Holocene Paleoclimatology in the South Saskatchewan River Basin

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Introduction

Three aspects of the importance of paleoclimatic research are: 1. it gives information about climate and climate change on longer time scales -millennial and centennial- than those provided by instrumental or historical records –that go back just to few centuries ago-. 2. Through these longer records it is possible to detect low frequency climate variability -not always detectable in shorter records- which in turn offer the opportunity to search for forcing mechanisms at global, regional and local scales. 3. The evaluation of the sensitivity of a particular area to climate variability and specifically to which climatic forcings, e.g. are droughts more recurrent than floods? In other words paleoclimatic research helps the characterization of past climate in a particular area: the identification of cycles and hopefully, the forcing mechanisms. With the growing concern about the global increase in temperature and its impact on global human population, information derived from paleoclimatic research is a necessity. For instance, the Little Ice Age has been lately the focus of intense research because it can provide information to inform the debate about if the present increase in temperature is a natural phenomenom, -part of a natural climatic oscillation following the LIA- or if it is caused by human activities (Cronin, 1999). According to Sauchyn et al. (2002) instrumental and tree-ring records in the Canadian prairies have showed particularly "good" climatic conditions for the 1900s, and that particularly, the period between 1961-1990 was the most benign in terms of climate in the last 750 years. The 20th century is not at all representative of what has been the "usual" climate for the prairies before the 1900s where dry periods and droughts have been frequent as indicated by paleoclimatic research (Sauchyn et al. 2002-2003, Vance et al. 1992-1993, Wolfe et al. 2001).

Paleoclimatology is in a way a unique science as it involves the interaction of scientists of varied disciplines. Climatologists, stratigraphers, geochemists, geomorphologists, oceanographers and glaciologists among the "earth scientists". In the biological sciences palynologists, dendroclimatologists, archaeologists and limnologists, play an important role in the deciphering of past climates and its effects on ecosystems and human populations.

The earth has suffered major climate changes, mainly alternations between glacial stages, the term applied to the advance of glaciers and the decrease in global temperatures, and interglacial stages, when glaciers retreat and global temperatures increase. Nowadays the most accepted theory to explain these climate changes is the "Astronomical Theory" that involves changes in three main aspects of the Earth's configuration: 1. Eccentricity of the orbit. 2. Obliquity of the eclipse and 3. Precession of the equinoxes (Lowe and Walker, 1997; Cronin, 1999; Houghton, 1997). At present time we are in an interglacial stadial that started at about 10,000 years Before Present (yr. B.P.). This period is also known as the Holocene (the most recent), which along with the Pleistocene, form the Quaternary Period. The Holocene is divided into the Early Holocene, dated from 10,000 to 8000 yr. B.P., the Mid Holocene, ranging from 8000 to 4,000 yr. B.P. and the Late Holocene, that covers the last 4,000 yr. Worldwide the climate during the Early and Mid Holocene has been characterized by climate warmth and for many regions it has been characterized by altered precipitation (Cronin, 1999). The climate variation detectable for the Early and Mid Holocene include millennial and centennial cycles. For the Late Holocene, the resolution can be higher including centennial, decadal and annual frequencies.

The focus of this particular report is climate variability during the Late Holocene. The reason to focus on the Late Holocene is because the climate of the early and early-mid Holocene was still under the influence of glacial retreat, ice melt and crustal rebound (Last and Teller, 1983; MacDonald and Case, 2000). The great majority of the climate records included in this report come from the study of lake sediments and these lakes have been formed as a consequence of glacial retreats; therefore, the climate signal can be analysed after all the influence from glaciers has ended.

During the Late Holocene there have been two main shifts in climate that have been recognized almost everywhere, particularly in the higher latitudes. The first shift consisted of an increase in temperature known as "The Medieval Warm Period" (MWP) and the second one, a subsequent period of decreased temperature known as "Neoglaciation" (Lowe and Walker, 1997). The MWP started in the 9^{th} century and ended in the 14th century. It includes the Medieval Warm Epoch dated between 1100 and 1250 A.D. The neoglaciation, dated between 3500 and 2000 yr. B.P includes the Little Ice Age (LIA), a period from the 14th (15th) to the 18th (19th) centuries (Lowe and Walker, 1997; Cronin, 1999), characterised overall by a general decrease in temperature. These shifts between cooler or warmer temperatures do not necessarily mean that for the entire period the temperature was constantly low or high. Cronin (1999) concludes that those were periods of punctuated increases or decreases in temperature and that they did not occur simultaneously worldwide. Among the main forcing mechanisms for centennial and decadal climate variability are (Cronin, 1999): volcanism, solar variability, changes in oceanic circulation and atmospheric trace gases.

Paleoclimatic reconstructions in drylands -the Canadian Prairies is included in this category (Wolfe and Running, 2002)- are challenging because one of the characteristics of these regions is the variability in seasonal and annual precipitation, which is frequently manifested as too much or too little water (Wolfe and Running, 2002). This variability makes it difficult to detect climate patterns of lower frequencies and to decipher normal from abnormal. In the detection of past drier periods, it is important to differentiate dry periods from droughts. According to Beaudoin (2002) low resolution records show periods of aridity, rather than droughts. Periods of aridity are understood as several dry intervals that in conjunction last for more than a decade. According to the same author a drought is a short-term phenomenon only visible through high resolution records offered by proxies such as tree rings and laminated or varved sediments.

