The Past, Present and Future of Prairie Droughts: How Bad is Bad?

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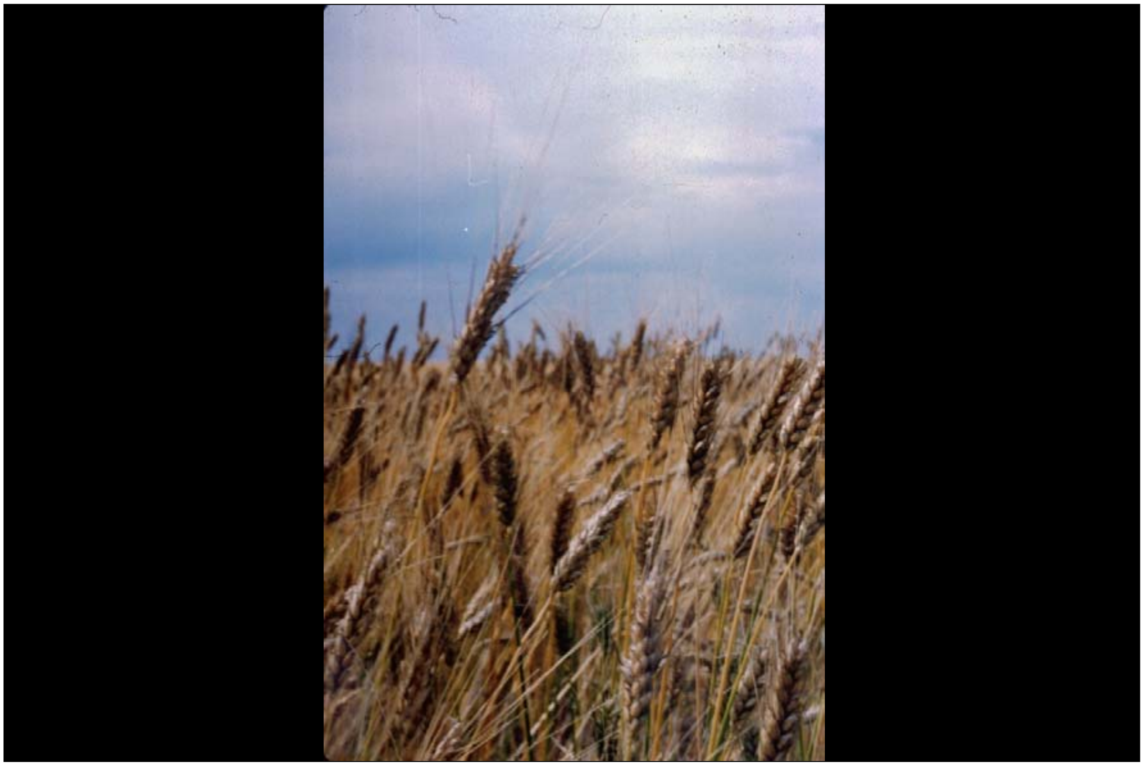
This file summarizes the basic findings of the Prairie Drought Project. Please see individual lake files, methods and land-use reports for additional details.



Agriculture is an essential component of the western Canadian economy, particularly in Saskatchewan where between 15 and 30% of total gross economic product is directly related to agricultural activities. This value is about four times greater than that in any other Province or US State, and underlines the sensitivity of western Canadian economy and society to successes in the agricultural sector.

Drought represents the single largest source of economic hardship to the farming community. The last major drought in the Canadian Prairies occurred in 1988-1989, and resulted in over 1 billion dollars in crop insurance payments and over $50 billion US dollars in total economic losses in North America. Farm abandonment rates increased significantly as a result of this drought.

