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ARIDITY ON THE CANADIAN PLAINS

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ABSTRACT The Prairie Ecozone is the only major region of Canada where drought is a landscape hazard; aridity is linked to soil erosion. Management of prairie ecosystems and soil landscapes therefore requires an understanding of past and future trends and variability in regional aridity. We used instrumental and paleoclimatic records to define a regional baseline for prairie aridity, to evaluate the utility of modern climate normals (*i.e.* 1961-1990) as a benchmark for future climatic change, and to provide a historical context for a range of General Circulation Model (GCM) forecasts of regional aridity. A warm-dry scenario derived from the Canadian GCM projects a significant increase in the area of subhumid and semiarid climate. Tree rings and diatom-inferred lake salinity record prolonged arid events and show that the climate normal period of 1961-1990 may have been the most benign climate of the past 750 years. The climate of the 20th century was anomalous in terms of the absence of sustained drought. Because both lake and tree-ring analyses recorded an abrupt amelioration of climatic conditions near the start of the instrumental record, we suggest that the immediate impacts of future global warming may be to return the prairies to past conditions in which persistent aridity was recorded for intervals of decades or longer.

RÉSUMÉ *L'aridité dans les Prairies.* L'écozone des Prairies est la seule grande région du Canada où la sécheresse constitue un risque environnemental ; l'aridité est liée à l'érosion du sol. Une compréhension des tendances et des variations de l'aridité passées et à venir des écosystèmes et des sols des Prairies est donc nécessaire pour en rendre possible l'aménagement. Les données paléoclimatiques et climatiques récentes consignées ont servi à définir un niveau d'aridité de base pour la région des Prairies, à évaluer l'utilité des normales climatiques modernes (de 1961 à 1990) comme points de référence pour les changements climatiques à venir et à fournir une base historique à divers scénarios de prévision de l'aridité à l'échelle régionale à partir de modèles de circulation générale. Le scénario du changement vers un climat chaud et sec découlant du modèle canadien prévoit une expansion importante des zones subhumide et semi-aride. Les relevés dendrochronologiques et les données de salinité lacustre obtenues à partir des diatomées signalent l'existence de périodes de sécheresse prolongées et montrent que les normales climatiques enregistrées de 1961 à 1990 pourraient avoir été les plus clémentes des 750 dernières années. Le climat du XXe siècle a été anormal en ce qu'il a été caractérisé par l'absence d'une période de sécheresse prolongée. Les données dendrochronologiques et de salinité lacustre montrent une amélioration soudaine des conditions climatiques vers le début de la période de l'enregistrement des données climatiques ; on croit, de ce fait, que le réchauffement climatique prévu pourrait avoir comme effet immédiat le retour du climat qui prévalait dans le passé dans les Prairies, alors que les périodes d'aridité persistaient pendant des décennies, parfois plus.

RESUMEN *Aridez de la praderas canadienses.* La ecozona de las praderas es la única región de Canadá donde la sequía representa un riesgo ambiental ya que está relacionada con la erosión del suelo. La gestión del ecosistema de las praderas y del suelo requiere la comprensión de las tendencias presentes y futuras de la variación regional de la aridez. En este estudio se usaron registros instrumentales y paleoclimáticos para definir un umbral regional de la aridez de las praderas; para evaluar la utilidad de valores climáticos normales actuales (i.e. 1961-1990), como un punto de referencia para futuros cambios climáticos; y para proporcionar un contexto histórico para el rango del pronostico de la aridez regional con base al Modelo de Circulación General. Un escenario de calentamiento seco derivado del modelo canadiense pronostica un incremento significativo del área de zonas de clima subhúmedo y semiárido. Los datos obtenidos a partir de anillos de crecimiento y de salinidad lacustre basados en diatomeas dan cuenta de periodos prolongados de sequía y muestran que el clima normal en el periodo 1961-1990 pudo ser el clima más clemente de los últimos 750 años. El clima del siglo XX fue anómalo en términos de la ausencia de una sequía persistente ya que tanto los datos proporcionados por anillos de creciendo de los árboles como los obtenidos del lago sugieren un mejoramiento abrupto de las condiciones climáticas ocurrido próximo al inicio del registro instrumental. Se sugiere que el impacto inmediato del futuro calentamiento global podría reconvertir las praderas a su condición pasada durante la cual una aridez persistente fue registrada por intervalos de décadas o aun por periodos de tiempo más prolongados.

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INTRODUCTION

Transient climate change simulations from the Canadian Centre for Climate Modelling and Analysis suggest that the largest CO_2-induced rise in mean surface temperature in southern Canada will occur in the Interior Plains (Boer *et al.*, 2000). Most general circulation models (GCM) also forecast an increase in winter precipitation for this region, coupled with decreased net soil moisture and water resources in summer, and more frequent extreme departures from mean conditions, including severe drought (Hengeveld, 2000). Unfortunately, long-term forecasting of precipitation is problematic for dry environments (Hostetler and Giorgi, 1993; Herrington *et al.*, 1997), where precipitation is variable and occasionally extreme (Hunter *et al.*, 2002). Subhumid ecosystems and soil landscapes are sensitive to fluctuations in the surface and soil water balances (Lemmen and Vance, 1999). Sustained periods of low precipitation and soil moisture lower the resistance to disturbance such that future climatic variability may exceed thresholds for landscape degradation. The recovery of natural systems to a previous or new equilibrium can take decades or centuries (Wolfe *et al.*, 2001).

Both aridity and drought refer to a negative soil and surface water balance. Aridity is a long-term condition and thus is characteristic of a regional climate, while drought is a short-term (seasons to years) departure from mean conditions and thus represents climatic variability. GCM forecasts of increased aridity and more frequent drought have major implications for rates of erosion and sediment yield in the southern Canadian plains. In general, biophysical systems react to short-term climate variability and to extreme events before they respond to gradual changes in mean conditions (Knox, 1984; Hulme *et al.*, 1999). Extreme and anomalous climate can exceed natural and engineering thresholds beyond which the impacts of climate are more severe. The link between aridity and erosion is well established from paleoenvironmental records (Wolfe *et al.*, 2001; Last and Vance, 2002) and from the monitoring of geomorphic processes and regional sediment yields (Knox, 1984). Less protection of the soil surface from wind and rain splash is generally given or implied as the cause of higher rates of erosion in semiarid landscapes, however, plants also reduce runoff erosion through the transpiration of soil water and the positive influence of stems, roots and organic matter on the infiltration or rain and snowmelt water (Thornes, 1985).

Thus aridity lowers resistance to wind and water erosion (Wheaton, 1984; Wolfe and Nickling, 1997; Campbell, 1998). Wheaton (1990) established an exact rank correlation between the number of days with dust and the Palmer Drought Severity Index for the Prairie Province during 1977-88. Wolfe *et al.* (1995) described the control of soil moisture on the stability of dunes, with the onset of dune reactivation closely corresponding to the incidence of drought during the past 1000 years. Optical dates defined an interval of minimal dune activity between 560 and 220 BP, implying that drought severity did not exceed a threshold for demise of vegetation cover. In contrast, sand dunes were active between about 1000 and 900 BP and since about AD 1800, following droughts of the 1790s known from tree-ring records (Sauchyn and Skinner, 2001; Wolfe *et al.*, 2001). Current sand dune activity in the driest area of the southern Canadian Prairies may serve as an analogue of the potential response of other eolian landscapes in the region to future global warming (Thorpe *et al.*, 2001).

Long-term changes in net precipitation characteristics may also impact fluvial geomorphic systems in the Canadian Prairies (Campbell, 1998; Ashmore and Church, 2001). The climate sensitivity of prairie fluvial geomorphic systems is recorded in late Holocene sedimentary and morphologic records (O'Hara and Campbell, 1993; Rains *et al.*, 1994) with episodes of channel aggradation and incision roughly coinciding with climate fluctuations recorded in lacustrine records (Lemmen and Vance, 1999). Streams that are fed wholly from sources within the plains may be expected to be more responsive to changes in precipitation than the rivers that are derived from glaciers and snowmelt in the Rocky Mountains (Campbell, 1998; Ashmore and Church, 2001). Because the stream channels of the Interior Plains are incised into Quaternary sediments and poorly consolidated sedimentary strata, slope and bank failure have been integral processes in the Holocene history of glacial meltwater channels and tributary valleys (Sauchyn, 1998). Although drier climate and lesser porewater favour slope stability, slope failure during extreme events may occur with greater frequency.