The area of study, the South Saskatchewan River Basin has been under variable climate during the Mid and Late Holocene (Teller and Last, 1990; Sauchyn and Sauchyn, 1991; Vance et al. 1992; Last, 1994; Leavitt et al. 1999; MacDonald and Case 2000). The purpose of this report is to present the main results of paleoclimatic research in the area and to bring the past to the present in a way of contributing to the understanding the present and future climate change. Most of the information presented here is derived from paleolimnological, palynological and geomorphological studies. Paleolimnology refers to the study of lakes, mainly variations in the physico-chemical characteristics of the water.

Variations in lake levels usually obey changes in the relation between evaporation and precipitation, if the lake is a close basin (it has no inlets neither outlets) therefore the reconstruction of variations in their levels is a direct measure of changes in Evaporation/Precipitation. Several tools or proxies can be use to track these changes. Among the most powerful are diatoms, ostracods and geochemistry. Palynology is the study of plant remains (seeds, leaves, wood). Through a palynological study is possible to reconstruct the vegetation type that existed once in a particular area. As vegetation changes are often caused by changes in precipitation and or temperature and soil cover, it is possible then to infer past climate conditions. Geomorphology is the study of land processes and the forms they leave behind. For the study area the main proxy used for climate change was dunes. Dunes are formed during periods of aridity and their reactivation and stabilization are indications of increase in aridity or moisture respectively. For higher resolution climate change, a powerful proxy commonly used is tree rings. Through this analysis is possible to reconstruct changes in temperature and precipitation at seasonal scale.

This report includes 6 sections: (1) a summary of the present climate, (2) the main findings from the limnological and palynological records, (3) the climate changes detected by the geomorphogical evidence, mainly dune activity, (4) the changes in biomes as a response to climate change, (5) the general trends of climate change for the last centuries as indicated by tree ring analysis, and (6) a discussion about climate change in the SSRB area.

1. Present Climate

In order to understand past climate variability is necessary to know the general parameters that influence climate today. This section presents the main climate characteristics of North America and then specifically in the provinces of Alberta and Saskatchewan, where the SSRB is located. The North American continent is under two high pressure systems most of the year. The North Atlantic high pressure cell, on the East, also know as the Bermuda or Azores High and the Pacific high pressure cell, on the

West. It is also affected by the Polar High pressure system, and therefore, northwestern Canada has a high pressure cell known as the Canadian high. This high pressure cell is stronger in winter and weaker in summer. Two low pressure cells are present East and West of the North American continent. One, off of Alaska on the northeastern Pacific known as the Aleutian Low and another one, on the North Atlantic, known as the Icelandic Low. During summer these lows tend to disintegrate. On the upper atmosphere the main features in North America are the Polar and Subtropical Jet Streams. The Polar Front Jet Stream is the main weather control in northern latitudes and depending on its position over the continent it can produce storm or fair weather. The Subtropical Jet Stream affects normally the mid latitudes but when it shifts, it will affect the northern latitudes. The drought occurred in 1988 in North America, with devastating effects on the Great Plains was caused by a northward shift of this Jet Stream that created a persistent high pressure cell over North America east of the Rocky Mountains (de Blij et al. 2004).

The climate of Alberta and Sasktachewan is highly affected by the barrier of the Rocky Mountains that cuts off moist coming from the Pacific. Therefore in Saskatchewan air masses tend to enter the province from either the northwest or southwest, but only rarely directly from the west. One exception is the Chinook, a westerly wind that blows down lee side of the Rockies and causes a sudden rise of temperature, most noticeable in the middle of the winter. The predominance of west and southwest winds is also indicated by the alignment in those directions of active and stabilized parabolic dunes in the Great Sand Hills, at the border Alberta-Saskatchewan (Wolfe, 1997). Summer precipitation is largely convective, but it is also affected by continental tropical air masses that bring thunderstorms, hail and even tornadoes (Fung, 1999).

According to Lac and Conlan (2004) the temperature in the SSRB increases southwards. The mean ranges between 2 and 6ºC. Total annual precipitation in the area ranges between 282 to 800 mm with higher values on the West (on the foothills of the Rocky Mountains) and on the North. Highest evapo-transpiration (>560 mm $year^{-1}$) occurs in Southeast Alberta, Southwest and Southeast Saskatchewan (Wolfe, 1997). Part of the area known as the “Palliser Triangle” is included in the SSRB. This area features warmer and drier conditions that the rest of the Canadian Plains (Last and Conlan, 1994); warm summer temperatures combine with low humidity and strong winds give to the area an annual moisture deficit of generally greater than about 1 m. Several fields of sand dunes are present in this area, the Duchess, the Middle Sand Hills, and the Great Sand Hills (Wolfe, 1997). Spanning the Saskatchewan-Alberta border, there is an area of higher relief known as the Cypress Hills. This area is slightly more humid and cooler than the surroundings with annual mean precipitation of 450 mm (Lac, 2004).

2. Limnological and palynological records tracking climate change

This section includes a summary of the Holocene climatic history of the area reconstructed from limnological and palynological analyses published in different papers. Lakes included in this report are (Fig. 1): Crawfoot, Pine, Harris, Chappice, and Waldsea. Other lakes like Redberry, Andrew Pothole, Ceylon and Manitoba (Fig. 1) are also included although they are not located inside the study area but they contributed to the regional context of climate change. Most of the papers used in this summary use uncalibrated ^{14}C radiocarbon dates which are referred in this text as yr. B.P. Few papers presented calibrated ages and those are referred as cal. B.P. The lakes are organized in a west to east transect, with number 2.1 the westernmost one. The name of the lake is provided first, followed in brackets by the location -Al. for Alberta, SK. for Saskatchewan and Mb. for Manitoba- and then by the publication. Figure 2 presents a graphic summary of the climate history.