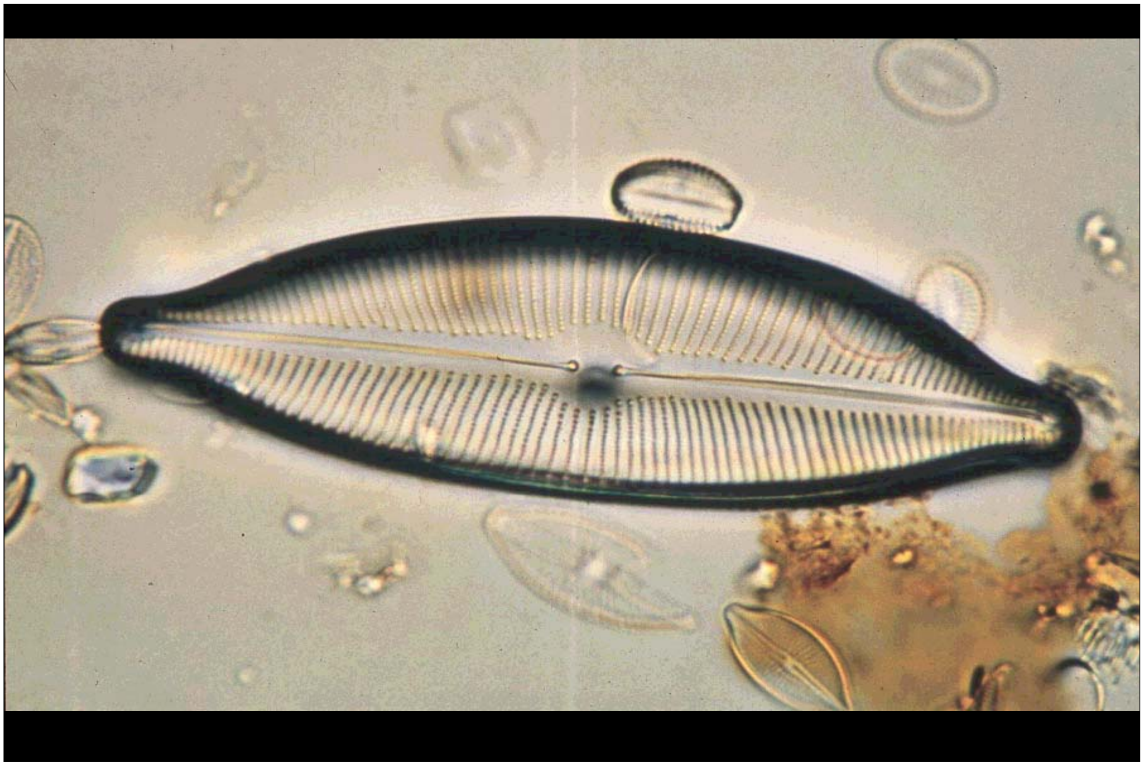
Unfortunately, there is obvious evidence that the 1988-1989 drought was not particularly severe, especially when considered in the context of the 1930s. During that era, a combination of 6 dry years and relatively ineffective land management practices, lead to widespread loss of soils (hence the 'Dirty Thirties') and displacement of over 25% of human prairie populations. This drought, combined with the second World War, also signaled the start of a move away from rural lifestyles, towards a more urban existence in western Canada.

Our project was founded on the premise that it is essential to better understand the risk of such severe events if we are to safeguard modern Prairie society against future droughts. For example, crop insurance data records are based on fewer than 40 years of data. While in principle, it is possible to use 100-year long meteorological records to evaluate drought risk, there is evidence from longer-term historical accounts (explorers records, etc.), that modern climate since 1900 AD might not be representative of the true frequency of drought events.

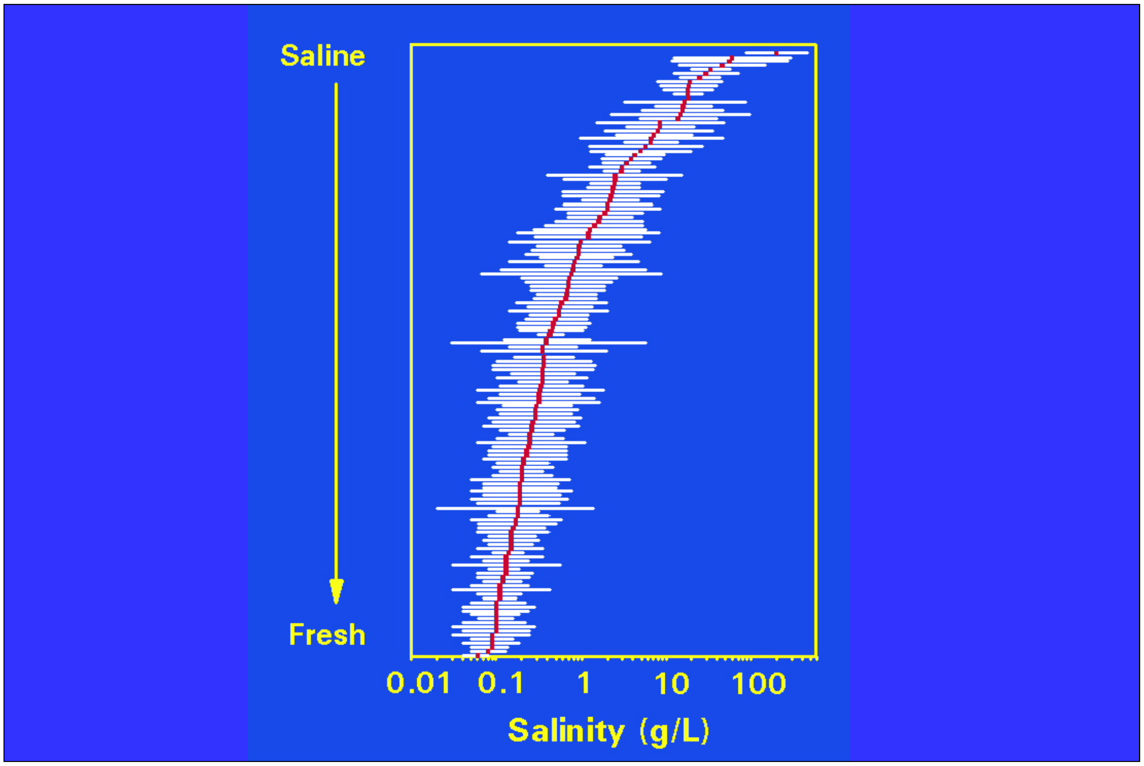
The Prairie Drought Project was developed to extend instrumental records back 1000s of years in order to better measure past drought occurrence. These records are then to be used to forecast drought occurrence and measure the *risk* of future economically-damaging events. In this project, fossils from lake sediments are collected and analyzed to reconstruct the history of droughts in the Canadian Prairies. The same climatic conditions which cause droughts (prolonged hot and dry) also cause prairie lake levels to drop and lake water to become more salty. As salt content increases, it causes changes in the the types of algae living in lakes. By analyzing the fossil record of algae, we are able to reconstruct the past changes in water chemistry and lake level, and hence climate. These new historical records can then be used to estimate the probability of future drought (and flood) events.

