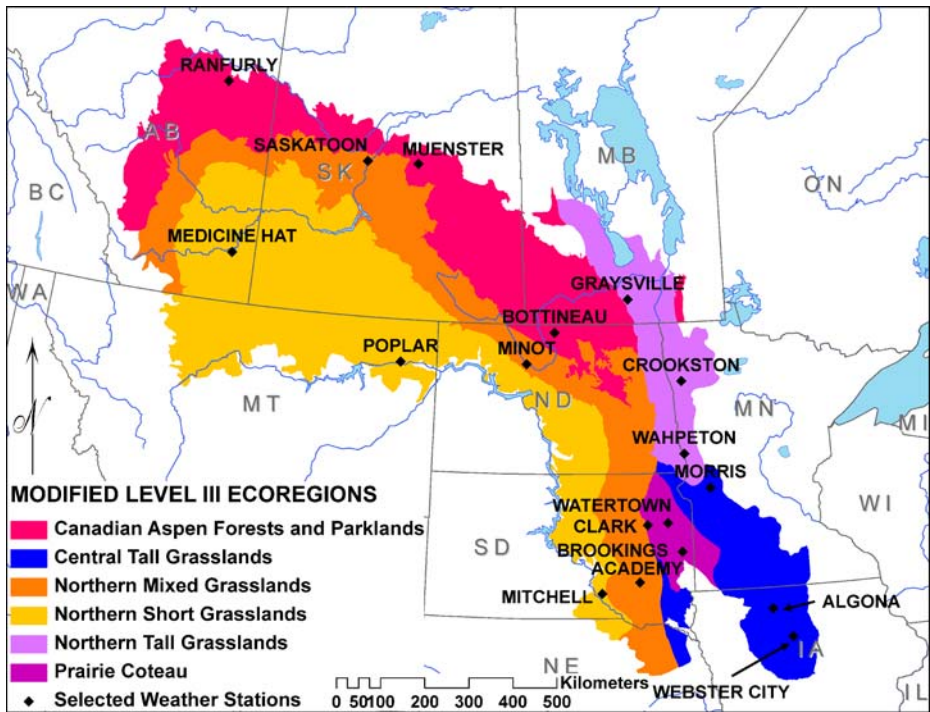
Fig. 2 Map of the modified Level III ecoregions based on USEPA (1996). The weather stations selected for analysis are shown

from two or three neighboring stations, usually within 40 km (25 mi). For the few stations where only one nearby station was available for reconstruction, the single best estimator method (Eischeid et al. 2000) was used. Because topographic relief of the PPR is gradual, differences in elevation between target station and neighboring stations were nearly always less than 100 m.

2.2 Missing data accuracy assessment

Data from target and neighboring stations were compared to determine the reliability of the reconstruction method. Spearman rank correlations were calculated for paired daily precipitation data while Pearson correlation coefficients were calculated for maximum and minimum daily temperature data. Spearman rank correlations are more appropriate than Pearson correlations when normal distributions cannot be assumed, as is the case for daily precipitation (Clark and Hay 2004). Seven of the eighteen target stations were randomly chosen, and from these, 5 months with no missing data were randomly chosen, thus producing 35 months of data. Correlation coefficients were computed between target and neighboring stations for corresponding months.

The majority of weather stations were missing fewer than 2% (694 days) of the total records for each weather element (Table 1). Two stations required extensive supplemental data. Graysville, MB was missing data for 13,095 days (37.7%). The

Table 1 Number and percentage of missing daily precipitation and maximum and minimum temperature records for selected weather stations in the Prairie Pothole Region of North America for 1906 to 2000

Station	Daily precipitation		Daily maximum temperature		Daily minimum temperature	
	Days	Percent	Days	Percent	Days	Percent
Academy, SD	206	0.6	464	1.3	494	1.4
Algona, IA	624	1.8	575	1.7	670	1.9
Bottineau, ND	94	0.3	234	0.7	195	0.6
Brookings, SD	84	0.2	192	0.6	186	0.5
Clark, SD	890	2.6	948	2.7	1,008	2.9
Crookston, MN	184	0.5	209	0.6	219	0.6
Graysville, MB	13,373	38.5	12,956	37.3	12,957	37.3
Medicine Hat, AB	129	0.4	173	0.5	163	0.5
Minot, ND	218	0.6	251	0.7	291	0.8
Mitchell, SD	419	1.2	436	1.3	463	1.3
Morris, MN	233	0.7	325	0.9	330	1.0
Muenster, SK	5,417	15.6	1,278	3.7	1,223	3.5
Poplar, MT	4,726	13.6	4,697	13.5	4,702	13.6
Ranfurly, AB	38	0.1	46	0.1	50	0.1
Saskatoon, SK	13	0.0	16	0.0	89	0.3
Wahpeton, ND	1,937	5.6	2,066	6.0	1,977	5.7
Watertown, SD	11,404	32.9	11,410	32.9	11,405	32.9
Webster City, IA	386	1.1	370	1.1	319	0.9

two longest periods of missing data were from January 1, 1906 to August 1, 1925 (7,152 days) and from November 1, 1988 to December 31, 2000 (4,444 days). Watertown, SD was missing approximately 11,406 days (32.9%). The longest data gap occurred between January 1, 1906 and December 31, 1931 (9,496 days). A shorter gap occurred between January 1, 1996 and December 31, 2000 (1,827 days). Although these two stations required extensive reconstruction, they provided the most complete weather records and the needed geographic distribution within each ecoregion.

Median Spearman's rank correlations between observed and estimated precipitation were higher for southern stations (Academy, SD; Clark, SD; Morris, MN; and Watertown, SD) than for northern stations (Bottineau, ND; Graysville, MB; and Muenster, SK). Of the 35 year/month combinations tested at the seven weather stations, 25 had moderate to strong correlation coefficients ($r = 0.40$ to 0.90) and 10 year/month combinations had very weak to low correlations coefficients ($r < 0.40$). Precipitation was underestimated for Academy, SD; Clark, SD; and Muenster, SK and overestimated for Bottineau, ND; Graysville, MN; Morris, MN; and Watertown, SD (Table 2).