2.1. *Crowfoot Lake* (Subalpine lake Al. Hickman and Reasoner, 1998)

The climatic reconstruction obtained from this lake is based on diatom and palynological analyses. Their main findings show that warm and arid climates prevailed before ca. 6800 yr. B.P. manifested mainly by the upper displacement of the timberland ecotone, the appearance of xerophytic vegetation and the increase in lake productivity. Between 4160 and 3500 yr. B.P. there was an increase in precipitation and decrease in temperatures as reflected by the decrease of xerophytic vegetation, the increase of *Picea-Abies* forest and the decrease in lake productivity. Around 900 yr. B.P. there is an increase in moisture and glaciogenic sedimentation in the lake as inferred from the sharp decline in arboreal taxa. This glaciogenic sedimentation was the result of the alpine glacial retreat occurring after 1800 yr B.P. According to the authors, glaciers advanced in this area between ca. 3100 (possibly 3400) and 2500 yr B.P. and maintain advanced positions until 1800 yr. B.P.

2.2. *Pine Lake* (South Al. Campbell, 1998)

This climate record is inferred from granulometric variation in the core and only covers the last 4000 cal yr B.P. (ca. 3600 yr B.P.). This record is not presented in Figure 2, to keep calibrated ages apart from uncalibrated. The climate interpretation is based on the fact that coarse sediment supply increases with inflow while fine grained sediments are removed from the water column by outflow with increasing fine sediments being retained and deposited as streamflow declines. Prior to 2000 cal yr B.P. the author reports minimal climate fluctuations; after this date, two maxima of increased moisture occurred. One at 2000 cal yr ago and a second between ca. 300-350 cal yr B.P. This latter one correlated to the LIA. A minimum in moisture was dated at 1000 yr ago and was correlated to the MWP. The historical dry periods (droughts) of 1980, 1960, late 1920-1930s and 1890s were also recorded in the sediments. The author detected a 1000 yr periodicity of climate change.

2.3. *Chappice Lake* (Southeast Al. Vance et al. 1992-93)

The climate record from Chappice Lake comes from mineral, sedimentological and palynological analyses. The record indicates strong seasonal fluctuations for the period between 7300 and 6000 yr B.P. in which frequent and severe dry periods alternated with wetter and/or cooler periods. After 6000 and until 4400 yr B.P. the lake level increased and maintained its higher level until 2600 yr B.P. where there was a further increase in water level. The record indicates that dry periods were rare. This complacent condition changed but not for long: between 1000 and 600 yr B.P. drier periods became frequent again, as indicated by the decrease in lake level. Moister conditions returned once again and reigned between 600 and 100 yr B.P. The historical droughts of the 1800s, 1930s and 1980s left also their footprint in this record.

2.4. *Harris lake* (Southwestern SK. Sauchyn and Sauchyn, 1991; Last and Sauchyn, 1993; Wilson et al. 1997 and Porter et al. 1999).

This lake has been analysed for pollen, mineralogy and lithostratigraphy, ostracods and diatoms at different times (see publications above). Five different climatic periods were recognised on the basis of the pollen record. From 9120 to 7700 yr B.P. the vegetation developed in response to the beginning of more arid conditions. Between 7700 and 5000 yr. B.P. the driest conditions were recorded by minimum levels of trees and aquatic plants and maximum levels of herbs. The continuous low lake levels indicate a uniform climatic period. Between 5000 and 4500 yr B.P. cooler and wetter conditions prevailed as indicated by the increase in aquatic plants. From 4500 to 3200 yr B.P. wetter conditions are indicated by the increase in spruce forest, *Pinus* and aquatic plants. Modern climatic conditions, of relative moisture for the Cypress Hills, were reached at about 3200 yr B.P. as indicated by the establishment of the modern vegetation. Little climate variation is recorded since then.

The next climatic record comes from the ostracods. They suggest that from 9200 to 6400 yr. B.P. the climate was highly variability. The authors conclude that the precipitation must have been of less than 400 mm and temperatures of 1-1.5 °C higher than present. At 8500 yr B.P. there was a marked environmental change that the authors attribute to a possible decrease in temperatures and the establishment of a more continental climate. Between 6400 and 4500 yr. B.P. the ostracod record suggests the prevalence of low lake levels and a harsh limnologic environment. According to the authors this change was possibly caused by a decrease in precipitation. The period from 4500 to 3600 yr B.P. was transitional between high temperatures and low precipitation from the preceding period to more precipitation and lower summer temperatures. The last 3600 yr B.P. consist of present climate conditions without evidence of major climatic events.

The diatom analysis came after the ostracod study and shows a relatively stable limnological environment. The most notorious change in the diatom composition occurred between 6500 and 5200 yr B.P. and although this change is not very well understood, the authors suspect could be pointing to warmer conditions or to an increase in nutrient water levels as a consequence of an increase in inorganic sediments arriving to the lake due to a change in the vegetation cover (Wilson et al. 1997; Porter et al. 1999).

Ostracods, diatoms and mineralogic analyses point to a limnological change between ca. 6400 and 5200 yr B.P. as there is no indication of vegetation change. Thus it is likely that this change was confined to the water itself. As Last and Sauchyn (1993) have stated, the groundwater dynamic of this basin is poorly understood and could be the cause of the observed change. This highlights the importance of the study of groundwater dynamic and the effect of climate change on it.