Because aridity is closely linked to soil erosion and degradation, future management of prairie ecosystems and soil landscapes will require an improved understanding of past and future trends and variability in regional aridity. Land use and management practices have more immediate impacts on rates of surface processes than climate change (Jones, 1993), and thus they have the potential to significantly mitigate the impacts of climate; forest and farm management practices enable adaptation to climate change. An expansion of agriculture into the currently forested margins of the Prairie Ecozone will require assessment of the sensitivity of these soil landscapes to both climate change and an altered vegetation cover. To address these issues, we use both instrumental and paleoclimatic records to define regional baseline aridity for the Prairies, and to evaluate the utility of modern climate normals (*i.e.* 1961-1990) as a metric of environmental change. The proxy and instrumental climate data are compared to a range of GCM forecasts spanning the next 80 years to evaluate the usefulness of historical climate reconstructions as analogs for future climate change.

DATA AND METHODS

Aridity is simply a lack of moisture expressed in terms of mean annual precipitation and potential evapotranspiration as a ratio (P/PET) or deficit (P-PET). P/PET, the Aridity Index (AI), is the basis for classifying drylands as hyperarid (< 0.05), arid ($0.05 \leq AI < 0.2$), semiarid ($0.2 \leq AI < 0.5$) and dry subhumid ($0.5 \leq AI < 0.65$) and for identifying land at risk of desertification, "land degradation in arid, semiarid and dry subhumid areas resulting mainly from adverse human impact" (Middleton and Thomas, 1992). Wolfe (1997) demonstrated that the distribution of sand dunes on the Canadian plains could be modeled with P/PET. Hogg (1994, 1997) was able to map the distribution of vegetation zones in the Canadian interior using

the Climate Moisture Index, P-PET. Because our objective was to describe and compare past and future changes in aridity, rather than evaluate different methods of AI calculation, all estimates of PET were based on the widely used Thornthwaite formula (Dunne and Leopold, 1998):

$$\text{PET} = 1.6 \left(\frac{T}{I}\right)^{a} \qquad [1]$$

where PET = potential evapotranspiration (cm month^{-1}), T = mean monthly air temperature (°C) and

$$a = 0.49 + 0.0179I - 7.71 \times 10^{-5} I^2 + 6.75 \times 10^{-7} I^3. \qquad [2]$$

Annual heat index, I, was estimated as

$$I = \text{annual heat index } I = \sum_{i=1}^{12} \left(\frac{Ti}{5}\right)^{1.5}. \qquad [3]$$

With Thornthwaite PET, temperature is the sole measure of the energy available for evapotranspiration. Monthly PET calculated using equation (1) must be adjusted using a correction factor for daylength according to latitude and month. Net radiation and wind data are available for few stations in the Prairie Provinces and thus an energy balance approach to calculating PET would not enable the mapping of aridity. We use Thorntwaite PET for this reason and because it works best in mid-latitude continental climates where air temperature if strongly correlated with net radiation.

To map recent and future aridity we first loaded a gridded database of historical climate observations into a GIS. This database of mean monthly temperature and total precipitation was derived from all of the available monthly climate data in the Canadian Climate Archive for the Prairie Provinces and the surrounding climate regions. The FORTRAN program GRANAL2 used an inverse square distance weighting procedure to interpolate from the station locations to a 50 km grid on a polar stereographic secant projection true at 60° N. The values at the grid points should be viewed as representative of the region within 25 km of the grid point, although the gridded analysis cannot reproduce the high spatial variability associated with precipitation events. Further information on the database and interpolation procedure is available at (http://www.cics.uvic.ca/climate/data.htm). In the GIS, a more dense 5 km grid was constructed to smooth the raster boundaries between map units created by classifying the climate data. The aridity index was computed for each original grid point and interpolated to the 5 km grid by Kriging.

Scenarios of future climate change were applied to the gridded temperature and precipitation data for 1961-1990 to produce maps of future aridity centered on the 2020s (2010-2039), 2050s (2040-2069) and 2080s (2070-2099). The IPCC Task Group on Scenarios for Climate Impact Assessment (IPCC-TGCIA, 1999) strongly recommended the use of more than one GCM for any assessment of climate impacts and that the selected GCMs show a range of changes in the key climate variables for the study region. In a recent study of climate change impacts on the island forests of the northern Great Plains, Henderson *et al.* (2002) thoroughly analyzed the available GCM scenarios and chose three that captured the range of annual temperature and precipitation changes projected for the region. Given the very similar scenario requirements of this very recent study and the forecasting of future aridity attempted here, we accepted the conclusions reached by Henderson *et al.* (2002) and used the same climate change experiments as listed in Table I. HadCM3 B21 forecasts the least increase in temperature and greatest increase in precipitation. CGCM2 A21 forecasts the smallest change in precipitation and the largest increase in temperature. CSIROMk2b B11 is a mid-range scenario. The names of the models refer to the national modeling centres (Table I), the version of the coupled atmosphere-ocean model, and the emission scenario (the last three digits). The greenhouse gas emission scenarios are those most recently recommended by the IPCC from the Special Report on Emission Scenarios (Nakicenovic and Swart, 2000). The scenario data were downloaded from the web site of the Canadian Climate Impacts and Scenarios project (http://www.cics.uvic.ca/scenarios/).

TABLE I

The climate change experiments (from Henderson et al.*, 2002) used for the forecasting of future aridity*

Modelling Centre	Model	Emission scenario[1]
U.K. Hadley Centre for Climate Prediction and Research	HadCM3	A21
Canadian Centre for Climate Modelling and Analysis	CGCM2	B21
Australian Commonwealth Scientific and Industrial Research Organization	CSIROMk2b	B11

1 Special Report on Emission Scenarios (SRES) emission scenarios (Nakicenovic and Swart, 2000).

High-resolution records of paleo-aridity were derived from analyses of lake sediments and tree rings. The tree ring chronology is from *Pinus contorta* (lodgepole pine) in the Cypress Hills of southwestern Saskatchewan and southeastern Alberta (Fig. 1). Standard procedures were used to process the tree cores and disks and measure ring width to within 0.001 mm (Cook and Kairiukstis, 1990). Cross dating of all tree-ring series enabled the detection of anomalous series and missing or false rings and ensured that the correct calendar year was assigned to each tree ring. There are 53 ring-width series with an intercorrelation of 0.481 and a mean sensitivity of 0.231. The raw ring-width data were converted to index chronologies (averaged standardized ring widths) using the program ARSTAN (Cook and Holmes, 1999). The raw data were detrended with a best-fit negative exponential curve or linear regression and filtered to remove first-order autocorrelation. A biweight robust