Proximity and number of stations used to estimate missing data influenced the strength of correlation coefficients. Use of three nearby stations matched observed data at target weather stations better than did those of one or two nearby stations. Correlation coefficients between observed data at target and neighboring stations were weaker for northern than for southern stations probably because northern stations were farther apart. Correlations generally were higher for temperature than for precipitation. There were 32 months with strong to very strong correlation

Table 2 Spearman's correlation coefficients between target and neighboring weather stations calculated to assess accuracy of reconstructing missing daily precipitation data

Station	Date	Number	r value	p value
Academy, SD	1908FEB	28	0.7087	0.0000
	1922DEC	31	0.4808	0.0089
	1940JUN	30	0.5293	0.0036
	1954AUG	31	0.7144	0.0000
	1975MAR	31	0.8242	0.0000
Bottineau, ND	1913APR	30	0.5836	0.0011
	1930JUL	31	0.3028	0.1103
	1962MAR	31	0.5821	0.0011
	1979MAY	31	0.6674	0.0001
	1998NOV	30	0.8863	0.0000
Clark, SD	1912AUG	31	0.8505	0.0000
	1924DEC	31	0.2153	0.2515
	1946MAR	31	0.7053	0.0000
	1971APR	30	0.7857	0.0000
	1991JUN	30	0.6906	0.0000
Graysville, MB	1909AUG	31	0.4189	0.0219
	1943APR	30	0.1599	0.3955
	1959SEP	30	0.456	0.0120
	1984DEC	31	0.2728	0.1442
	1999JUL	31	0.1162	0.5388
Muenster, SK	1909MAY	31	0.2668	0.1531
	1920JAN	31	0.1726	0.3595
	1953JUN	30	0.3901	0.0337
	1965SEP	30	0.5577	0.0016
	1988MAR	31	0.5314	0.0029
Morris, MN	1919JUL	31	0.8291	0.0000
	1937MAY	31	0.5123	0.0042
	1951JUN	30	0.2906	0.1190
	1980NOV	30	0.6137	0.0004
	2000DEC	31	0.647	0.0002
Watertown, SD	1932FEB	28	0.2707	0.1548
	1950AUG	31	0.4055	0.0298
	1968APR	30	0.6063	0.0006
	1987MAY	31	0.515	0.0047
	1992DEC	31	0.4174	0.0250

Correlation coefficients reported are of the five randomly selected months for each randomly selected PPR weather station

coefficients ($r > 0.70$) for maximum daily temperature and 3 months with weak to moderate correlation coefficients ($r = 0.20$ to 0.70) (Table 3). Minimum daily temperature patterns were similar; there were 33 months with strong or very strong correlations and 2 months with moderate correlations (Table 4). Because our method of estimating missing data was satisfactory for the large majority of months and stations we used this approach to complete the data files and to conduct our climate trend analyses.

2.3 Daily weather data trend analysis

Simple linear regression was used to determine trends in total annual precipitation and mean annual temperature data over the period of record. Annual temperature and precipitation data for each station were smoothed at 3-year periods to reduce

Table 3 Pearson correlation coefficients between target and neighboring stations calculated to assess accuracy of reconstructing missing daily maximum temperature data

Station	Date	Number	r value	p value
Algona, SD	1906JAN	31	0.8296	0.0000
	1935MAR	31	0.9750	0.0000
	1949NOV	30	0.9742	0.0000
	1981MAR	31	0.9229	0.0000
	1989AUG	31	0.6707	0.0000
Brookings, SD	1912JUL	31	0.9129	0.0000
	1920JUN	30	0.9420	0.0000
	1957NOV	30	0.9521	0.0000
	1973JAN	31	0.8770	0.0000
	1995FEB	28	0.9394	0.0000
Crookston, MN	1909OCT	31	0.9129	0.0000
	1923JUN	30	0.9420	0.0000
	1938MAR	31	0.9521	0.0000
	1966SEP	30	0.8770	0.0000
	1987AUG	31	0.9394	0.0000
Medicine Hat, AB	1907SEP	30	0.9171	0.0000
	1924MAY	31	0.7935	0.0000
	1939SEP	30	0.7154	0.0000
	1956JAN	31	0.8251	0.0000
	1979MAR	31	0.8294	0.0000
Minot, ND	1920MAY	31	0.8720	0.0000
	1943MAY	31	0.9283	0.0000
	1965FEB	28	0.9572	0.0000
	1975SEP	30	0.8537	0.0000
	1991DEC	31	0.9532	0.0000
Poplar, MT	1912MAR	31	0.8911	0.0000
	1927DEC	31	0.9032	0.0000
	1939SEP	30	0.8506	0.0000
	1966APR	30	0.9079	0.0000
	1978JAN	31	0.9189	0.0000
Watertown, SD	1934MAY	31	0.9589	0.0000
	1959JUL	31	0.7233	0.0000
	1965OCT	31	0.3340	0.0712
	1976APR	30	0.5345	0.0023
	1984NOV	30	0.7731	0.0000

Correlation coefficients reported are of the five randomly selected months for each randomly selected PPR weather station

year-to-year variability and to help detect trends in magnitude and duration. Similar approaches have been used by others in cases where high temporal variability in weather data exists (Karl et al. 1995; Hansen et al. 1998; Garbrecht and Rossel 2002; NCDC 2008). Estimates from regression equations for the year 1906 were subtracted from those for the year 2000 for each weather station to show the magnitude of change and the sign (positive or negative trend) over the 95-year period. Minimum and maximum temperature data for summer (June, July, and August) and winter (December, January, and February) seasons were selected to examine long-term trends.

2.4 Palmer drought severity index

The Palmer Drought Severity Index (PDSI) is a widely used drought assessment measure (Alley 1984; Lohani and Loganathan 1997; Winter and Rosenberry

	Station	Date	Number	*r* value	*p* value
Table 4 Pearson correlation coefficients between target and neighboring stations calculated to assess accuracy of reconstructing missing daily minimum temperature data	Academy, SD	1911JUL	31	0.9482	0.0000
		1937SEP	30	0.8343	0.0000
		1956FEB	28	0.9203	0.0000
		1973NOV	30	0.9427	0.0000
		1989JAN	31	0.7753	0.0000
	Brookings, SD	1909JAN	31	0.9777	0.0000
		1934NOV	30	0.9167	0.0000
		1944AUG	31	0.9471	0.0000
		1982MAR	31	0.9557	0.0000
		1996APR	30	0.9313	0.0000
	Clark, SD	1917JUL	31	0.9019	0.0000
		1922SEP	30	0.9016	0.0000
		1954JUN	30	0.9610	0.0000
		1978DEC	31	0.8455	0.0000
		2000MAR	31	0.9506	0.0000
	Graysville, MB	1926AUG	31	0.6621	0.0001
		1933OCT	31	0.7280	0.0000
		1956MAY	31	0.9063	0.0000
		1970JAN	31	0.9232	0.0000
		1984JUN	30	0.7990	0.0000
	Minot, ND	1915JUL	31	0.7974	0.0000
		1927MAY	31	0.4594	0.0107
		1946MAR	31	0.7778	0.0000
		1963SEP	30	0.8623	0.0000
		1989DEC	31	0.9707	0.0000
	Morris, MN	1909DEC	31	0.9683	0.0000
		1922OCT	31	0.9280	0.0000
		1945MAR	31	0.9500	0.0000
		1957APR	30	0.9485	0.0000
		1993AUG	31	0.9229	0.0000
	Wahpeton, ND	1918NOV	30	0.9319	0.0000
Correlation coefficients reported are of the five randomly selected months for each randomly selected PPR weather station		1935MAR	31	0.9173	0.0000
		1957APR	30	0.9797	0.0000
		1981OCT	31	0.9758	0.0000
		1995JAN	31	0.9072	0.0000

1998; Cook et al. 1999; Nkemdirim and Weber 1999; Hayes et al. 2002). The index uses temperature, precipitation, the available water content of the soil, and Thornthwaite's method for calculating potential evapotranspiration (Thornthwaite and Mather 1957). PDSI values above +4.00 or below -4.00 represent extreme deluge and drought, respectively. PDSI values from -0.50 to $+0.50$ lie within the normal range. PDSI values were calculated using the PDSI program version 2.0 available from the National Agricultural Decision Support System (NADSS 2003).