2.5. *Redberry Lake* (Van Stempvoort, et al. 1993).

The climatic reconstruction of Redberry Lake is based on mineral, stable isotopes and pigment analyses. According to this study, dry and or warm conditions prevailed between 2500 and 1500 yr B.P. After 1500 yr B.P. cooler and or more humid conditions, like those of today were established. Two warmer and or drier periods occurred between 1100 and 900 yr B.P. and 600 and 300 yr B.P. These periods were correlated to the Medieval Warm Epoch.

2.6 *Waldsea lake* (South Sk. Last and Schweyen, 1985).

The climate record in this paper was inferred from pollen and mineral analyses and covers the last 4000 yr B.P. Between 4000 and 3000 yr B.P. the climate was cooling down and becoming wetter than in the previous years, as indicated by increase of *Pinus*, *Betula*, *Alnus* and *Quercus* over the grasslands. After 3000 yr B.P. the climate became wetter and cooler as indicated by deeper lake levels of probably > 5m and the forest advance over the grasslands. The period between 2800 and 2200 yr B.P. was a short time of drier conditions that caused the lake level to drop, however the general trend to wetter climates was back again at around 2000 yr B.P. as indicated by deeper lake levels. Around 700 yr B.P. a lowering in the lake level might be an indication of drier climates.

2.7. *Andrew Pothole* (Southern SK. Yansa, 1998)

The climate signal from this pothole record is derived from a paleovegetation study. The formation of the basin took place some time before 10,000 yr B.P. and at this time, the pothole was a perennial fresh water body deeper than 2 m. It probably originated from residual stagnant ice. Between 10,000 and 8800 yr B.P. the climate was warmer favouring evaporating conditions in the pothole and causing the water to become alkaline and brackish. These warmer conditions continued and between 8800 and 7700 yr B.P. the lake levels dropped. Dry periods were frequent as indicated by the presence of frequent fires. For the rest of the Holocene the water table was high enough to prevent complete desiccation of the basin. From 7700 to 5800 yr B.P. there was possibly an increase in precipitation as indicated by increasing water levels. After this time, deposition stopped at this site. The author thinks that this termination is synchronous with the increase in aridity recorded in other sites nearby.

2.8. *Ceylon Lake* (Southern SK. Last, 1990)

Although this lake is not within the study area, it is close enough to complement the regional climate reconstruction. It is important to bear in mind that this is an ephemeral lake, in other words water level is maintained in the spring but by late summer the lake dries out. Before ca. 7000-6000 yr B.P. the lake level was high, but by 6000 yr. B.P. the level dropped and the basin became hydrologically closed. Hypersaline, evaporitic conditions began during the mid Holocene and have existed since 5000 yr BP. Although the sedimentary record shows some cyclicity in the deposition, the author found no evidence for extended dry periods.

2.9. *Lake Manitoba* (Southeast Mb. Teller and Last, 1981).

The proxies used are sediment geochemistry and palynology. Between 11,000 and 9000 yr B.P. the main environmental changes in the basin are caused by changes in the outlets, crustal rebound and position of the ice margin so the climate signal is not clear. However, until about 10,000 yr B.P. the climate was cool and moist, as indicated by the domination of spruce boreal forest. From 9000 and 4500 yr B.P. warmer and drier conditions prevailed in the area as indicated by a shift in the vegetation from a spruce dominated boreal forest to prairie type vegetation. The fluctuations in lake level were still affected by differential rebound. Dry climate conditions intensified and at about 5500 yr B.P. the lake dried out, perhaps as a consequence of higher mean annual temperature and lower precipitation. After 5000 yr. B.P. there was a return to a somewhat wetter and cooler climate favouring aspen parkland vegetation with *Betula, Alnus, Quercus* and *Acer* and the rising of the lake level. Between 5000 and 2000 yr B.P. the fluctuations in lake level were affected by hydrological changes. The last 2000 yr. B.P. have been stable with higher precipitation than before and cooler temperatures as reflected by the hydrologic stability.

3. The Geomorphological evidence of climate change

This section presents the main findings about climate change that occurred in the area from the geomorphological evidence, mostly from dunes studies. Dunes and dune fields are formed during periods of increased aridity. Through a study of dunes it is possible to recognise periods of dune formation, stabilization and reactivation and to reconstruct changes in wind direction. Through a careful study it is possible to infer the frequency and duration of dry periods. Usually local reactivation of stabilized dunes require dry periods that last for months or years, however to reactive a regional dune field dry periods of several years to decades are required (Vance and Wolfe, 1996). The dates provided by dune studies are not always ^{14}C radiocarbon but optical dating. These dates indicate calendar years before present (yr ago). The records are organized in a west-east transect, with number 3.1 the westernmost site. The name of the area is provided first, followed in brackets by the location -Al. for Alberta, SK. for Saskatchewan and Mb. for

Manitoba- and then by the publication. The main results are presented in Figure 3; for an approximate location of the fields, please refer to Figure 1.

3.1. *Duchess field* (Southern Al. Wolfe et al. 2002c)

Dunes in this field are oriented northwest, indicating the predominant wind direction. Dune activity in this area ocurred between 4500 and 2900 yr ago and between 400 to 230 yr ago. Dune stabilization occurred between 980 and 400 yr ago (1020-1600 A.D). Episodes of dune activity and stabilization were contemporaneous with periods of increased aridity and increased moisture availability, respectively. At this site (unlike the Great Sand Hills of Southwest SK.), there was no evidence of significant dune activity for the last 200 yr. For the authors this is a possible indication of a predominance of northwesterly wind that has provided greater moisture to this area.