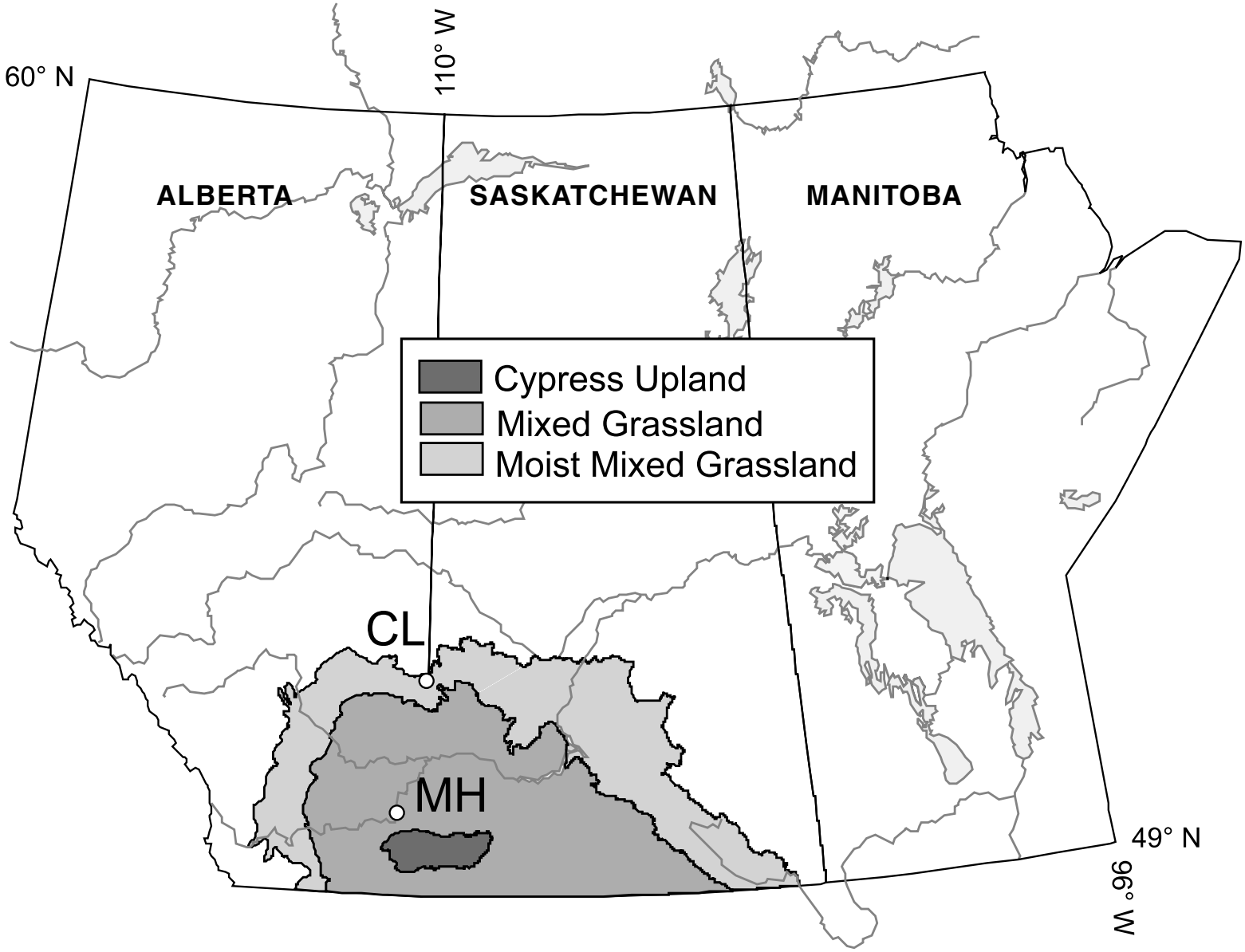

FIGURE 1. The Prairie Provinces of Canada and the ecoregions that correspond to the semiarid and dry subhumid climates mapped in Figure 1. Chauvin Lake (CL) is the source of the paleosalinity data presented in this paper. The tree-ring chronology from the Cypress Hills (Upland) was calibrated using instrumental climate data from Medicine Hat (MH).

Les écorégions des Prairies présentant des climats semi-aride et subhumide sec. Les données de paléosalinité présentées dans cet article proviennent du lac Chauvin (CL). La dendrochronologie des Cypress Hills a été étalonnée à l'aide de données climatiques enregistrées à Medicine Hat (MH).

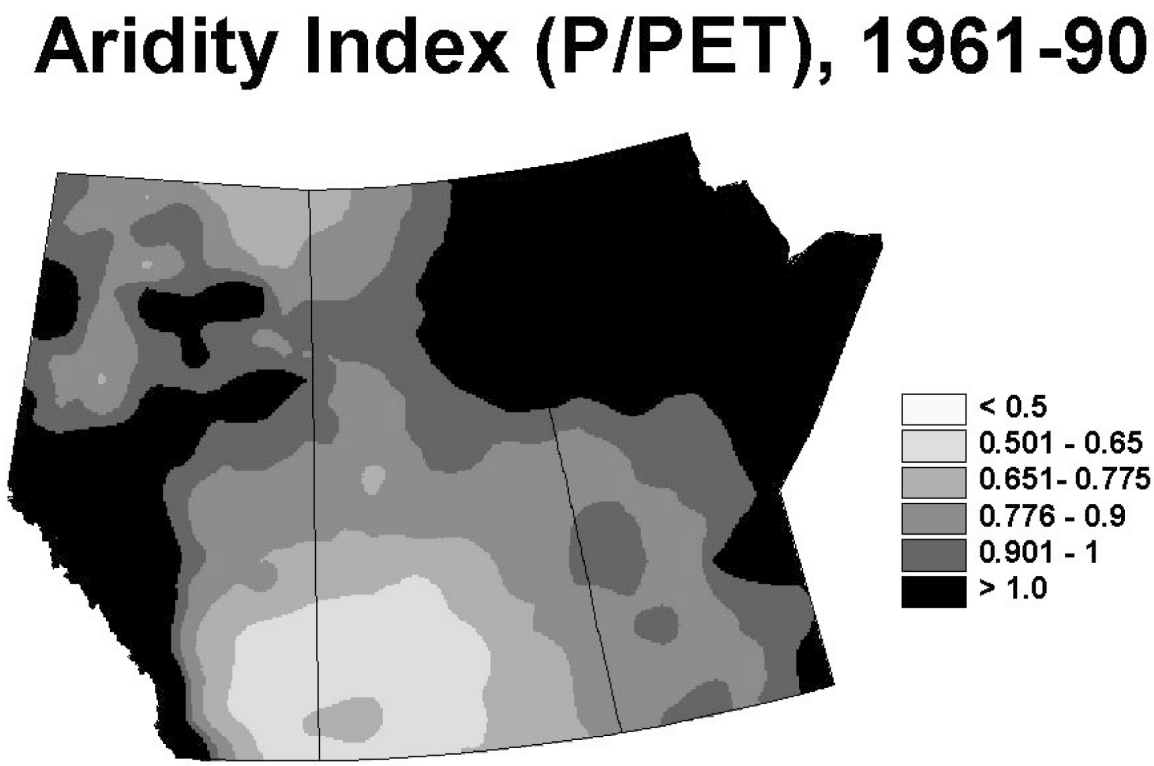

FIGURE 2. Aridity map for the Prairie Provinces of Canada for the "normal period" 1961-1990. The most arid region is the dry subhumid (P/PET = 0.501-0.65) landscape of southwestern Saskatchewan and southeastern Alberta. Near the geographic center of this driest region is the moist subhumid (P/PET = 0.651-0.775) Cypress Hills, straddling the Alberta-Saskatchewan boundary.

Carte d'aridité des provinces des Prairies pour la « période normale » de 1961 à 1990. La région la plus aride est la zone subhumide sèche (P/EPT = 0,501-0,65) du sud-ouest de la Saskatchewan et du sud-est de l'Alberta. Près du centre géographique de cette région se trouve la zone subhumide humide des Cypress Hills (P/EPT = 0,651-0,775) qui chevauche la frontière Alberta-Saskatchewan.

estimate of the mean ring-width index for each year comprised the tree-ring index chronology. The reconstruction of June-July P/PET from standardized residual ring width was validated using a split sample approach; two regression models were calibrated using different halves of the instrumental record and then cross-validated using the remainder of the record.

Chauvin Lake (Fig. 1) is ideally suited for climatic research because it is located within a very small effective drainage. Analysis of aerial photographs between 1940 and the present demonstrate that lake levels have varied in accordance with historical changes in precipitation. Lake sediments cores were collected using standard piston-coring procedures and sediments were cut into 2.5 mm intervals equivalent to an average of 1-3 years of lake history. Fossil diatoms were isolated, identified to species and quantified for alternate sediment levels, and changes in species composition were used in published inference models (Wilson *et al.*, 1996) to reconstruct past changes in lake water salinity at intervals of 3-5 years. Analysis of past changes in chemistry show that lake water salinity accurately records the occurrence of major drought events (Laird *et al.*, 1996), with greatly elevated salinity representing the most arid conditions. Sediment age was determined by analysis of naturally-occurring radioisotopes in recent bulk sediments (^{210}Pb) and individual plant macrofossils (AMS ^{14}C).

Diatom-inferred changes in lake salinity were compared to instrumental climate records from 1910 to 1990 to evaluate the ability of fossil reconstructions to infer changes in aridity. PET data were filtered using three-year running mean to match the temporal resolution of the fossil time series. All time series were detrended by linear regression, and residual curves compared using correlation analysis. Lags of 1-5 years are applied to fossil data to evaluate the possibility of delayed hydrologic response to climatic forcing functions.

RESULTS AND DISCUSSION

A map of "normal" (*i.e.* 1961-1990) aridity for the Prairie Provinces (Fig. 2) illustrates that, at 50 km resolution, the "normal" climate of the Prairie Provinces cannot be described as semiarid anywhere (P/PET < 0.5), even though this terminology is often used to describe the southern Prairies. The driest region, the dry subhumid (0.5 < P/PET < 0.65) landscape of southwestern Saskatchewan and southeastern Alberta, corresponds to the mixed grass prairie ecoregion. This moist subhumid Cypress Hills are near the geographic center of this driest region. Analysis of the longest instrumental record (Medicine Hat, Alberta) showed that annual P/PET varied from 0.34 (1943) to 1.24 (1927), with 26 years of semiarid conditions (Fig. 3). On average, these dry events occurred approximately every third year, although only eight semiarid years were seen after 1950.