The PDSI program used four input files: monthly temperature, monthly precipitation, normal monthly temperature, and the parameters. The parameters file contained the underlying soil moisture value and the negative tangent of latitude of the station. The negative tangent of latitude of the station was determined by converting the latitude for each weather station from degrees, minutes, and seconds into decimal degrees. The underlying soil moisture value was held constant across

all weather stations. The monthly temperature input values were the average of the daily high and low for each month. The monthly precipitation values were the monthly precipitation sums for each month. The normal monthly temperatures were the long-term (95-year) average temperature for each month.

3 Results

3.1 Precipitation and temperature gradients

Precipitation and temperature gradients across the PPR were orthogonal to each other (Fig. 3) consistent with larger continental gradients. Average annual precipitation varied across the PPR from over 300 mm/year in the extreme northwest (Alberta) to nearly 900 mm/year in the extreme southeast (Iowa). For example, Poplar, MT and Crookston, MN are at similar latitudes (48°N); however, Poplar, MT had a mean annual rainfall of 333 mm, while Crookston, MN had a mean annual rainfall of 516 mm. Mean annual temperature increased latitudinally from 1°C at the northern limit of the PPR to 10°C at the southern limit. To illustrate, Webster City, IA located at 42°28′N had a mean annual temperature of 8.7°C, while Muenster, SK at latitude 52°11′N had a mean annual temperature of 0.9°C.
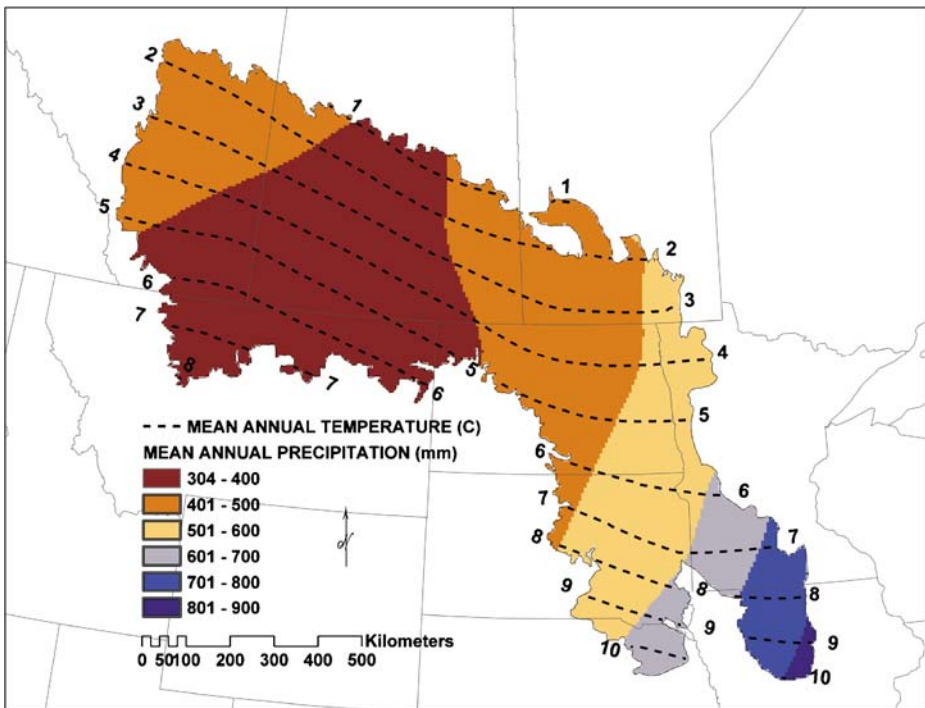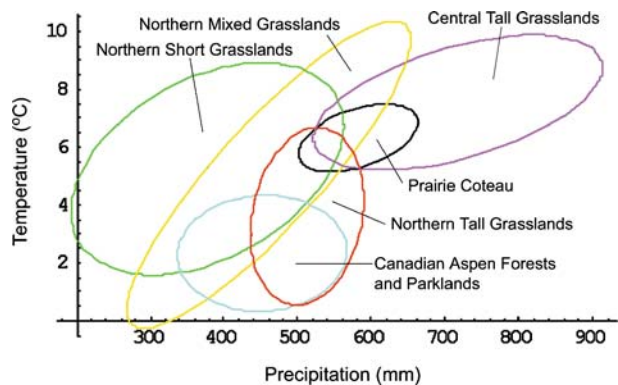

Fig. 3 Geographic patterns of mean annual precipitation and temperature for the PPR based on data from 30-year climate normals 1961–1990 for 394 weather stations

Fig. 4 Ellipses for each
ecoregion representing the
90% confidence intervals of
mean annual precipitation and
temperature data from 394
weather stations for the PPR

3.2 Ecoregion climates

Historic climate varied substantially across the ecoregions of the PPR. Ellipses
were created to represent the climatic realm of each ecoregion and to portray the
amount of climatic overlap among regions (Fig. 4). Precipitation in the Central
Tall Grasslands exceeded that of any other ecoregion. Average temperature for the
Aspen Parklands ecoregion was the coolest and did not intersect the Prairie Coteau
or Central Tall Grasslands ecoregions. The area where most ellipses overlapped
(approximately mean annual temperature of 5°C and mean annual precipitation
of 530 mm) is an area of highly productive and dynamic wetlands in the eastern
Dakotas (Johnson et al. 2005). Generally, average temperature correlated positively
with precipitation.

3.3 Precipitation and temperature trends

3.3.1 Annual

Precipitation generally increased across the PPR during the twentieth century;
regression lines for ten of the eighteen weather stations had statistically significant
($p < 0.05$) positive slopes for precipitation (Table 5). The average increase in
annual precipitation across all stations calculated from the regression equations was
49 mm/95-years or 9%.

The largest increases in precipitation generally occurred along the eastern and
northeastern fringe in the tall grassland ecoregions (Fig. 5), historically the wettest
areas of the PPR (Fig. 4). For example, precipitation at Graysville, MB increased by
155 mm and by 140 mm at Webster City, IA. Most of the stations in the eastern half
of the PPR posted significant increases in precipitation over the 95-year period, while
none of the five stations did in the western half of the PPR.