The first step in our analysis is to collect a tube (core) of lake mud using the coring device seen here. This tube is pushed slowly into the sediments, and can be retrieved with the undisturbed mud remaining within the tube.

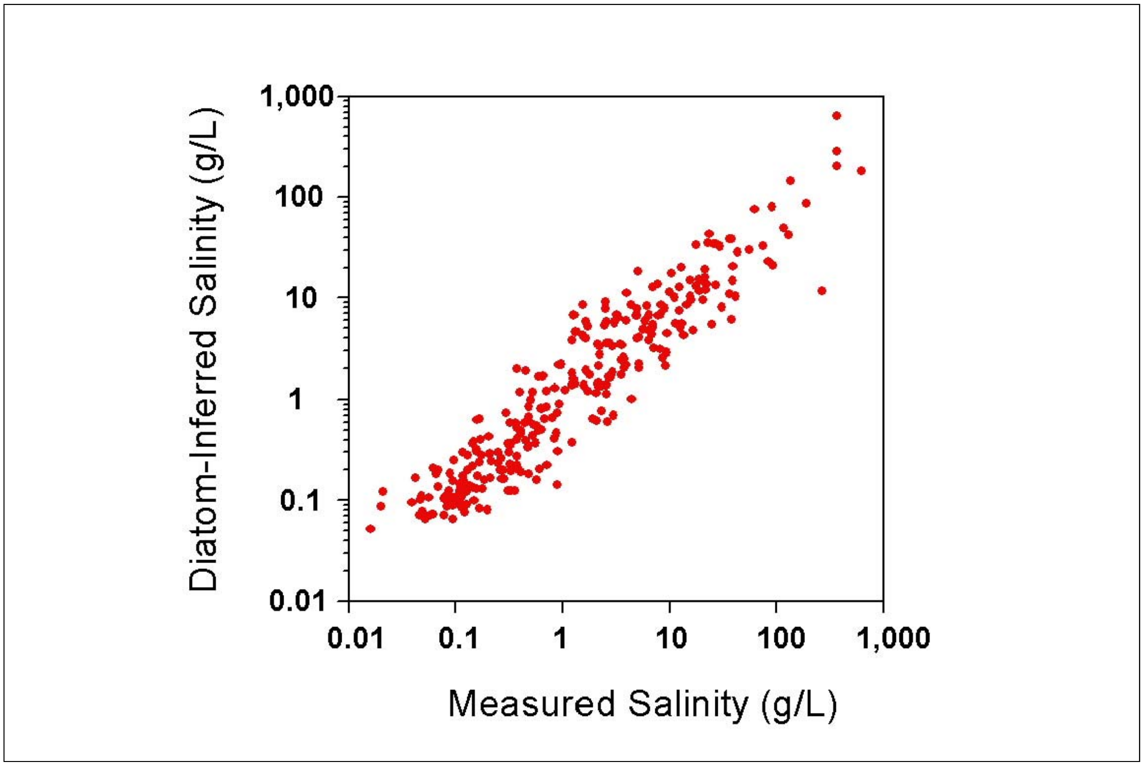
The sediment (mud) of each lake showed clear evidence of internal banding. These bands demonstrate that the mud is not mixed or disturbed by collection methods, and suggest that the fossil record may contain a fine-scale record of past climatic change. These sediments are then cut into 2.5 mm thick intervals and analyzed for a number of fossils (see methods web pages; previous updates).