This large inter-annual variation in the aridity index translates into varying geographic extent of annual drought. Each

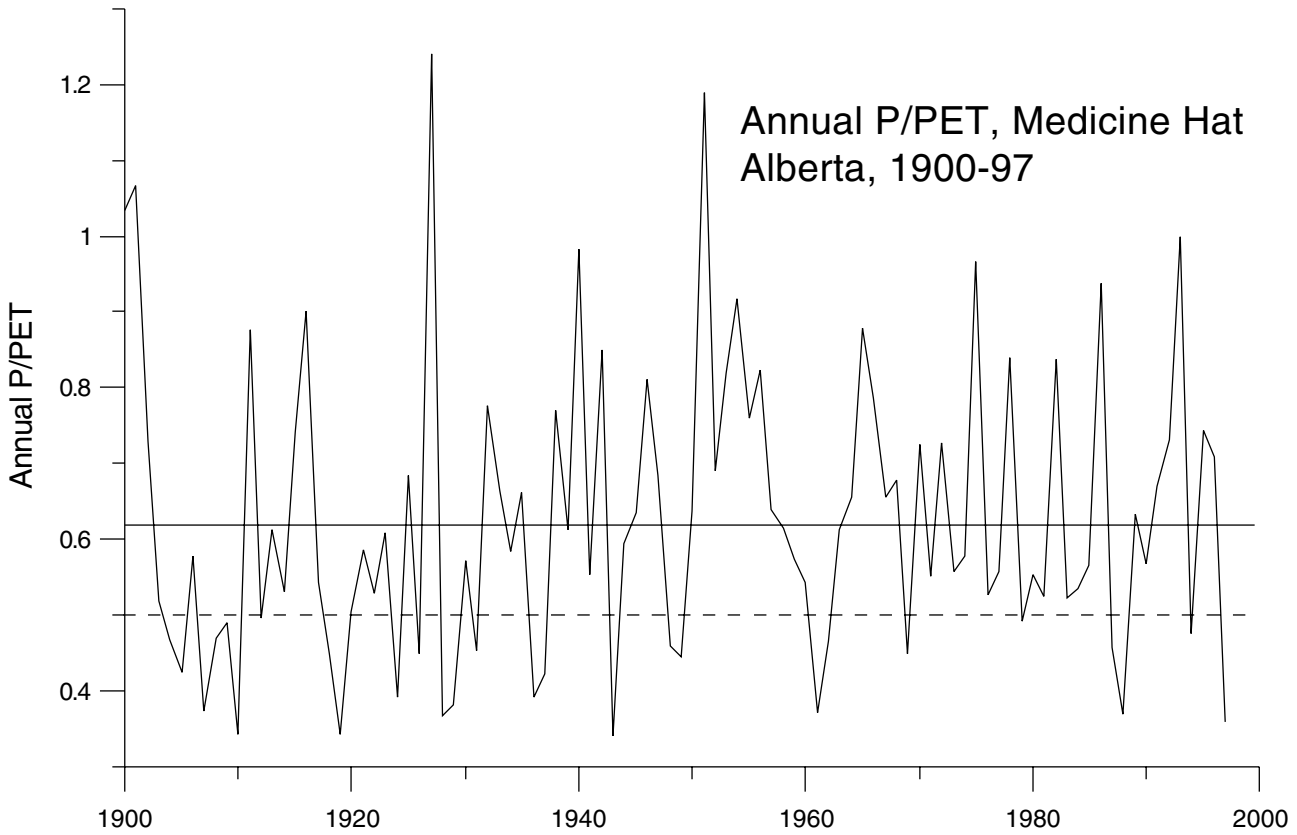

FIGURE 3. Annual aridity (P/PET) for Medicine Hat, Alberta for the period 1900-1997. Aridity varies from 0.34 in 1943 to 1.24 in 1927. The straight line marks the mean aridity (0.627) for the period of record. The dashed line at P/PET = 0.5 marks the upper threshold for a semiarid conditions. Twenty-six years classify as semiarid.

Aridité annuelle (P/EPT) à Medicine Hat, en Alberta, pour la période de 1900 à 1997. L'aridité varie de 0,34, en 1943, à 1,24, en 1927. La ligne continue correspond à l'aridité moyenne (0,627) pour la période couverte. La ligne hachurée à P/EPT = 0,5 représente le seuil supérieur des conditions semi-arides. Vingt-sic années se classent dans la catégorie semi-aride

documented drought had a unique geographic extent and intensity, although semiarid conditions were consistently recorded in southeastern Alberta and southwestern Saskatchewan (Fig. 4). The "normal" dry subhumid climate of this region reflects the frequency of low annual precipitation and P/PET. The most extensive drought was in 1961.

Scenarios of future aridity centered on the 2020s, 2050s and 2080s are mapped for the Prairie Provinces in Figures 5-7 for the CGCM2 A21 (warm-dry), CSIROMk2b B11 (mid-range), HadCM3 B21 (cool-wet) climate change scenarios. Under the CGCM2 A21 scenario, a small area of continuously semiarid climate (P/PET < 0.5) appears in western Saskatchewan by the 2020s and expands significantly by the 2050s. In contrast, forecasts using the CSIROMk2b B11 mid-range scenario (Fig. 6) suggest that perpetually semiarid conditions will be evident only by 2080, but that a dry subhumid climate will extend to southwestern Manitoba. The HadCM3 B21 scenario indicates the least climate change, with a marginal increase in the area of subhumid climate and maximum aridity in mid century. Taken together, these forecasts suggest a general increase in the geographic extent of dry conditions, with possible risks of desertification in the more extreme scenarios (CGCM2 A21).

Analysis of tree-ring indices of past climate suggest that very dry conditions have been common on the Prairies during the past 300 years (Fig. 8). The residual index tree-ring widths for *Pinus contorta* from the Cypress Hills are significantly correlated ($p < 0.01$) with June, July, annual and plant year (August to July) precipitation for Medicine Hat, Alberta for the period 1900-1999 (Table II). The correlation of ring width with potential evapotranspiration (PET) is weak ($p > 0.05$) because Thornthwaite PET is a function of temperature and heat has both positive and negative effects on tree growth depending on the ambient air temperature and antecedent moisture conditions. The negative influence would be confined to warm dry days. Thus the aridity (P/PET) signal in the tree rings mostly reflects large interannual variability in annual, and especially summer, precipitation. Not only is the response to precipitation direct and unambiguous, but amounts of rain and snow are much more variable from year to year than mean temperature and in turn evapotranspiration.

The reconstruction of summer (June-August) aridity for 1723-2000 is plotted in Figure 8. The similar standard errors of estimation (SE_e) and validation ($RMSE_v$) in Table III suggest an acceptable regression model. Events of high aridity occurred regularly during the past three centuries, with major