Variation in long-term precipitation patterns was considerable over short dis-
tances in some sections of the PPR. For example, the two nearby Iowa stations
exhibited different trends; Webster City became considerably wetter, while Algona
showed no long-term trend (Fig. 5). Also, three of the five stations in eastern South
Dakota showed no long-term change in precipitation, while two others showed

Station	Trend	p value
Academy, SD	+	0.0041
Algona, IA		0.6624
Bottineau, ND	+	0.0001
Brookings, SD	+	0.0005
Clark, SD		0.9505
Crookston, MN	+	0.0304
Graysville, MB	+	0.0001
Medicine Hat, AB	+	0.0398
Minot, ND	+	0.0001
Mitchell, SD		0.7983
Morris, MN	+	0.0141
Muenster, SK		0.0507
Poplar, MT		0.1711
Ranfurly, AB		0.1057
Saskatoon, SK		0.1986
Wahpeton, ND	+	0.0002
Watertown, SD		0.6875
Webster City, IA	+	0.0001

Table 5 Annual precipitation trends from 1906 to 2000 for 18 weather stations based on linear regression

The (+) signifies a positive trend (wetter). Stations in bold were statistically significant ($p < 0.05$)
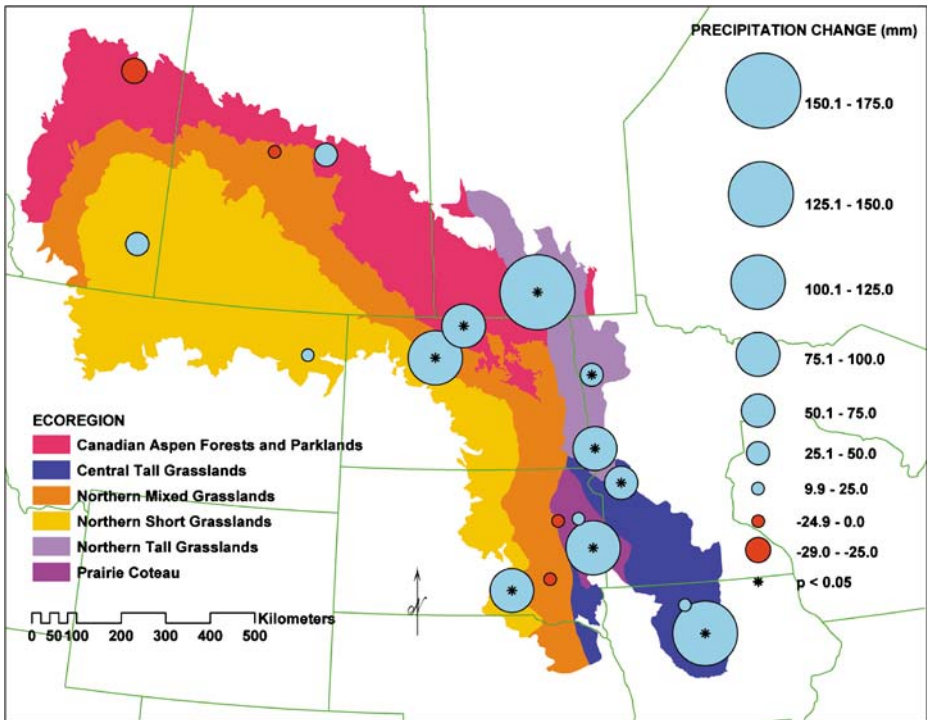
Fig. 5 Map of historic trends in annual precipitation for 18 weather stations and six ecoregions in the PPR

significant increases. Trends among nearby stations were more consistent in the
northeastern PPR but less consistent in Saskatchewan and Alberta (Fig. 5).

Long-term trends for maximum daily temperature were weaker and more vari-
able than those for minimum temperature. Based on linear regression analysis the
average maximum daily temperature across weather stations was 11.72°C in 1906
and 11.58°C in 2000, a statistically non-significant decrease of 0.14°C ($p = 0.5006$).
Twelve stations had negative slopes for maximum daily temperature; seven of these
were statistically significant ($p < 0.05$) (Table 6). Three of the six stations with
positive slopes for maximum temperature were statistically significant ($p < 0.05$).

Trends towards cooler maximum temperatures were concentrated in the south-
eastern portion of the PPR, historically the warmest stations (Fig. 6). Trends in the
central and western portions of the PPR were more variable but included the only
stations with significant warming. Based on linear regression analysis, the magnitude
of change in temperature ranged from near 0°C to approximately 2°C (Fig. 6).

Minimum daily temperature (Fig. 7) changed more uniformly across the PPR than
did maximum daily temperature. Average daily minimum temperature regressed
across stations in 1906 was −1.54°C and −0.54°C in 2000, a significant increase of 1°C
($p = 0.0049$). Ten of 13 stations showed statistically significantly ($p < 0.05$) increases
in minimum temperature, while two stations had significant negative slopes (Table 6).

Stations trending toward warmer minimum temperatures were widespread
(Fig. 7); however, the greatest magnitude of increase occurred in central and western
portions of the PPR. The largest increases of nearly 3.5°C occurred in western
portions of the Canadian Aspen Forests and Parklands ecoregion (Fig. 7). The few

Table 6 Annual mean maximum (TMAX) and minimum (TMIN) temperature linear regression
trends from 1906 to 2000 for 18 weather stations

Station	Tmax trend	Tmax *p* value	Station	Tmin trend	Tmin *p* value
Academy, SD		0.2082	**Academy, SD**	−	0.0021
Algona, IA	−	0.0022	Algona, IA		0.0701
Bottineau, ND		0.9703	**Bottineau, ND**	+	0.0001
Brookings, SD	−	0.0001	**Brookings, SD**	−	0.0011
Clark, SD		0.0630	**Clark, SD**	+	0.0001
Crookston, MN		0.1007	Crookston, MN		0.3414
Graysville, MB	+	0.0030	**Graysville, MB**	+	0.0192
Medicine Hat, AB	−	0.0400	Medicine Hat, AB		0.0943
Minot, ND	−	0.0006	**Minot, ND**	+	0.0001
Mitchell, SD		0.1156	Mitchell, SD		0.0823
Morris, MN	−	0.0017	Morris, MN		0.8194
Muenster, SK		0.2377	**Muenster, SK**	+	0.0001
Poplar, MT	+	0.0001	**Poplar, MT**	+	0.0001
Ranfurly, AB		0.1925	**Ranfurly, AB**	+	0.0001
Saskatoon, SK	+	0.0008	**Saskatoon, SK**	+	0.0001
Wahpeton, ND		0.6447	**Wahpeton, ND**	+	0.0001
Watertown, SD	−	0.0128	Watertown, SD		0.1000
Webster City, IA	−	0.0001	**Webster City, IA**	+	0.0022