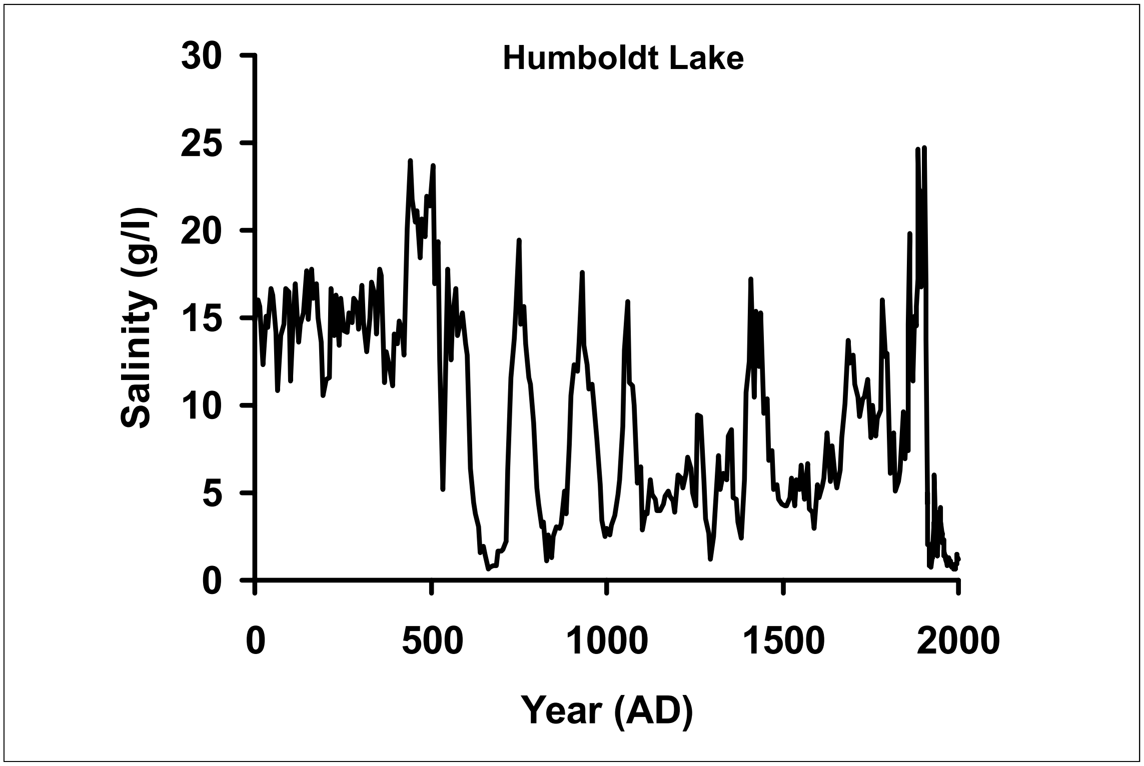
Among the most important fossils are remains of single-celled algae called diatoms. These plant-like diatoms have cell walls made of a glass-like material which can preserve in the sediments for 10s of 1000s of years. In addition, the pattern on each cell allows us to identify the species with little error. There are often over 100 diatom species in each sediment sample, and it is the changes in the diatom community composition through time that allows us to reconstruct past changes in lake chemistry and climate.



For example, if we survey the mud from 100s of lakes in western Canada, we find a wide range in the type of lake in which diatoms are found. Some species prefer to live in fresh water of low salt content (salinity), as indicated by the red dots above. While they can tolerate a range of salinity (white cross bars), these species are mainly indicators of fresh waters and low salt content. In contrast, at the top of this figure, there are a number of species that are characteristic of very salty conditions. Thus, because these algae live and die in a lake, their fossil remains gives us a quantitative record of past water chemistry. In short, if all fossil algae found in a given sample were characteristic of salty water, then the lake must have been salty at the time the algae died and sank.



When the *diatom-inferred* lake salinity is compared with actual historical measurements, we see that there is a strong predictive relationship between fossil-derived and measured lake saltiness. This *transfer function* is then applied to the fossil records from our prairie lakes in order to reconstruct past changes in lake conditions.

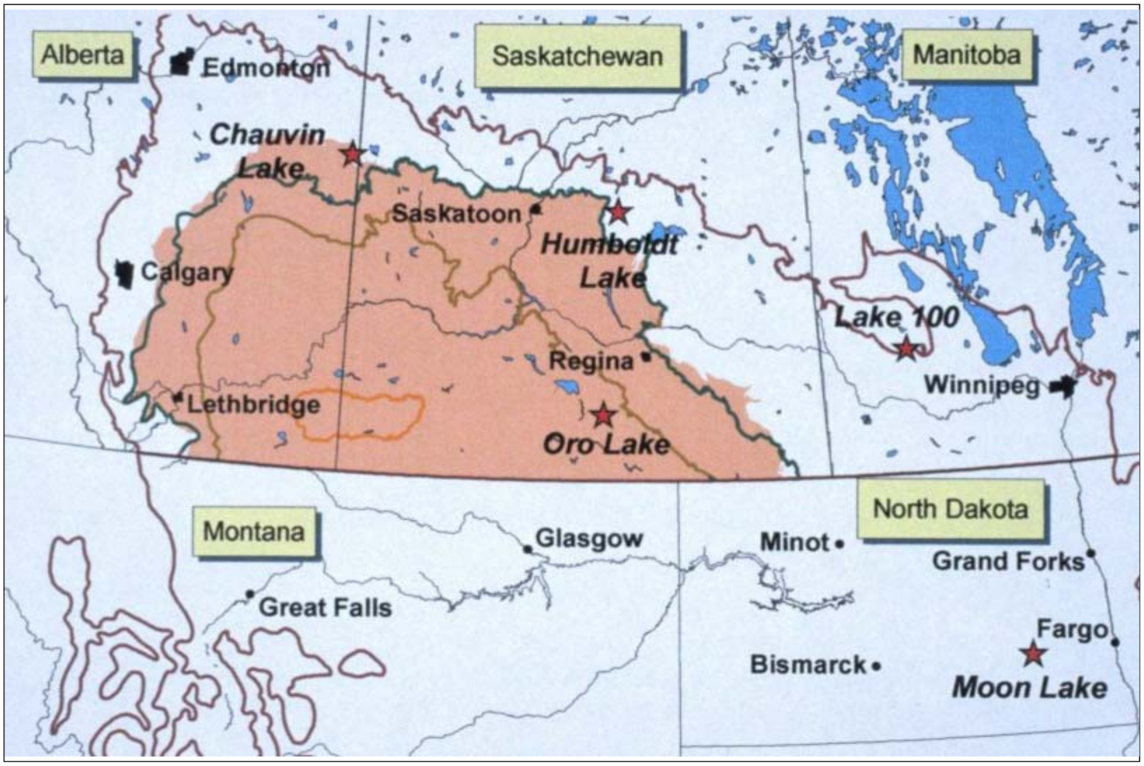


The end result is a long record of changes in lake chemistry and climate. When these long recorded at characterized using advanced statistics, they can be used as the basis for our drought risk assessments.