3.2. *Great sand hills* (Southwest Sk. Wolfe et al. 2001)

A period of dune stability occurred around 2600 yr ago. Dune reactivation occurred was dated at 600 and 300 yr ago and has occurred for last 200 yr.

3.3. *Saskatoon and Beaver Creek Area* (South central SK. Wolfe et al, 2002b)

Eolian activity was present between 11,300 and 8400 cal yr BP. After this time and until 5600 cal yr BP, there were no chronologies available. However the authors suspect that there were periods of eolian activity and that the climate alternated between arid and humid intervals.

In Elbow Sand Hills there has been very late Holocene eolian activity; the latest episode occurred within the last 220 yr. According to the authors this last episode was caused by either drought or some sort of disturbance confined to this area and not present in the north.

3.4. *Manitoba* (Wolfe, 1997; Wolfe et al. 2000;2002a)

In the Lauder Sand Hills of southwestern Manitoba, dune activity was recorded between 7600 and 6100 yr ago. Periods of soil development, indicative of dune stability, occurred at around 2300 to 2000, 1400 to 1000 and 600 to 500 yr ago. There was also evidence of dune reactivation during the dry periods of the 1700s. Periods of eolian activity occurred at about 2000, 3100, 4000 and prior to 5200 yr ago.

4. Climate change and the biome response (Dyke et al. 2004)

A biome is a climate-controlled vegetation (Dyke et al. 2004). From the extensive study by Dyke et al. (2004) it is possible to see the evolution of the main biomes in the entire country since the last glacial maximum at 18,000 yr B.P. This report considers the biome changes that occurred in Southeastern Alberta and Southwestern Saskatchewan at windows separated by 2000 yr starting at 11,000 yr B.P. Changes in vegetation in a more local scale are provided in the section 1. From Figure 4 it is possible to see that the grassland biome has been predominant in the area since 11,000 yr B.P. with an exception at 9000 yr B.P. where the boreal parkland biome extended south over the grasslands. At 11,000 yr B.P. the area was dominated by grasslands, however boreal forest occupied the east part of the SSRB. At 9000 yr B.P. boreal parkland biome extended south and entered the studied area. After 7000 yr B.P. grassland biome extended again to the north almost as much as it did by 11,000 yr B.P. A southward displacement of the grassland biome occurred at 5000 yr B.P. at the same time that boreal parkland biome extended north and south. Little variation is observed for the last 3000 yr.; grassland biome is dominant in the area and boreal parkland and boreal forest are restricted to the north.

5. Climate signals from tree rings, in the search for droughts

This section presents the climate reconstructions obtained from tree-ring analysis specifically for the area of the SSRB. The majority of these studies have been focused on the detection of droughts and drought cyclicity.

The study by Case and MacDonald (2003) detected very low stream flows in the following years: the 1560s to 1570s, the first two decades of 1700s and the mid 19th Century. The following years were classified by them as periods of "critical droughts": 1717-1718, 1720-1721 and 1843-1844. The common dry years between the north and south SK river basins were 1580, 1631, 1720 and 1759. The most severe period of drought occurred in the decade of the 1791-1800 (Case and MacDonald, 1995) as there were 6 years droughts out of 10. In this century, the driest period in the Alberta prairies occurred between 1916 and1925.

For more detailed information about the most recent episodes of droughts obtained by tree rings see Lac and Conlan (2004).

6. Discussion

6.1. *Millennial Scale changes*

The postglacial early-mid Holocene (9000 to 5000 yr B.P.) has been recognized globally as a period of climate warmth and is often referred as the "hypsithermal" (Deevey and Flint, 1957 in Cronin 1999). In many regions of the world the temperatures during this period were higher than those from the late Holocene. In the study area this period is clearly indicated by most of the limnological records (Figure 2). Drier conditions started at around 9000 yr B.P. in all the records except at Andrews Pothole, where drier conditions are recorded earlier (10,000 yr B.P.). These drier conditions are also recorded by dune activity in the east of the studied area (Southcentral Sk. and Southwestern Manitoba, Figure 3) between 10,000 and 4600 yr ago. The dominance of grassland biome with a minimum extension around 9000 yr B.P and a maximum around 7000 yr B.P. (Figure 4) support drier conditions. This maximum extension of grasslands could be related to the very dry conditions recorded at 7000, 6000, 6400 and 5500 yr B.P. by several lake desiccations, further low lake levels in Harris Lake and the change from an open to a close hydrologic system in Ceylon Lake (Figure 2). This suggests a period of maximum aridity at around 6000-5500 yr B.P. All of the records are more or less synchronous during this period, except for Andrew Pothole that shows a change to more humid conditions between 7700 and 5800 yr B.P.