The (+) signifies a significant positive trend (warmer) and the (−) signifies a significant negative trend
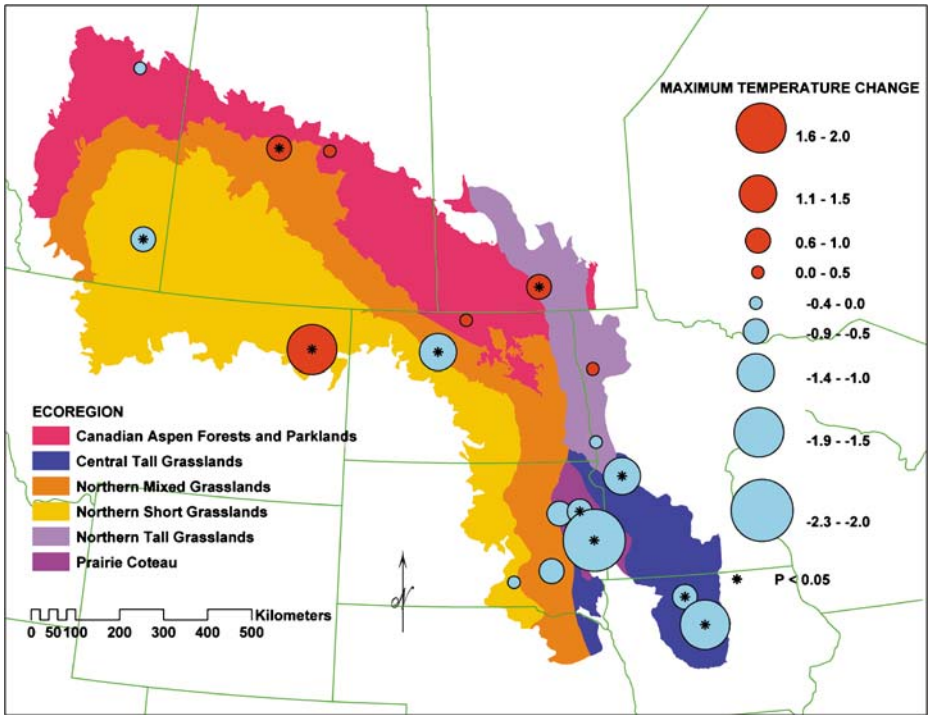(cooler). Stations in bold were statistically significant ($p < 0.05$)

Fig. 6 Map of historic trends in maximum daily temperature for 18 weather stations and six ecoregions in the PPR

stations with significantly cooler minima were in the southeastern portion of the PPR and these exhibited only slight cooling (<1°C).

3.3.2 Seasonal temperature trends

The temperature trends were not uniform seasonally. Although the same number (12 of 18) of stations experienced a significant rise in minimum temperatures in winter and summer, the magnitude of the warming was much greater in winter (Table 7). The average increase in minimum temperature was greater in winter than in summer, but the difference was not statistically significant [T test alpha <0.05 ($p = 0.1390$)].

For maximum temperatures more stations exhibited significant winter warming (7 of 18) than summer warming (5 of 18) (Table 8). In contrast, more stations exhibited significant summer cooling (8 of 18) than winter cooling (4 of 18) (Table 8). For the stations that exhibited significant warming, the magnitude of change was not statistically significant [T test alpha <0.05 ($p = 0.0917$)].

3.4 PDSI trends

To represent the broad ecoregion patterns across the PPR, one weather station was selected from the central part of each ecoregion, and Box and Whisker plots were created to graphically show trends of central tendency and variability of decadal
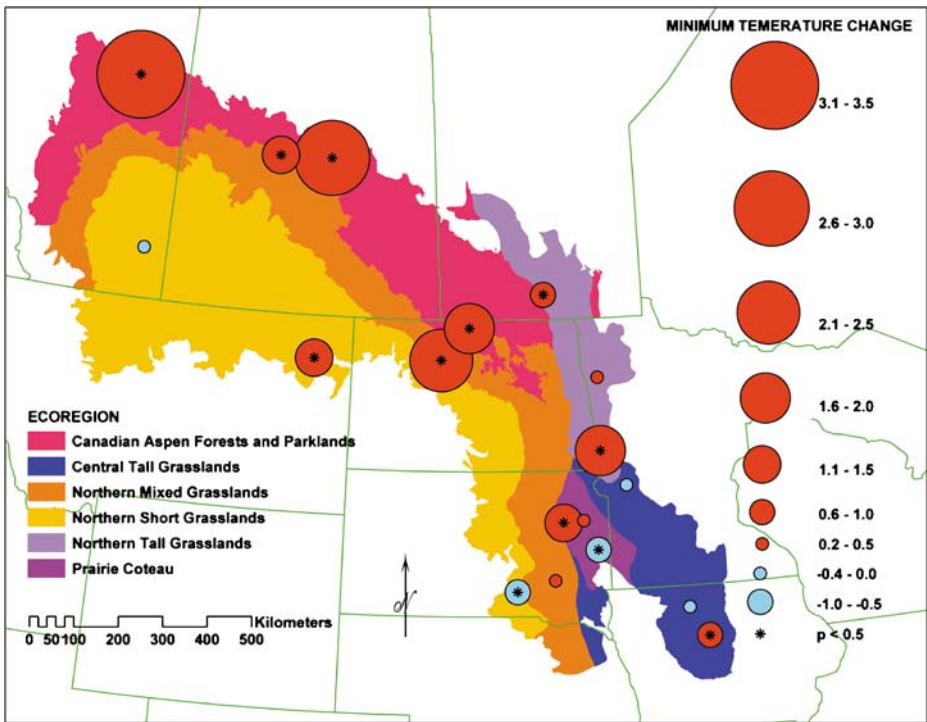
Fig. 7 Map of historic trends in minimum daily temperature for 18 weather stations and six ecoregions in the PPR

Table 7 Daily minimum temperature (TMIN) linear regression trends by season from 1906 to 2000 for 18 weather stations