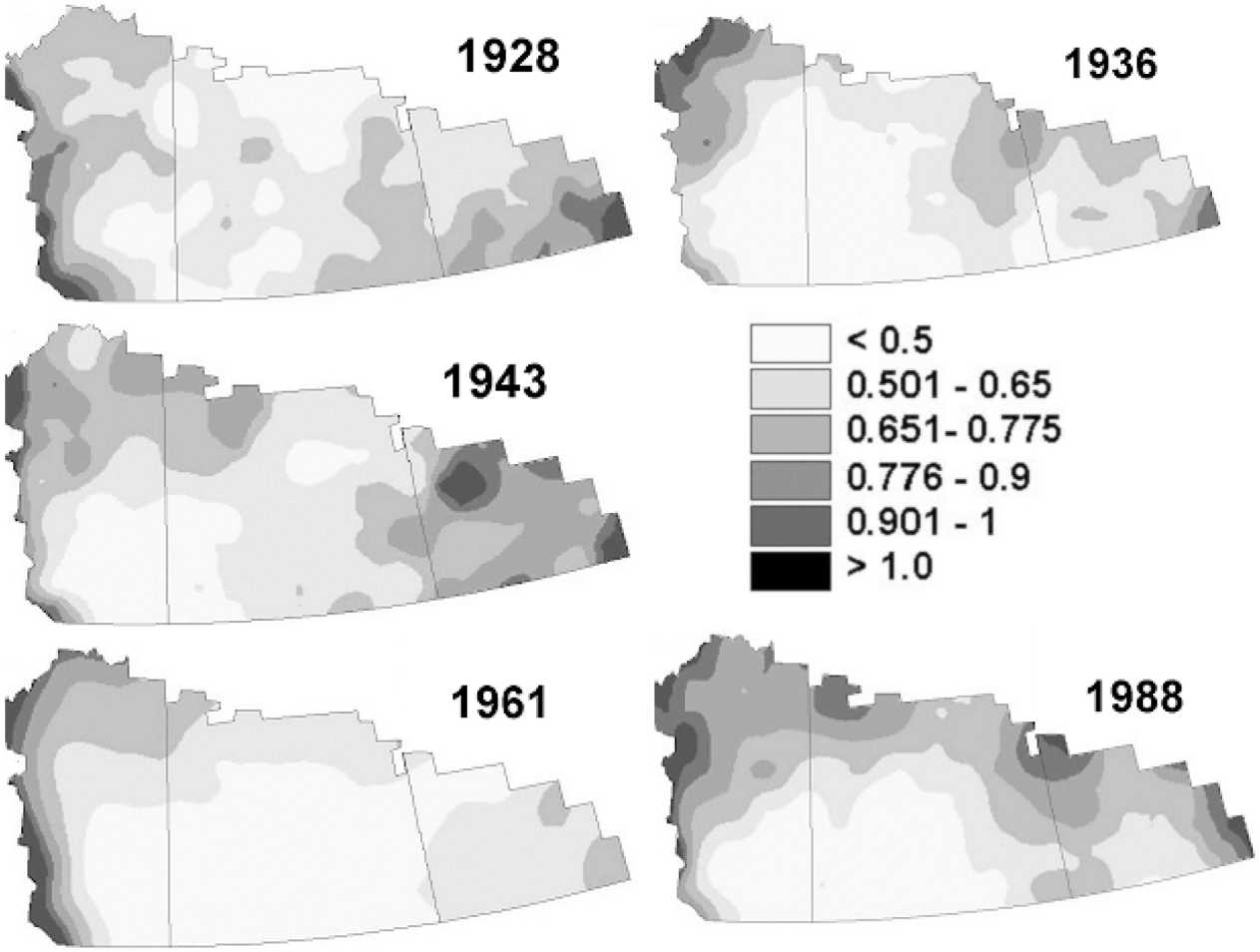

FIGURE 4. Annual aridity index for five drought years for the agricultural zone of the Prairie Provinces. During the drought years, aridity index was <0.5 (semiarid) over a large part of the agricultural zone. The most extensive drought was in 1961.

Indice annuel d'aridité de cinq années de sécheresse dans la zone agricole des Prairies. Pendant ces années, l'indice était <0,5 (semi-aride) dans une grande partie de la zone agricole. La sécheresse plus importante s'est produite en 1961.

droughts indicated for 1768-1782 and the 1786-1796 and 1851-1864. In addition, analysis of time series suggested that mean interannual variance (as standard deviation) was greater during the instrumental period (post-1884; SD = 0.080) than in the preceding period (1723-1883; SD = 0.063). This prominent increase in inter-annual variability may be related to a mid- 19th century shift in the Pacific Decadal Oscillation (D'Arrigo *et al.*, 2001). The consecutive years of summer aridity highlighted in Figure 8 are further evidence of prolonged aridity prior to Euro-Canadian settlement of the western Canadian plains and the instrumental observation of climate. The impacts of these droughts are described in Wolfe *et al.* (2001) and Sauchyn *et al.* (2003). Their relevance here is as possible analogues of anomalous precipitation expected with global warming in contrast to the climate of the 20th century, and particularly 1961-1990, the basis for our definition of the normal climate.

Paleoclimatic reconstructions based on the 2000-year salinity record from Chauvin Lake, Alberta, also suggest that past drought severity was greater than that recorded during the instrumental period. Validation using modern climatic records showed that detrended, diatom-inferred salinity was significantly and positively correlated ($p < 0.05$) with PET during 1910-1990 (Fig. 9). Correlations were also positive and significant at lags of one or two years. Using this observation, and the drought of 1988-1989 as a benchmark, analysis of past salinities revealed that climatic conditions were continuously arid during the 4th to 8th centuries and regularly dry during CE 1300-1750 (Fig. 10). Severe events were also recorded during 1860-1890, an interval of broadscale droughts in central North America. Salinities declined substantially during the 20th century, reaching values during the 1960s and 1970s that were the lowest of the past 750 years.

Other recent studies of the past hydroclimate of the northern Great Plains (Woodhouse and Overpeck, 1998; St. George and Nielsen, 2002) have similarly concluded that the droughts of the 20th century were of comparatively short duration. Much of the previous paleo drought research has focused on the United States (Cook *et al.*, 1999). Our results fit with the timing of droughts (*e.g.*, 1790s, 1860s, 1880s) in

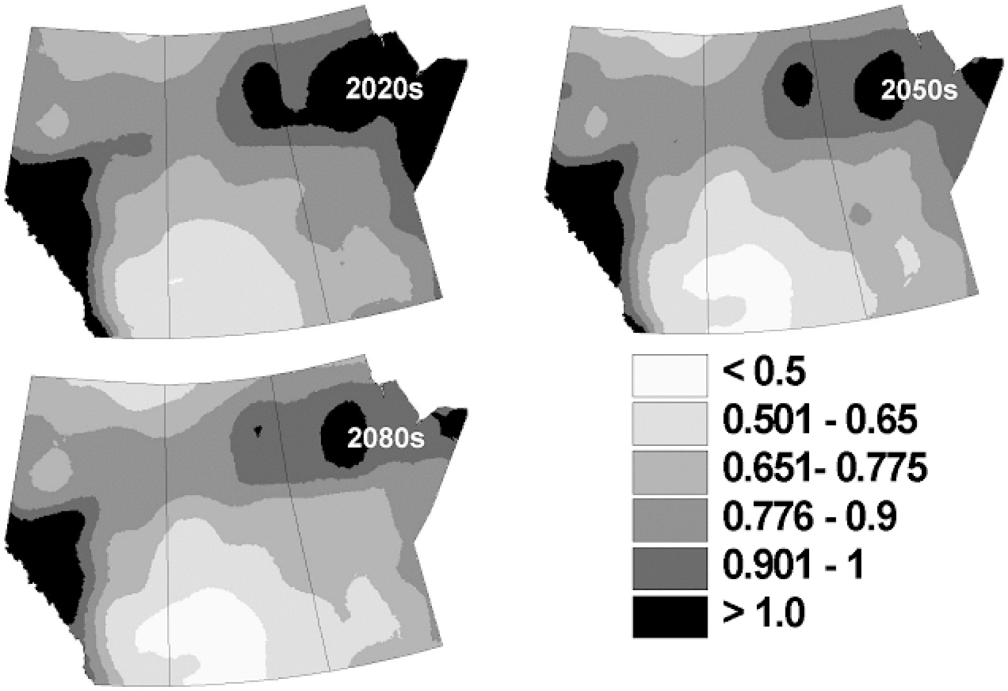

FIGURE 5. Aridity scenarios for the 2020s, 2050s and 2080s based on forecasts of precipitation and temperature from the Canadian GCM, CGCM2, the warm-dry climate change scenario. A small area of semi-arid climate (P/PET < 0.5) appears in western Saskatchewan by the 2020s and then expands significantly by the 2050s with further increase in the area of semiarid and subhumid climate by the 2080s.

Scénario d'aridité pour les années 2020, 2050 et 2080 fondé sur les prévisions de précipitations et de température tirées du modèle de circulation générale canadien MCCG2 (changement vers un climat chaud et sec). On constate qu'une petite zone climatique semi-aride (P/EPT < 0,5), présente dans l'ouest de la Saskatchewan vers les années 2020, s'étend considérablement vers 2050 et poursuit son expansion dans la zone climatique semi-aride et subhumide vers les années 2080.