Between 5200 (6000 yr B.P. at Chappice Lake) and 4000 yr B.P, (mid-late Holocene) most of the limnological records show a shift to humid conditions, except for Andrew Pothole that changed from semi-permanent to ephemeral conditions. This increase in humidity is also recorded by dune stabilization in central Saskatchewan, by the extension of the boreal parkland biome and the southward displacement of the grassland biome and by the starting of lacustrine sedimentation in Waldsea lake. According to Fritz et al. (2001) the termination of the mid-Holocene dry interval in North America was time transgressive, starting earlier in the northwest and later in northcentral. Our studied are is not extensive enough to see such transgression, however we observed that the lakes in the centre of the studied area, closer to the boundary Sk-Al, responded first to the increase in humidity. As suggested by most of the records (Figure 2), these humid conditions have lasted until today; in other words, no other major millennial changes have taken place. This humid late Holocene is known globally as the "Neoglaciation" (Lowe and Walker, 1997; Cronin, 1999). Specifically in the studied area, the neoglaciation is recorded by Crawfoot, Chappice and Manitoba Lakes by a further increase in humidity between 3100 (3400), 2600, 2000 and 1800, 1500 yr B.P. respectively. Although Last and Schweyen (1985) do not specifically discuss the neoglacial in Waldsea Lake, it is possible that the increase in cooler and moister conditions recorded after 2000 yr B.P. correspond to the neoglacial, in the terms used by Hickman and Reasoner, (1998) and Vance et al. (1992-1993). At Pine Lake there is also an increase in humidity after 2000 cal yr B.P. that could correspond to the neoglacial interval. The earlier decrease in temperature at Crawfoot Lake is due to its closeness to Alpine glacials. The sites east of the Rockies respond later to the cooling temperatures. The regional paleosoil formation that occurred between 2700 and 1400 yr ago and again at 1400 yr ago and 1400-1000 yr ago confirm the regional shift to more humid climates. Redberry and Waldsea lakes, located on the easternmost part of the studied area and very close to the river, record a short period of drier conditions between 2500-1500 and 2800-2000 yr B.P. respectively that is not recorded elsewhere. Although very little is known about the paleohydrology of these lakes (Last, 1994), it is possible that the lower water levels recorded by these two lakes were due to lowering groundwater tables.

6.2. *Centennial scale changes*

For the last 1000 yr B.P. generally cooler and humid conditions have prevailed as indicated by the limnologic records, the dune activity in Alberta and biome reconstructions. However, dry periods have been recorded on Chappice Lake at around 1000 yr B.P., on Redberry at 1100, 900, 600 and 300 yr B.P. and on Waldsea at 700 yr B.P. These dry periods were intense and long enough to reactive dune activity (Figure 3) between 400-230, 600-300-200-100 and 500 yr ago in Duchess, South Central Sasktachewan and Southwestern Manitoba respectively.

Dune studies in Alberta and Saskatchewan (Wolfe, 1997; Wolfe et al. 2001 and Wolfe et al. 2002b-c) allowed Wolfe et al. (2002a) to conclude that there was an increase in moisture in southwest Alberta from 1500 to 1600s and that this moist period was followed by an arid period with below normal precipitation through the 1800s. The 1600s for central Saskatchewan were dry with numerous dry periods comparable to those of the 1790s. In this region, the onset of widespread dune activity that occurred after 200 yr ago was preceded by relatively dry conditions throughout the 1700s and by a severe dry period in the 1790s. A lag is apparent between peak in dryness ca. 1800 and the onset of dune activity ca. 1810. Dune stabilization has occurred since AD 1890. The authors conclude that the droughts occurred during the 1930s and 1980s were insufficient to initiate dune activity. While the geomorphologic record shows relatively humid conditions in the westernmost part of the studied area for the 1500 -1600s, dry conditions prevailed in the centre and east. The 1700-1800s were generally dry with a peak in aridity at ca. 1790.

6.3. *Cyclicity and duration of the shifts*

The longest cycle reported is of 1000 yr for dry periods and was detected through streamflow discharges (Campbell, 1998). According to Leavitt et al. (2004), extreme droughts as the one in 1930 occur every 60-100 yr with 23-45% probability of occurring by 2030. According to Campbell (1998) the climate fluctuations between wetter and drier conditions and that finally led to the droughts of the 1920-1930s were extremely rapid and they all took place over a period of 50 yr or less. Sauchyn and Beaudoin (1998) suggest the two major climate stages that have occurred in the last millennium. The first one between 1000 to 600 (500) yr ago (950-1350 AD) with warmer temperatures and more frequent droughts episodes and the last one from 500 yr ago to present times, characterised by cooler temperatures. Events of extreme droughts have some periodicity of 14, 22, 30 and 100 yr cycles (Sauchyn and Skinner, 2001; Leavitt et al., 2004). Case and MacDonald (1995) found an additional cyclicity of approximately 30 to 50 yr. Data other than historical for drought duration is presented in Leavitt et al. (2004). According to them severe droughts last for periods of 5 to 10 yr.

According to Leavitt et al. (2004) floods have cycles of 25 and 300 yr.

6.4. *Differential response to climate shifts in the Canadian Great Plains.*

Sauchyn and Sauchyn (1991) detected that the onset of cooling and wetter conditions after the hypsithermal occurred first west of Harris Lake and then east of it. This delayed arrival of postglacial warmth in the east is explained by the late deglaciation of the ice caps in this area (Dyke et al. 2004; MacDonald and Case, 2000; Teller and Last, 1981).

The droughts of 1929-1937 were stronger in the southeast while droughts of the 1918, 1919 and 1922 affected mainly the southwest (MacDonald and Case, 2000). The drought of the 1961 impacted first and strongly Manitoba and then it decreased its impact westward (Mac Donald and Case 2000). During the last 200 years there has been dune activity in the Great Sand Hills and not in the Duchess field (Wolfe et al. 2002). According to the authors a possible cause of this difference is the predominance of northwesterly winds over the Duchess field that have provided more moisture to this area.

Additionally, the presence of the Rockies is another factor that causes wetter conditions to the western sites.