Tmin winter			Tmin summer		
Station	p value	Trend (°C)	Station	p value	Trend (°C)
Academy, SD	0.5703		**Academy, SD**	0.0001	−0.61
Algona, IA	0.2012		**Algona, IA**	0.0331	−0.31
Bottineau, ND	0.0000	2.40	**Bottineau, ND**	0.0000	1.25
Brookings, SD	0.0007	−1.04	**Brookings, SD**	0.0326	−0.35
Clark, SD	0.0001	1.24	**Clark, SD**	0.0000	1.96
Crookston, MN	0.0019	1.00	Crookston, MN	0.1832	
Graysville, MB	0.0190	0.78	**Graysville, MB**	0.0000	1.19
Medicine Hat, AB	0.0363	0.79	**Medicine Hat, AB**	0.0000	−0.82
Minot, ND	0.0000	2.92	**Minot, ND**	0.0000	2.42
Mitchell, SD	0.3106		**Mitchell, SD**	0.0000	1.43
Morris, MN	0.4645		**Morris, MN**	0.0034	0.44
Muenster, SK	0.0000	3.98	**Muenster, SK**	0.0000	2.23
Poplar, MT	0.0000	3.59	Poplar, MT	0.1886	
Ranfurly, AB	0.0000	4.3	**Ranfurly, AB**	0.0000	2.40
Saskatoon, SK	0.0000	2.48	**Saskatoon, SK**	0.0000	0.57
Wahpeton, ND	0.0000	1.98	**Wahpeton, ND**	0.0000	2.29
Watertown, SD	0.0435	0.61	**Watertown, SD**	0.0000	0.90
Webster City, IA	0.2531		**Webster City, IA**	0.0000	1.00

Stations in bold were statistically significant ($p < 0.05$)

Table 8 Daily maximum temperature (TMAX) linear regression trends by season from 1906 to 2000 for 18 weather stations

Tmax winter			Tmax summer		
Station	p value	Trend (°C)	Station	p value	Trend (°C)
Academy, SD	0.4570		Academy, SD	0.1425	
Algona, IA	0.0000	−1.18	**Algona, IA**	0.0000	−0.66
Bottineau, ND	0.0000	1.05	Bottineau, ND	0.3438	
Brookings, SD	0.0000	−1.66	**Brookings, SD**	0.0000	−2.02
Clark, SD	0.7125		Clark, SD	0.1892	
Crookston, MN	0.0033	0.86	**Crookston, MN**	0.0093	0.44
Graysville, MB	0.0005	1.10	**Graysville**	0.0000	0.90
Medicine Hat, AB	0.0005	1.34	**Medicine Hat, AB**	0.0000	−1.91
Minot, ND	0.2298		**Minot, ND**	0.0011	−0.64
Mitchell, SD	0.7213		Mitchell, SD	0.1701	
Morris, MN	0.0133	−0.73	**Morris, MN**	0.0000	−0.74
Muenster, SK	0.0026	1.02	Muenster, SK	0.1136	
Poplar, MT	0.0000	2.49	**Poplar**	0.0000	1.56
Ranfurly, AB	0.1081		**Ranfurly, AB**	0.0002	−0.69
Saskatoon, SK	0.0000	1.82	**Saskatoon, SK**	0.0132	0.47
Wahpeton, ND	0.1722		**Wahpeton, ND**	0.0002	0.63
Watertown, SD	0.8129		**Watertown, SD**	0.0136	−0.44
Webster City, IA	0.0000	−1.50	**Webster City, IA**	0.0000	−2.33

Stations in bold were statistically significant ($p < 0.05$)

PDSI values (Fig. 8). Decadal patterns showed considerable variability among PPR weather stations. For example, Medicine Hat, AB experienced near normal PDSI values during the 1930s but had consistently lower PDSI values during the 1920s and 1980s (Fig. 8). Similar results were found at other Canadian weather stations indicating that the northern portion of the PPR was more affected by the 1980s drought than the 1930s drought. In contrast, the 1950s drought was more severe than that of the 1930s in the southeastern PPR (Iowa).

The PDSI value of −2.39 for the 1930s was the driest decade for the PPR, based on a comparison of decadal averages for the 18 weather stations (Table 9). Drought during this decade also was the most widespread with 17 of the 18 weather stations with negative PDSI values. The lowest PDSI values occurred in the Dakotas and western Minnesota. Thirteen of 18 stations also had negative PDSI values in the 1920s.

Conversely the incomplete decade from 1906 to 1910 ranked as the wettest period, followed by the 1990s (Table 9) when 16 of the 18 weather stations had positive PDSI values. The next wettest decade was the 1970s when 10 of 18 weather stations had positive values. The 1960s represented a near "normal range" decade with a PDSI of 0.00.

The 95-year PDSI trends across all eighteen stations indicated variable but mostly increasing moisture availability during the twentieth century in the eastern half of the PPR (Fig. 9). No stations in this region showed a significant decrease in moisture availability. The western half of the PPR exhibited a mix of trends; two stations had significantly wetter conditions (Medicine Hat, AB and Muenster, SK) and two developed significantly drier conditions (Ranfurly, AB and Saskatoon, SK).
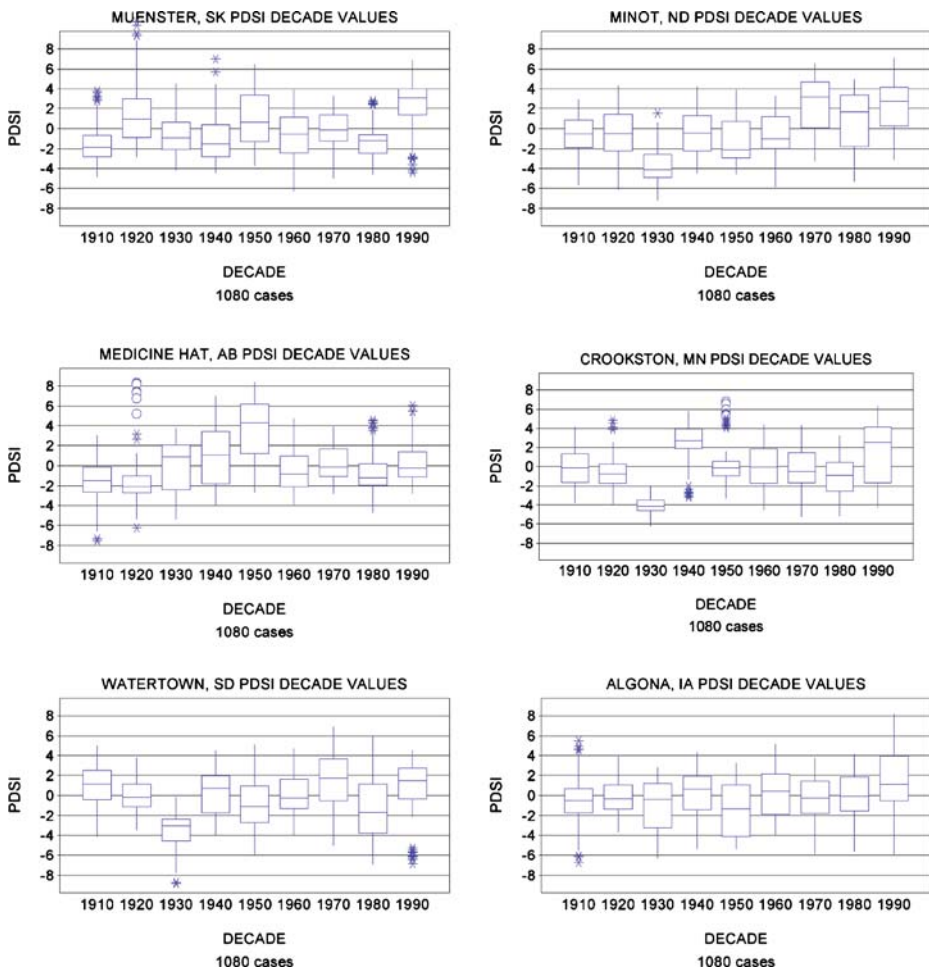
Fig. 8 Decadal PDSI box plots for six selected weather stations, one for each ecoregion. The *box* encloses the middle half of the data and the *line* that intersects the box is the median. The *vertical lines* at the top and the bottom of the box show the range (first and third quartile) of "typical" data values