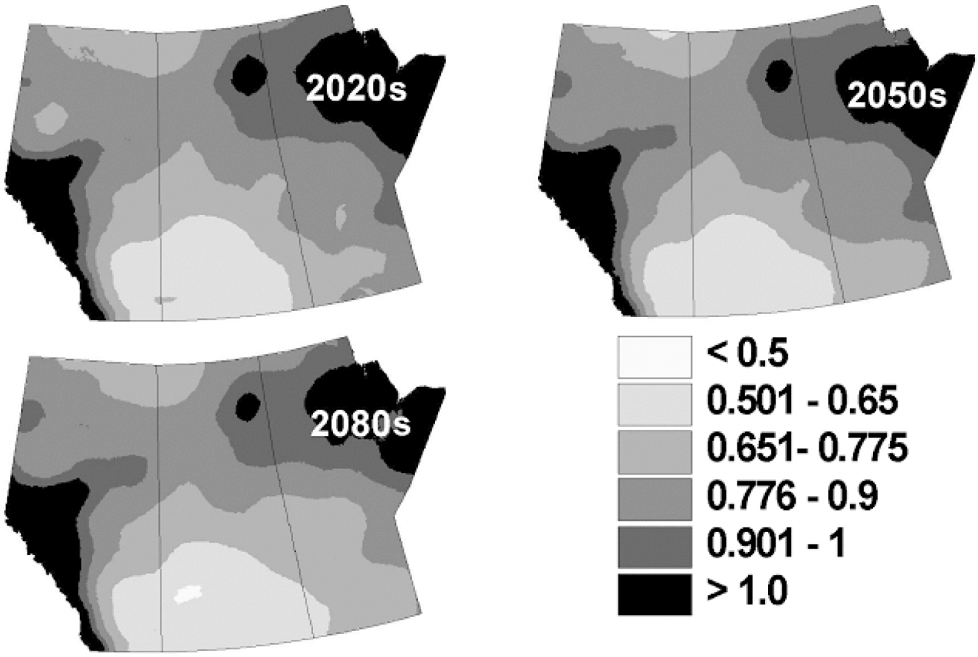

FIGURE 6. Aridity scenarios for the 2020s, 2050s and 2080s based on forecasts of precipitation and temperature from the Australian GCM, CSIROMk2b, the mid-range climate change scenario. By the 2080s, dry subhumid climate extends as far east as southwestern Manitoba and an area of semiarid climate appears in western Saskatchewan.

Scénario d'aridité pour les années 2020, 2050 et 2080 fondé sur les prévisions de précipitations et de température tirées du modèle de circulation générale australien CSIROMk2b (changement intermédiaire). Vers les années 2080, le climat subhumide sec s'étend vers l'est jusqu'au sud-ouest du Manitoba et une zone au climat semi-aride est présente dans l'ouest de la Saskatchewan.

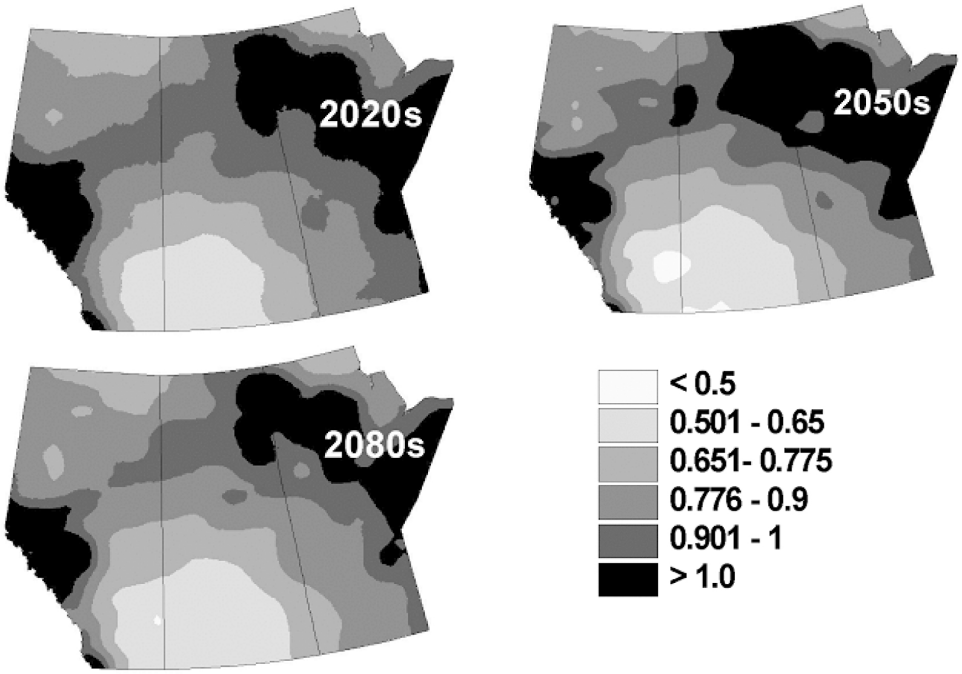

FIGURE 7. Aridity scenarios for the 2020s, 2050s and 2080s based on forecasts of precipitation and temperature from the UK Hadley Centre GCM, HadCM3, the cool-wet climate change scenario. This scenario forecasts the least change in climate. There is a marginal increase in the area of subhumid climate with maximum aridity occurring in mid-century.

Scénario d'aridité pour les années 2020, 2050 et 2080 fondé sur les prévisions de précipitations et de température tirées du modèle de circulation générale du United Kingdom Hadley Centre, HadCM3 (changement vers un climat frais et humide). Ce modèle prévoit le moins grand changement climatique. Il s'agirait d'un léger accroissement de la zone subhumide, avec un maximum d'aridité en milieu de siècle.

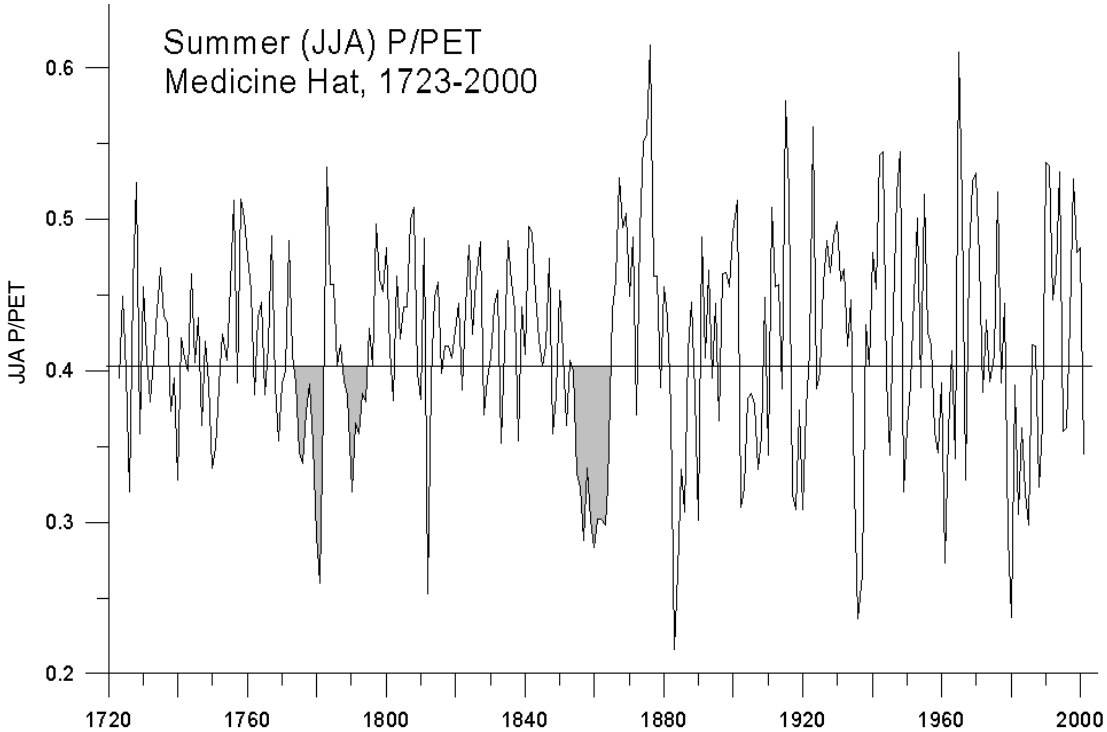

FIGURE 8. Proxy summer (JJA) aridity for Medicine Hat, Alberta as reconstructed from residual index tree ring chronology from *Pinus contorta* from the Cypress Hills. The gray fill highlights prolonged summer droughts of the 18th and 19th centuries. The straight line marks the mean aridity (0.415) for the period of record.