6.5. *Possible causes of climate change*

Early Holocene changes are due to changes in insolation (Fritz et al., 2001). The final melt of the Laurentide ice sheet brought to this area increase in aridity. For Fritz et al (2001) the west-east moisture pattern is possibly explained by a sequence of changes in the location and configuration of the Rossby waves. According to Fritz et al. (2001) the Great Plains have featured more climatic variability during the last 2000 yr than during 7000-5000 yr B.P. possibly related to the onset El Niño Southern Oscillation (ENSO) phenomenon dated at about 6100 yr B.P. (Riedinger et al. 2002).

In terms of droughts, they have been related to anomalies in sea surface temperature (SST) in the North Pacific. Anomalies in the SST of the North Pacific may vary on decadal scales and produce decadal scale variations in climate over northern North America (Case and MacDonald, 1995).

6.6. *Modern trends in lake levels*

Modern lake levels in the area have a decreasing trend, particularly since 1970 (Van Stempvoort et al. 1993, Vinebrook et al. 1998, Leavitt et al. 1999). No major climatic signal has been associated with this trend and the authors suspect that human activities might be responsible.

6.7. *Sensitivite areas*

From the records discussed above there are two salient aspects of climate change in the studied area. One is the differential response in time among the records to the dry periods and a second one is the more or less uniform response to humid conditions. This time lag among the records makes it difficult to define sensitive areas to climate change in the studied region on the basis of paleoclimate records. However from the records from Waldsea and Redberry Lakes and the dune activity history in Central Saskacatchewan, it seems like Central Sasktachewan, particularly the area east and west of Saskatoon is more sensitive to dry conditions. The area surrounding the Duchess dune Field could be less affected by drought than the Great Sand Hills field in Sk. because apparently the south westerly airflow seems to have a minimal effect in the Duchess Field (Wolfe et al. 2002c).

7. References

Beaudoin, A. (2002). On the identification and characterization of drought and aridity in postglacial paleoenvironmental records from the northern great plains. *Géographie physique et Quaternaire*. 56: 229-246.

Campbell, C. (1998). Late Holocene lake sedimentology and climate change in souther Alberta, Canada. *Quat. Res*. 49: 96-101.

Case, R. and MacDonald, G. (1995). A dendroclimatic reconstruction of annual precipitation on Western Canadian Prairires since A>D. 1505 from Pinus flexilis James. *Quat. Res*. 44: 267-275.

Case, R. and MacDonald, G. (2003).Tree ring reconstructions of streamflow for three Canadian prairie rivers. *J.Am.Water resources association,* 703-716.

Cronin, T. (1999). Principles of Paleoclimatology. Perspectives in paleobiology and Earth History. Bottjer, D and Bambach (Eds). Columbia University Press. New york.560 pp.

De Blij, H.J., Muller, P.O. and Williams, R. (2004). Physical geography. Third Ed. Oxford University Press. New York, Oxford. 702 pp.

Dyke, A., Giroux, D and Robertson, L. (2004). Paleovegetation maps of Northern North America, 18000 to 1000 BP. Geological Survey of Canada, *Open File* 4682.

Fritz, S., Ito, E., Yo, Z., Laird, K. and Engstrom, D. (2000). Hydrologic variations in the Northern Great Plains during the lasy two millennia. *Quat. Res*. 53:175-184

Fritz, S., Metcalfe, S. and Dean, W. (2001). Holocene Climate Patterns in the Americas Inferred from Paleolimnological Records. In: *Interhemispheric Climate Linkages*. Markgraf, V. (Ed.). Academic Press, San Diego. 241-163

Fung, K. (ed). Atlas of Saskatchewan. (1999). Second Ed. University of Saskatchewan.

Hickman, M. and Reasoner, M. (1998). Late Quaternary diatom response to vegetation and climate change in a subapline lake in Banff National Park, Alberta**.** *Journal of Paleolimnology,* 20:253-265

Houghton, J. (1997). Global Warming. Second Ed. Cambridge University Press. 251 pp.

Lac, S and Conlan, C. (2004). South Saskatchewan River Basin Biogeography. Report Prepared for the SSHRC MCRI-Institutional Adaptation to Climate Change Project, Canadian Plains Research Centre. U. of Regina.

Last, W. (1990). Paleochemistry and paleohydrology of Ceylon Lake, a salt dominated playa basin in the northern Great Plains, Canada. *J. Paleolimnology* 4:219-238

Last, W. (1994). Paleohydrology of playas in the northern Great Plains: perspectives from Palliser's Triangle. Geol. Soc. of America Special paper 289.

Last, W. and Sauchyn, D. (1993). Mineralogy and lithostratigraphy of Harris lake, southwestern Saskatechewan, Canada. *J. of paleolimnology,* 9:23-39

Last, W. and Schweyen, T.H. (1985). Late Holocene history of Waldsea lake, Sk. Canada. *Quat. Res.*, 24:219-234

Last, W. and Teller, J. (1983). Holocene climate and hydrology of the lake Manitoba basin. In Glacial lake Agassiz ed. By Teller and Lee Clayton. *Geol. Ass. Can. Special paper* 26. p. 333-353

Lowe, J. and Walker, M. (1997). Reconstructing Quaternary Environments. 2nd. Ed. Longman Gr. 446 pag.