Objectives

1. Quantify the relationship climate, agriculture and past lake chemistry.
2. Measure the occurrence of past severe droughts and floods over 2000 years and determine if cycles are present.
3. Quantify the risk of climatic extremes in the next 30 years.
4. Compare risks along landscape gradients.

In order to use fossil-derived climate records (called paleoclimate records) for forecasting droughts, we must first demonstrate that there is a statistical relationship between changes in climate and changes in the fossil records over the past 100 years. By comparing these two records past changes in crop production, we can also determine whether fossil records are relevant to prairie agriculture. Once these relationships are established, we can then measure the intensity, frequency and duration of past droughts and apply these data to future drought forecasts. By comparing our analysis among all three prairie provinces, we can investigate whether these events show any geographic patterns which might be helpful in predicting future drought occurrence.

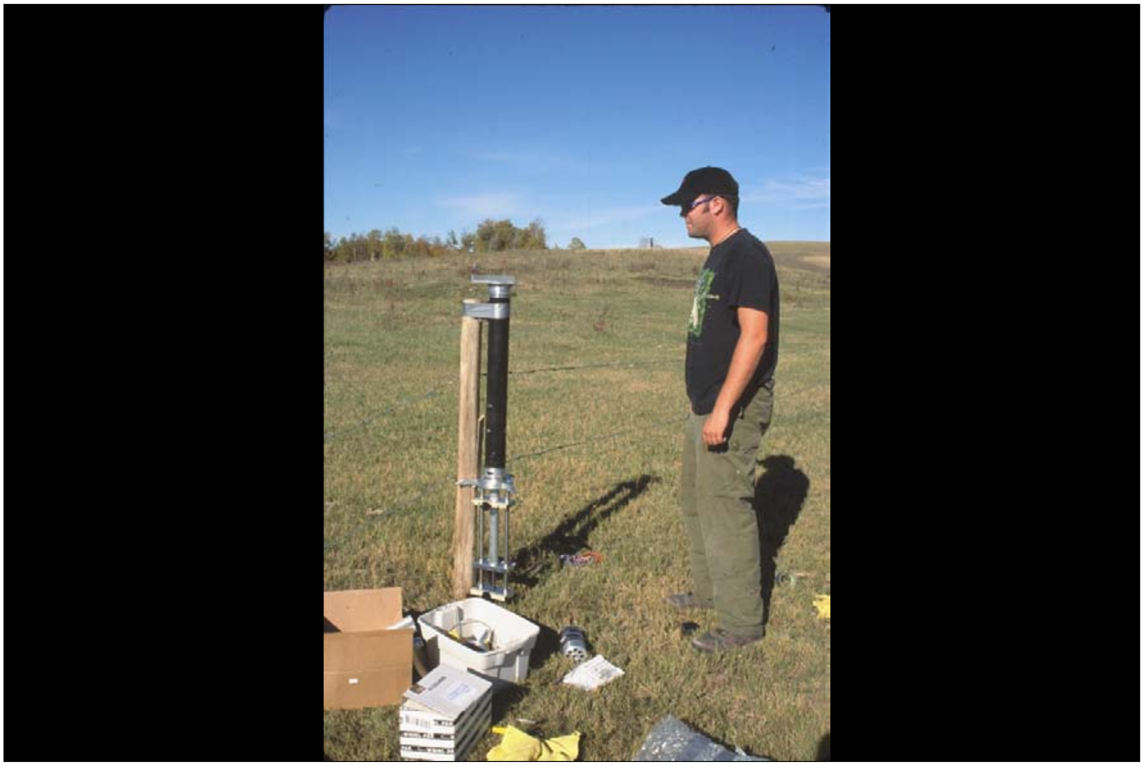


Our study sites are located throughout the Canadian Prairies and northern US grasslands (red stars). To begin with, we will go to Humboldt Lake in central Saskatchewan to address our first objective and determine the relationship between past climate, agricultural production and fossil records of lake chemistry.