Estimation de l'aridité estivale (JJA) à MedIcine Hat, en Alberta, telle que reconstituée à l'aide de l'indice dendrochronologique résiduel de Pinus contorta *dans les Cypress Hills. Les parties tramées mettent en évidence les périodes de sécheresse prolongées des XVIIIe et XIXe siècles. La ligne droite horizontale donne l'aridité moyenne (0,415) pour la période couverte.*

TABLE II

Correlations between the residual index chronology for Pinus contorta *(PICO) from the Cypress Hills (CH) and precipitation (P), potential evapotranspiration (PET) and P/PET for Medicine Hat, Alberta for the period 1900-1999. The bold coefficients are significant at p <0.01*

Climate variable	CH_PICO_residual
P_June	**0.430**
P_July	**0.321**
P_June-July	**0.493**
P_annual	**0.306**
P_August-July	**0.443**
PET_June	-0.129
PET_July	-0.186
PET_June-July	-0.129
PET_annual	-0.079
P/PET_June	**0.385**
P/PET_Jul	**0.299**
P/PET_Jun-Jul	**0.452**
P/PET_annual	**0.289**

TABLE III

Tree-ring regression model and validation statistics. The predictand is June – July P/PET at Medicine Hat and the predictor is standardized residual ring widths from Pinus contorta *from the Cypress Hills*

Calibration Period	1900-97	1900-48	1949-97
Validation Period	n/a	1949-97	1900-48
R2 (%)	20.4	22.8	18.6
F	24.6	13.9	10.7
p - value	< 0.0001	0.0005	0.002
SEe[1]	0.218	0.229	0.208
RMSEv[2]	n/a	0.207	0.228
RE[3]	n/a	0.339	-0.011

1 standard error of estimation

2 root mean square error of validation

3 reduction of error

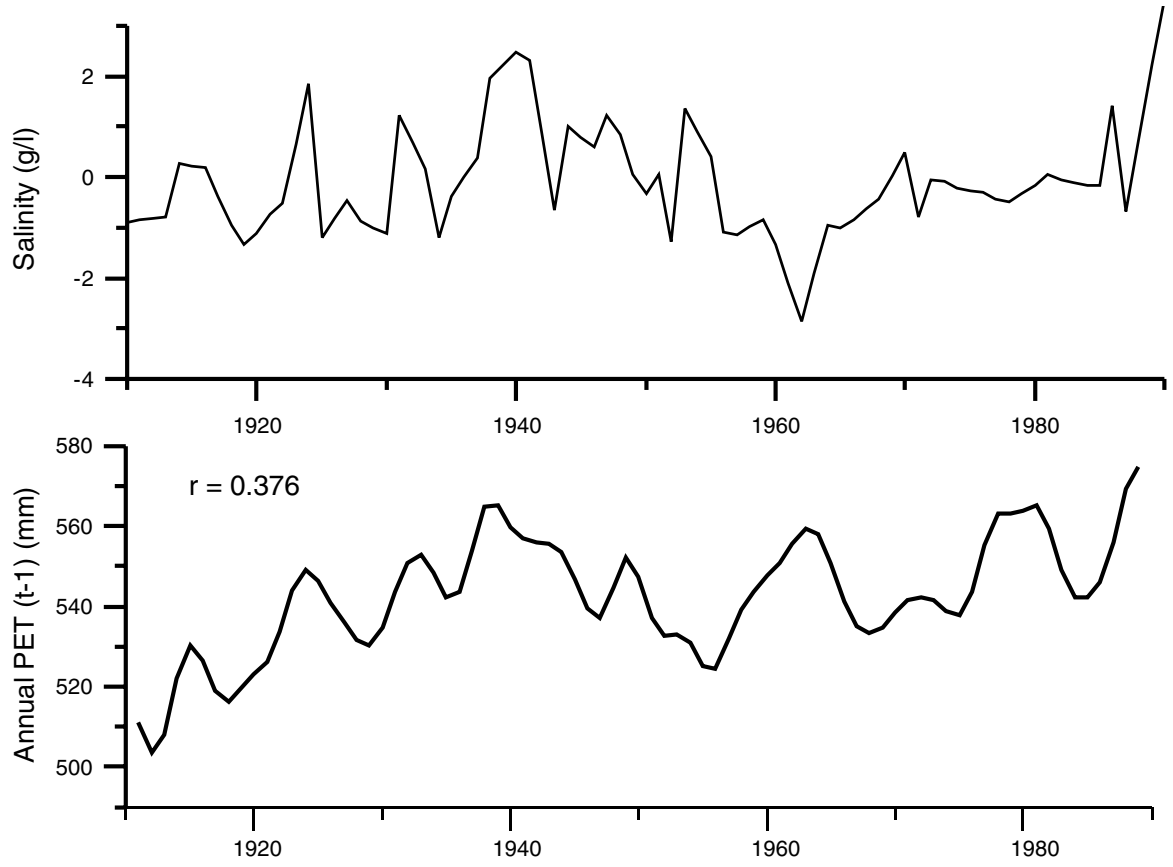

FIGURE 9. Plots of residual lake salinity for the period 1910-90 and potential evapotranspiration in the previous year. The PET data are from the location nearest to Chauvin Lake in the gridded climate database. The climate data have been filtered (three-year running mean) to match the lower temporal resolution of the salinity data.

Diagramme de salinité lacustre résiduelle pour les années 1910 à 1990 et diagramme d'évapotranspiration potentielle. Les données de l'ETP proviennent du lieu le plus proche du lac Chauvin dans la banque de données climatiques. Les données climatiques ont été filtrées (moyenne sur 3 ans) afin qu'elles correspondent à la plus faible résolution temporelle des données de salinité.

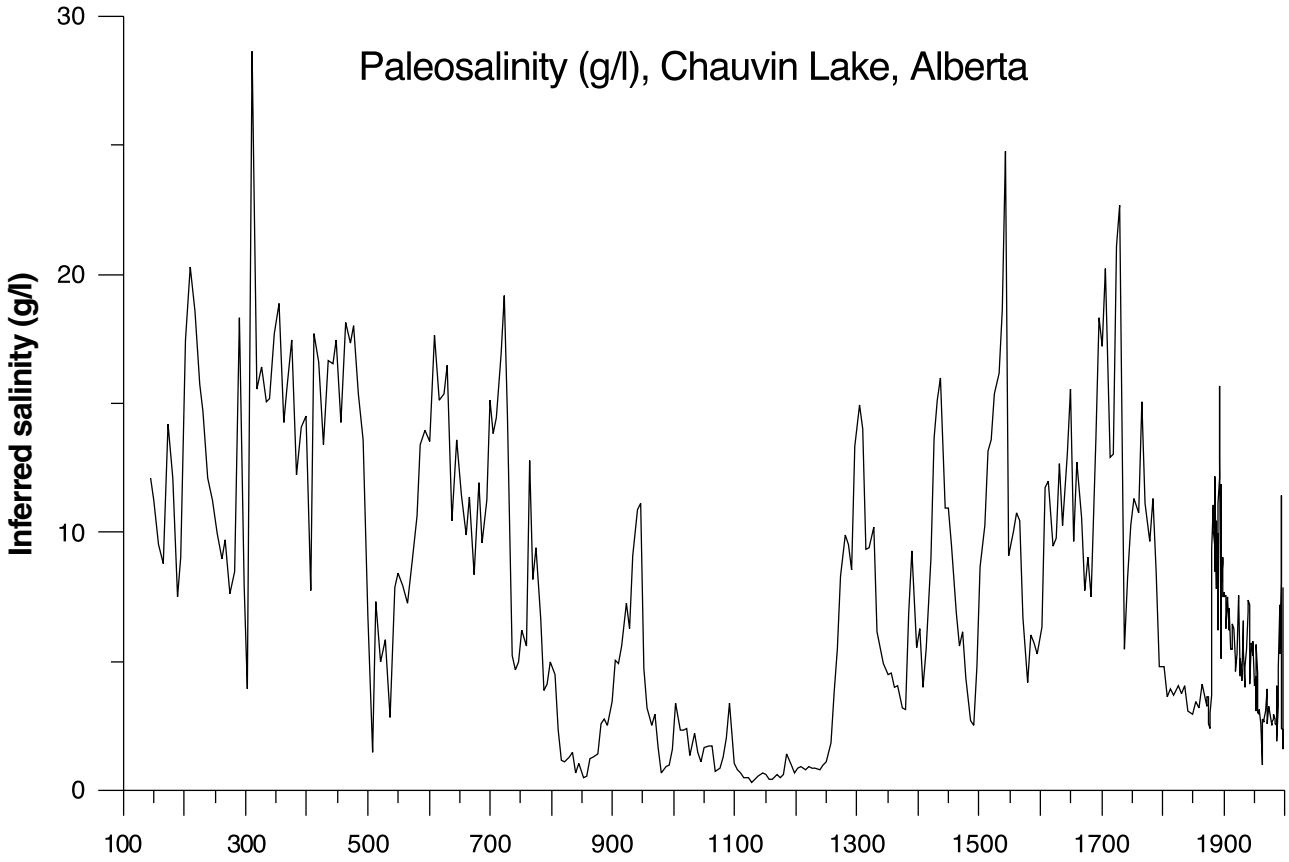

FIGURE 10. Diatom-inferred paleosalinity for Chauvin Lake, Alberta for the past two millennia. A record of this length provides a proxy of climate variation at various frequencies.