4 Discussion

Strong temperature and precipitation gradients across the PPR combined to produce multiple climates varying in the degree of aridity. The west-east precipitation gradient was particularly steep, from about 300 mm/year to 900 mm/year. The north-south temperature gradient was more gradual, but the mean annual temperature of stations in the south averaged nearly 10°C warmer than those in the extreme north. The dryness expected from the much lower annual precipitation in the western Canadian prairies was moderated somewhat by the cooler temperatures and shorter growing season. In general, warmer sections received more precipitation than cooler regions.

Table 9 Palmer Drought
Severity Index (PDSI)
averaged by decade for 18
Prairie Pothole Region
weather stations and ranked
from driest to wettest

PDSI		
Rank	Decade	Average
1	1930	−2.39
2	1920	−0.33
3	1980	−0.32
4	1950	−0.14
5	1910	−0.10
6	1960	0.00
7	1940	0.15
8	1970	0.47
9	1990	1.28
10	1900	1.97

The twentieth century climate of the PPR was punctuated by significant droughts. These conditions have occurred over small and large areas and lasted as short as several growing seasons or as long as a decade (Skaggs 1975; Laird and Cumming 1998; Nkemdirim and Weber 1999). Most PPR stations recorded their lowest PDSIs during the 1930s, however geographically restricted droughts also were severe.
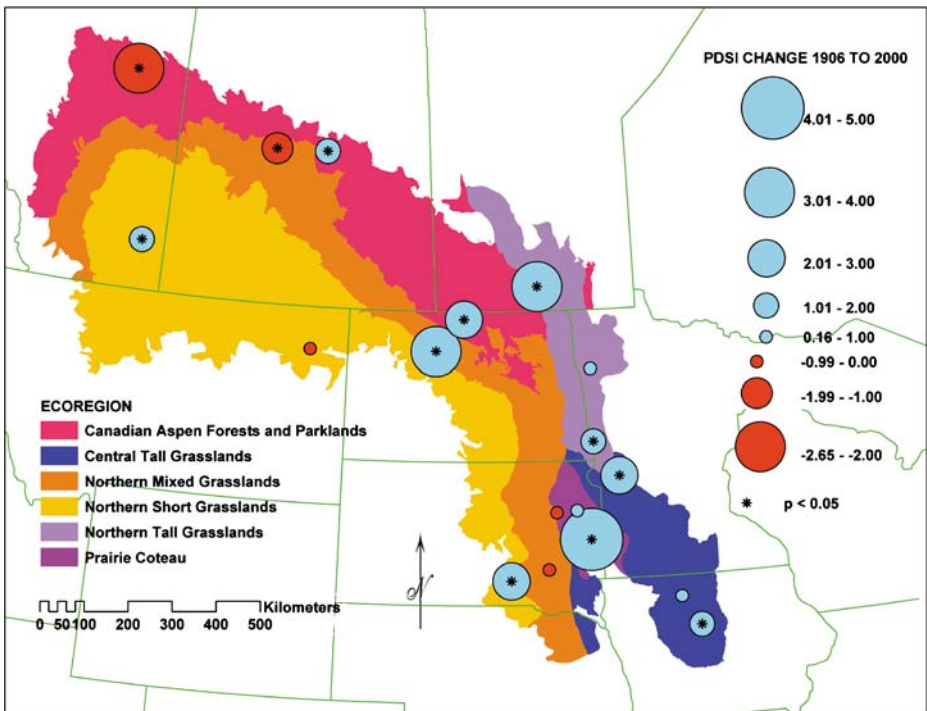
Fig. 9 Prairie Pothole Region PDSI trends from 1906 to 2000 based on simple linear regression. *Circle size* indicates the magnitude of change. *Red circles* represent negative slope or stations with decreasing PDSI values. *Blue circles* represent stations with increasing PDSI values

Nkemdirim and Weber (1999) found that the 1980s drought in the southern Canadian prairies was comparable in intensity to the 1930s drought with PDSI values of −1.33 and −1.39, respectively.

The PPR generally became warmer and wetter during the twentieth century. Our results showed that average daily air temperature rose by about 1.0°C/95 years, slightly above the global average of 0.6°C (±0.2°C) since the late-nineteenth century, and about 0.4°F (0.2 to 0.3°C) over the past 25 years (National Oceanic and Atmospheric Administration 2006). Similarly, Gullett and Skinner (1992) found that Canada had warmed by 1.1°C between 1895 and 1991. Nearly all of this increase was caused by higher daily minimum rather than daily maximum temperatures, except for some northern and western stations. Karl et al. (1993) found that these asymmetric trends also occurred globally. They reported the minimum temperature increased at a rate three times that of the maximum temperature during the period 1951–1990 (0.84°C versus 0.28°C). Both maximum and minimum temperatures have increased more at higher latitudes, but minimum temperatures more so (Karl et al. 1993; Easterling et al. 1997). The National Assessment Synthesis Team (2001) reported a 1.0°C increase in mean surface temperature for the northern and central Great Plains of the United States during the twentieth century. Larger increases in temperature of up to 3°C have been reported for parts of Montana and the Dakotas (National Assessment Synthesis Team 2000).

Temperature also has changed seasonally. Winters have been getting particularly warmer across North America. Bonsal et al. (2001) found fewer days in Canada with extreme low temperatures during winter, spring, and summer, and more days with extreme high temperatures during winter and spring. A shorter ice season has been caused by later freezing and earlier breakup on Northern Hemisphere lakes and rivers. Magnuson et al. (2000) using records derived from human observations in eastern North America showed that lakes and rivers were freezing at later dates and breaking-up on earlier dates in 38 of 39 records from 1846 to 1995. Model simulations have projected that the biggest reduction in the number of frost days (20 fewer days per year) will occur from the Great Plains westward by 2080–2099 (Meehl et al. 2004).