Leavitt, P., Vinebrooke, R., Hall, R., Wilson, S., Smol, J., Vance, R. and Last, W. (1999). Multiproxy record of prairie lake response to climate change and human activity, Clearwater Lake, Saskatchewan. In *Holocene Climate and Environmenal change in the Palliser Triangle: a Geoscientific Context for Evaluating impacts of Climate Change in the Southern Canadian Prairie* (eds.) D.S. Lemmen and R.E. Vance; Geological Sruvery of Canada, Bulletin 534.

Leavitt, P., Chen, G., Rusak, J. and Wunsam, S. (2004). The past, present and future of prairie droughts and their impacts. In: Canadian Prairie Drought Workshop 2004. www.parc.ca/events/conference proceedings and workshops summaries.

MacDonald, G. and Case, R. (2000). Biological evidence of multiple temporal and spatial scales of hydrological variation in the western interior of Canada. *Quat. Int.*, 67:133-142

Porter, S., Sauchyn, D. and Delorme, D. (1999). The ostracode record from Harris Lake, southwestern Sasktachewan: 9,200 years of local environmental change. *J. of paleolimnology*, 21: 35-44

Riedinger, M., Steinitz-Kannan, M., Last, W. and Brenner, M. 2002. A ~6100 14C yr record of El Niño activity from Galápagos Islands. *J. of Paleolimnology* 27: 1-7

Teller, J. and Last, W. (1981). Late Quaternary History of Lake Manitoba, Canada. *Quat. Res*. 16: 97-116

Teller, J. and Last, W. (1990). Paleohydrological indicators in playas and salt lakes, with examples from Canada, Australia and Africa. *Paleogeogr. Paleoclimatol. Palaeoecol*. 76: 215-240

Sauchyn, M. and Sauchyn, D. (1991). A continuous record of Holocene pollen from Harris lake, southwestern Sasktachewan, Canada. *Palaeogeogr., palaeoclimatol. Palaeocol*., 88:12-23

Sauchyn, D. and Beaudoin, A. (1998). Recent environmental change in the southwestern Canadian plains. *The Canadian Geographer*, 42: 337-353.

Sauchyn, D., Barrow, E., Hopkinson, R. and Leavitt, P. (2002). Aridity on the Canadian plains. Southwestern Manitoba. *Géographie physique et Quaternaire,* 56: 247-259.

Sauchyn, D., Stroich, J. and Beriault, A. (2003). A paleoclimatic context for the drought of 1999-2001 in the northern Great Plains of North America. *The Greog. J.,* 169: 158-167.

Van Stempvoort, D.R., Edwards, T., Evans, M. and Last, W. (1993). Paleohydrology and paleoclimate records in a saline prairie lake core: mineral, isotope and organic indicators. *J. Paleolimnology* 8:135-147

Vance, R., Mathewes, R.W. and Clague, J.J. (1992). 7000 year record of lake-level change in the northern Great Plains: a high resolution proxy of past climate. *Geology,* 20:879-882.

Vance, R., Clague, J. and Mathewes, R. (1993). Holocene paleohydrology of a hypersaline lake in southeastern Alberta. *J. Paleolimnology* 8:103-120

Vance, R. and Wolfe, S. (1996). Geological indicators of water resources in semi-arid environments:southwestern interior of Canada; in: *Geoindicators: Assessing Rapid Environmental Changes in Earth Systems,* (ed.). A.R. Berger and W.J. Iams; A.A. Balkema, Rotterdam, Netherlands, p. 251-263

Vinebrooke, R., Hall, R., Leavitt, P. and Cumming, B. (1998). Fossil pigments as indicators of photographic response to salinity and climatic change in lakes of western Canada. *Can. J. Fish. Aquat. Sci*, 55:668-681

Wilson, S. Smol, J. and Sauchyn, D. (1997). A Holocene paleosalinity diatom records from southwestern Sasktachewan, Canada: Harris Lake revisited. *J. of paleolimnology* 17:23-31

Wolfe, S. (1997). Impact of increase aridity on sand dune activity in the Canadian Prairies. *J. Arid Environments*, 36: 421-432

Wolfe, S., Muhs, D., David, P. and McGeehin, J. (2000). Chronology and geochemistry of late Holocene eolian deposits in the Brandon Sand Hills, Manitoba, Canada. *Quat. Int.*, 67:61-74.

Wolfe, S.A., Huntley, D.J., David, P.P., Ollerhead, J., Ssuchyn, D. and MacDonald, G.M. (2001). Late 18^{th} century drought-indiced sand dune activity, Great Sand Hills, Saskatchewan. *Can. J. Earth Sci.,* 38: 105-117

Wolfe, S. and Running, G. (2002). Drylands: Holocene climatic, geomorphic, and cultural change on the Canadian Prairies. *Géogr. phys. Quat.*.,56: 313-134

Wolfe, S., Huntley, D. and Ollerhead, J. (2002a). Optical dating of modern and Late Holocene dune sands in the Brandon Sand Hills, Southwestern Manitoba. *Géogr. Phys. Quat.*, 56:203-214.

Wolfe, S., Ollerhead, J. and Lian, O. (2002b). Holocene eolian activity in south-Central Saskatchewan and the southern Canadian prairies. *Géogr.Phys.Quat.,* 56: 215-227.

Wolfe, S., Ollerhead, J., Huntley, D.J. and Campbell, C. (2002c). Late Holocene dune activity in the Duchess Dune field, Alberta. *Geol. Sur. Can., Current Research,* 2002-B3, 8p.

Yansa, C. (1998). Holocene paleovegetation and paleohydrology of a prairie pothole in southern Saskatchewan, Canada. *J. of Paleolimnology* 29:429-441