Paléosalinité lacustre au cours des deux derniers millénaires obtenue à partir de diatomées provenant du lac Chauvin, en Alberta. Un relevé sur une aussi longue période permet d'obtenir un aperçu des variations climatiques à différentes fréquences.

eastern Montana, immediately south of our study area, but generally do not correlate with tree-ring data from the eastern plains (St. George and Nielsen, 2002). The lower frequency variation in hydroclimate (*i.e.*, aridity), on the other hand, tends to be consistent over a larger area. Our tree-ring and diatom data share decadal to century scale variability with dendroclimatic (Case and MacDonald, 1995; St. George and Nielsen, 2002) and lake sediment (Laird *et al.*, 2003) records from across the northern Great Plains. Common periods of sustained aridity encompass much of the 16th and 18th centuries.

CONCLUSIONS AND IMPLICATIONS

Analysis of climate normals (1961-1990) revealed that a large part of the southern Canadian Plains usually have dry subhumid conditions, and that P/PET was rarely < 0.5 (semiarid) when analyzed on a 50 x 50 km grid. In contrast, semiarid conditions were common, on average, one of every three years during the instrumental record, although the high degree of spatial variability suggested that any given site could experience a wide range of climate, from semiarid (P/PET < 0.5) to humid conditions (> 1.0). High temporal variability was evident in the tree-ring (Fig. 8) and lake sediment (Fig. 10) reconstructions, however, these records also demonstrated that more prolonged, intensely arid events were common in the past, and showed further that modern climate normals are not representative of the full range of potential climatic conditions, even in the absence of global warming.

The increasing aridity projected by the GCM scenarios represents a higher frequency of dry years over a larger area. As a result of an increase in mean annual temperature and, in turn, potential evapotranspiration, with even the coolest and wettest climate change scenario, there is a marginal increase in the area of subhumid climate in the Prairie Provinces by the 2080s. The Canadian GCM forecasts the least increase in precipitation and the largest increase in temperature and therefore an approximately 50 % increase in the area of subhumid climate and a significant area of semiarid climate by the 2050s. Past droughts may provide important benchmarks to evaluate potential impacts of increasing aridity forecast by GCMs. For example, comparison of climatic conditions observed in the pre-drought year 1987 shows a marked similarity to conditions forecast by the CGCM2 A21 scenario for 2050, in terms of the geographic extent of semiarid and dry subhumid climate (Fig. 11a). Dry conditions during 1987 are viewed as partly responsible for establishing more extensive droughts

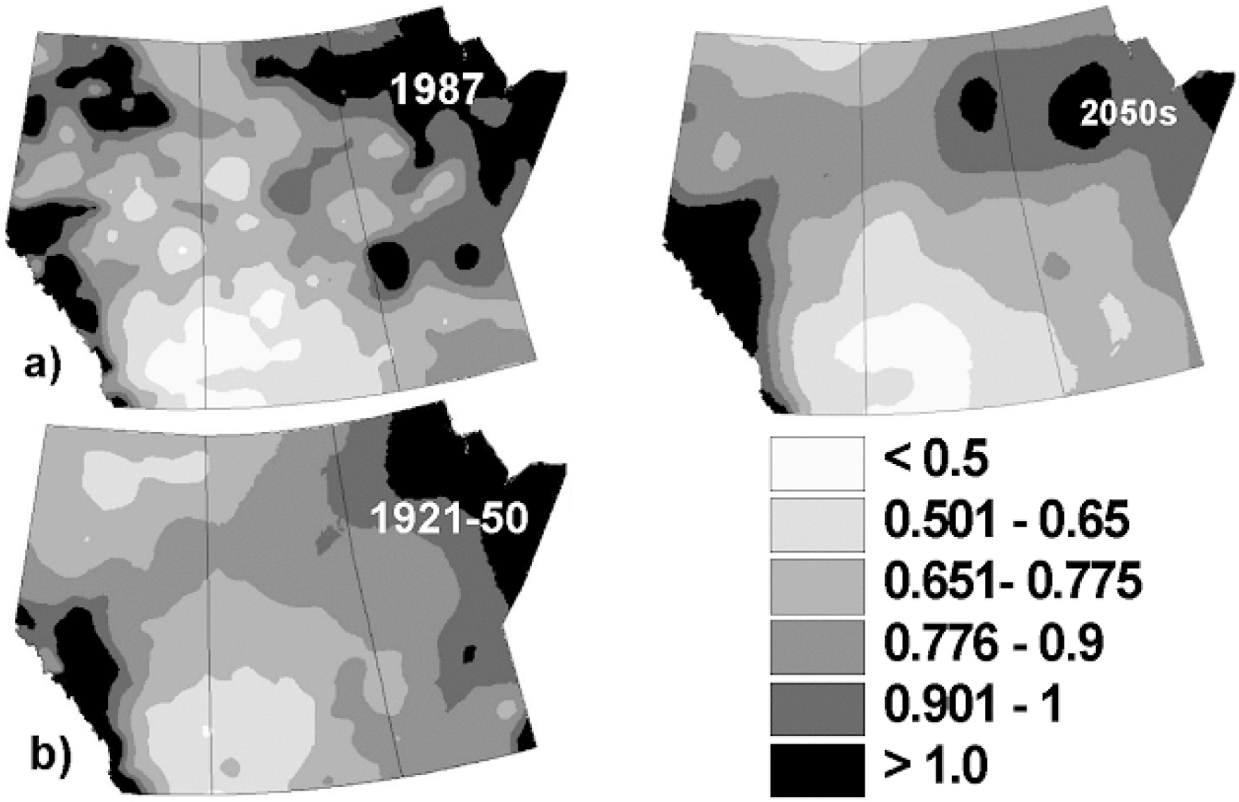

FIGURE 11. a) P/PET in 1987 and forecasted for the 2050s, showing that a dry year like 1987 can serve as an analogue of the extent of semiarid and dry subhumid climate expected by the 2050s under a warm and dry climate change scenario (CGCM2 A21). b) An aridity map for the Prairie Provinces for the period 1921-1950. In contrast to the "normal" climate for 1961-1990 (Fig. 2), the climate of 1921-1950 is drier throughout the Prairie Provinces and there are two small areas of semiarid climate (P/PET < 0.5) along the Alberta-Saskatchewan boundary.

a) Rapport P/ETP pour 1987 et prévisions pour les années 2050. Une année sèche comme celle de 1987 peut servir, par analogie, à illustrer l'étendue pressentie des zones semi-aride et subhumide sèche, selon le scénario du changement vers un climat chaud et sec (MCCG2 A21) pour les années 2050. b) Carte d'aridité des provinces des Prairies pour la période de 1921 à 1950. Contrairement au climat « normal » de la période 1961 à 1990 (fig. 2), le climat des années 1921 à 1950 est sec dans l'ensemble des provinces des Prairies ; on note aussi la présence de deux petites zones caractérisées par un climat semi-aride (P/ETP < 0,5) le long de la frontière Alberta-Saskatchewan.

during 1988-1989 (Fig. 4) and suggest that future increases in aridity may generate conditions that favour the regular development of large-scale droughts.

The implication of more frequent and widespread droughts is that they place a larger area at risk of desertification more often unless counteracting management strategies are enacted. The critical variable will be the duration of the semiarid conditions in any given area. The scenario of increased climate extremes includes unusually wet years during which social and biophysical systems may recover from drought. If aridity is prolonged, however, the resistance of systems could drop below critical thresholds, such that they will not recover during the next wet year. Based on evidence derived from climatic proxies, our analysis suggests that the climate of the 20th century was anomalous in terms of the absence of sustained drought. Further, comparison of instrumental records and climatic reconstructions suggests that the climate normal period of 1961-1990 may have been among the most benign of the past 750 years. Possibly, the climate of 1921-1950 (Fig. 11b) is more characteristic of the past and future climate of the Prairie Provinces than the "normal" climate of 1961-1990. Because both lake and tree-ring analyses recorded an abrupt amelioration of climatic conditions at near the start of the instrumental record, we suggest that the immediate impacts of future global warming may be to return the prairie environment to past conditions in which persistent aridity was recorded for intervals of decades or longer.

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