Our analysis determined that precipitation averaged across the PPR increased during the past century, despite a precipitation decrease in the western Canadian prairies. Because a large portion of the U.S. weather stations used in our analysis were extremely wet in the 1990s, the last decade in our data set, the regression analysis conducted could have overestimated precipitation increases during the twentieth century. Garbrecht and Rossel (2002) also found that the northern and northwestern Great Plains experienced a precipitation increase near the end of a 105-year record, but it was primarily confined to the final decade of the twentieth century. They stated, "fewer dry years over the last 10 years, as opposed to an increase in very wet years, were the leading cause of the observed wet conditions." Changnon (2001) showed that between 1950 and 1994 thunderstorms have not only been more frequent, but also have produced more rainfall in the Midwest and Great Plains. Over the last 100 years, however, annual precipitation has decreased by 10% in eastern Montana and in North Dakota (National Assessment Synthesis Team 2001). In the eastern Great Plains, precipitation has increased by more than 10% (National Assessment Synthesis Team 2001). Sauchyn et al. (2003) stated that droughts in northernmost Montana and Alberta in the twentieth century were more

frequent but shorter in duration than droughts in the eighteenth and nineteenth centuries derived from proxy data.

Wetlands respond to the strong spatial and temporal change in climatic conditions across the PPR. Wetlands in the midsection of the PPR (eastern Dakotas and southeastern Saskatchewan) experienced the most dynamic climate during the twentieth century, and as a result, they may be on average the most productive because they pass through all stages of the vegetation cover cycle more rapidly and more frequently (Murkin et al. 1997; Haig et al. 1998; Johnson et al. 2005). For example, high water produces a lake phase with little emergent vegetation and few nutrients in bottom detritus, while chronic low water produces the dry marsh phase with heavy emergent vegetation and high nutrient sequestering in plant material. The occurrence of both extremes during a weather cycle and intermediate stages (regenerating and degenerating marsh phases) creates plant population turnover (maintaining biological diversity) and nutrient mobilization (van der Valk and Davis 1978; Johnson et al. 2004). The central section of the PPR historically had faster cover cycle return times (Johnson et al. 2005); however, the wetter fringes historically have provided refugia from droughts. Wetlands occupying the northern and eastern fringes of the PPR (northern Saskatchewan, Minnesota, Iowa), where climate has historically been wetter, have more stable water levels but on average are probably less productive. In contrast, wetlands along the western fringes of the PPR (Montana, Alberta) more often experience prolonged periods of dry or low water conditions.

The eastern portion of the PPR has experienced the most wetland drainage for agriculture. From the 1870s to the 1930s, nearly all the prairie wetlands in Iowa, southwestern Minnesota, and the Red River Valley were drained (Schrader 1955; Dahl and Allord 1996). Iowa lost 89% of its prairie wetlands during the twentieth century (Dahl 1990). Minnesota lost more than 90% of its western prairie wetlands (Anderson and Craig 1984). Wetland losses were 49% in North Dakota, 35% in South Dakota, and 27% in Montana (Dahl 1990).

Current wetland densities are a function of geological history and the rate of drainage for agriculture across ecoregions; the tall grass ecoregion has 3 to 4 wetlands per square kilometer while ecoregions farther west (mixed and short grassland) have upwards of 15 wetlands per square kilometer (Table 10). Drainage of wetlands in the wetter, eastern PPR has lowered the potential of the PPR to produce waterfowl in a warmer greenhouse climate. Model simulations have shown that changes in climate of the magnitude predicted by global circulation models could shift climatic conditions favorable for wetland inundation eastward toward areas where most

Table 10 Wetland density based on the number of wetlands per square kilometer for Prairie Pothole Region ecoregions of the United States

Ecoregion	Wetlands/km^2
Canadian aspen forests and parklands	15.5
Central tall grasslands	3.6
Northern mixed grasslands	15.5
Northern short grasslands	11.0
Northern tall grasslands	4.2
Prairie coteau	7.8

Densities calculated from National Wetlands Inventory data (Guntenspergen, unpublished data)

wetlands have been drained for agriculture (Johnson et al. 2005) (Table 10). Climate change poses a conservation challenge because the highest densities of intact wetland basins and best upland nesting cover (Weller 1994; Reynolds et al. 2001) occur in the drier PPR where the effects of climate change are projected to be the most severe (USGS 2006). Restoration of drained wetlands in the east, albeit an expensive prospect (Interagency Workgroup on Wetland Restoration 2003), could help diminish the effects of increased droughts in the climatically drier west.

Scientists have yet to work out how waterfowl populations may be affected by likely changes in inter-annual variability and within-year distribution of precipitation. Uncertainty about the future periodicity in extreme events such as flooding and drought leads to even more uncertainty on the impacts to waterfowl. Future within-year distribution of precipitation will likely affect wetland dynamics such as cover cycles and return times but the degree to which these changes will influence waterfowl populations remains unclear.

While waterfowl have adapted to the historically high spatial and temporal variability of water and plant cover in the PPR (Hansen and McKnight 1964; Crissey 1969; Bethke and Nudds 1993), fewer options may exist in the future under the drier scenarios expected. Sorenson et al. (1998) estimated that duck populations breeding in the PPR could decrease by half under most climate scenarios.

Our results show that the climate during the twentieth century did not change uniformly across the PPR. In particular the climate of the Canadian Apsen Forests an Parklands warmed considerably more than the global mean during the twentieth century. The Central Tall Grasslands generally cooled rather than tracking the global trend of warming during the twentieth century. Model simulations (Johnson et al. 2005) indicate that an additional temperature change of this magnitude in the future without increased precipitation would strongly reduce the contribution of the western PPR to overall wetland-associated biodiversity. Conversely, the eastern and historically the wettest portion of the PPR, has become even wetter. Thus, the general trend of the climatic gradient from west to east steepened during the twentieth century periodically reducing the functional area of the PPR. Wetlands in the east have become less productive because they are too wet (fewer complete cover cycles per century) while wetlands in the west have become less productive because they dry out more frequently.

We do not know whether the trends in climate recorded during the twentieth century for the PPR will continue into the future. Predictions vary quite widely among General Circulation Models (GCMs) for precipitation but more narrowly for temperature (IPCC 2007). If climate trends from the twentieth century do continue, the steeper west to east gradient in wetness may further shrink the productive portion of the PPR. The consequences for wetlands and waterfowl could be substantial. Should the eastern PPR begin to warm, a more productive wetland climate would result; however, a significant portion of the previously drained wetlands would have to be restored to offset less productive conditions in the western PPR. The climate should be watched closely in the future to look for signs of higher evaporative demand and to prepare for a PPR with less productive wetlands and fewer waterfowl. Only three long-term monitoring sites for wetland hydrology and vegetation are available to assist in detecting future trends (Johnson et al. 2004). Expansion of this network would greatly improve our ability to forecast and plan for climate change in the PPR.

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