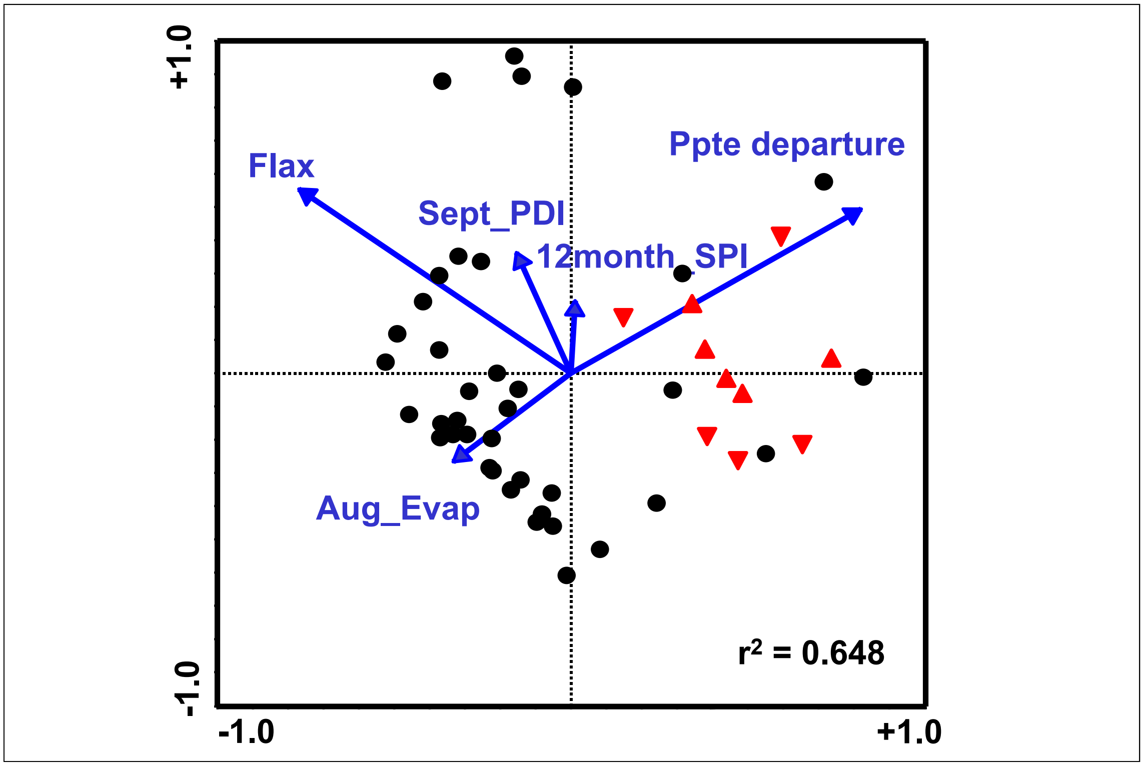
1949

1959

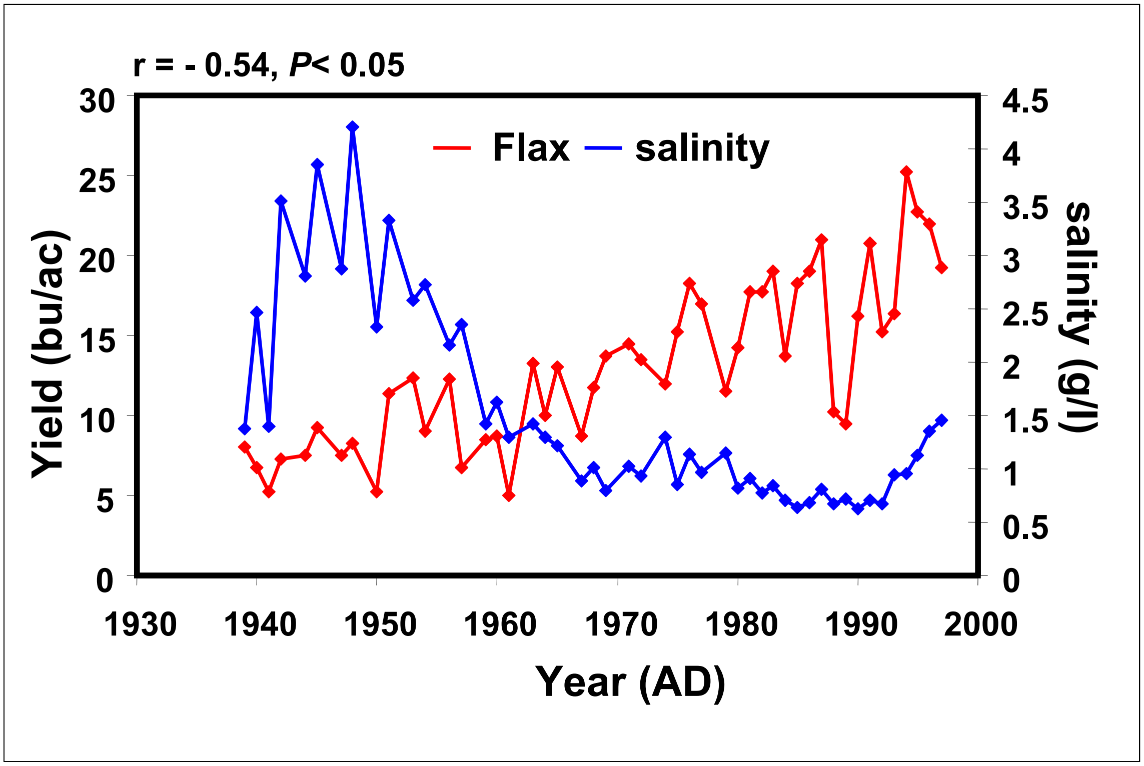
Humboldt Lake is ideally suited for climatic research because it is located within a small effective drainage (inner red line) that is tightly linked to past climatic variability. Analysis of aerial photographs between 1940 and the present demonstrate that lake levels have varied in accordance with historical changes in precipitation.



Cores of lake sediments were collected from the lake using standard procedures (see project update web pages) and sediments were cut into fine interval sections (2.5 mm thick). Each interval was equivalent to 3-4 years of lake history. The fossil records in these sediments were analyzed and historical changes in diatoms were measured. Changes in the fossil community during the past 100 years were then compared with changes in climate and crop production during the same period.



Statistical analysis of fossil, climate and crop data using canonical correspondence analysis showed that ~65% of all changes in past fossil records were statistically related to changes in climate and agricultural practices. In particular, salty lake conditions were negatively associated with past crop production, particularly flax and spring wheat. Other important climatic variables included annual evaporation (calculated in August), Palmer Drought Index (in Sept), annual Standard Precipitation Index (SPI) and cumulative departure from long-term precipitation patterns. This simple analysis shows clearly that there is a strong statistical relationship between past changes in climate, crops and diatoms during the 20th century. Similar, statistically-significant relationships were also recorded for all other study lakes.



The relationship between past lake salinity and agricultural production can be best presented by comparing historical production of flax or wheat (red line) with lake saltiness as estimated from analysis of fossil diatoms (blue). Crop production was significantly and inversely related to lake salinity, confirming that fossil analyses are reconstructing agriculturally-relevant climatic events. High inter-annual variability in crop production and lake chemistry reflect the fact that more than just water availability regulates these two factors (e.g., pests, timing of precipitation etc.).

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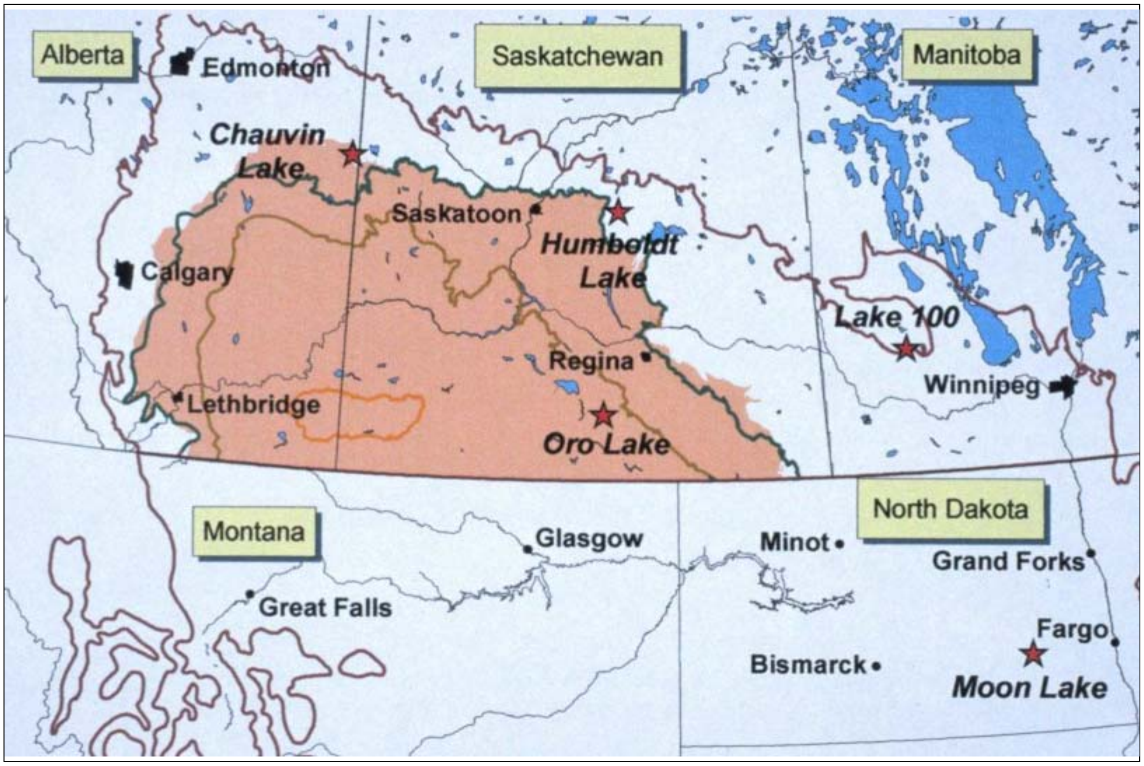
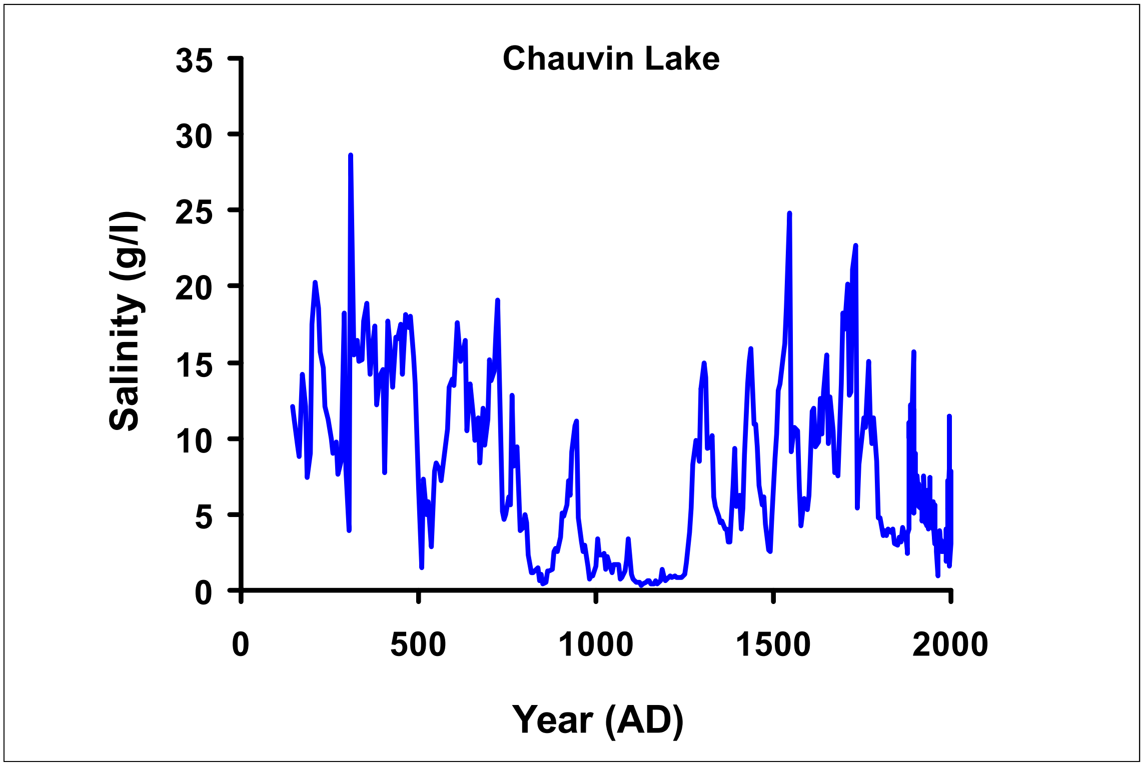
4. Compare risks along landscape gradients.

Having established that our fossil reconstructions accurately record past climatic conditions and that these conditions influence agricultural production, we sought to use our fossil diatom procedures to measure past drought occurrence (objective 2). Once past drought characteristics were described, we used this information to estimate the risk of future droughts (objective 3).

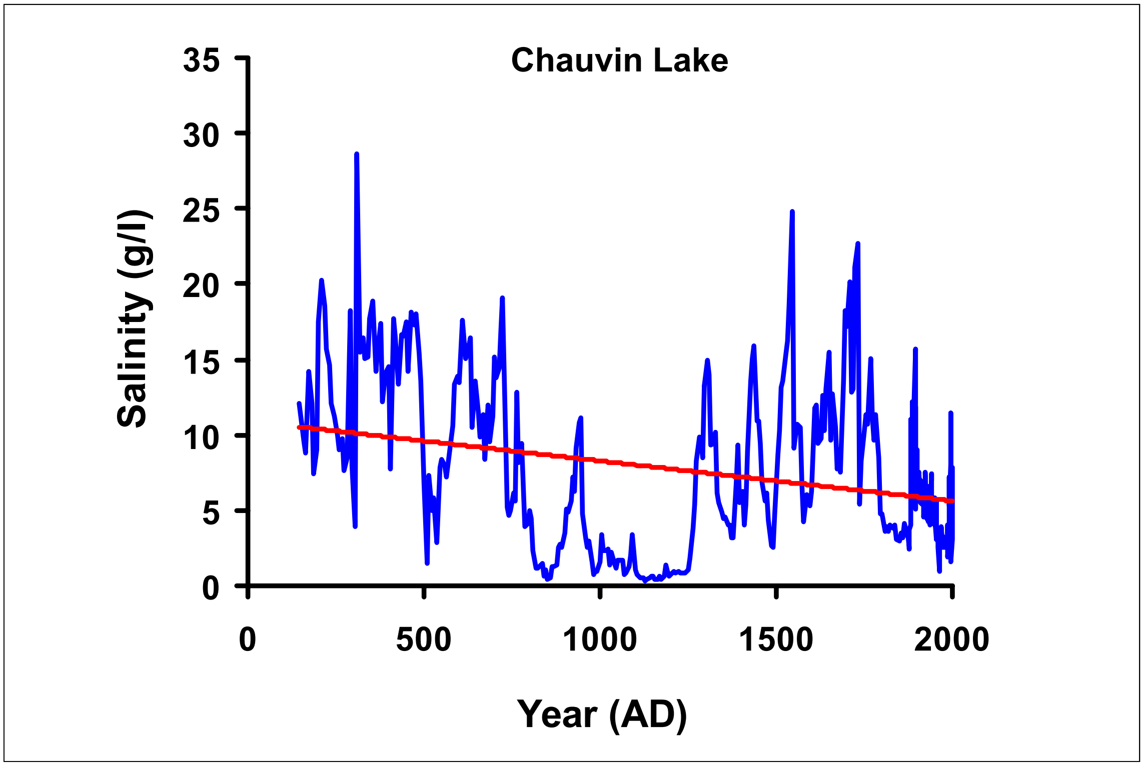


As an example our approach, we will use the fossil record from Chauvin Lake Alberta to illustrate our methods. Chauvin Lake is located in east-central Alberta, southwest of the city of Edmonton, Alberta, and west of the city of Saskatoon, Saskatchewan. This site is situated within the Prairie ecozone (purple line), at the edge of the short grass region (tan region). Chauvin Lake is located in the Battle River drainage, a region which has been experiencing precipitation shortfalls during the past 5-10 years. Comparison among sites shows that this site has experienced a higher than average drought frequency, and may be considered a 'worst case scenario'.

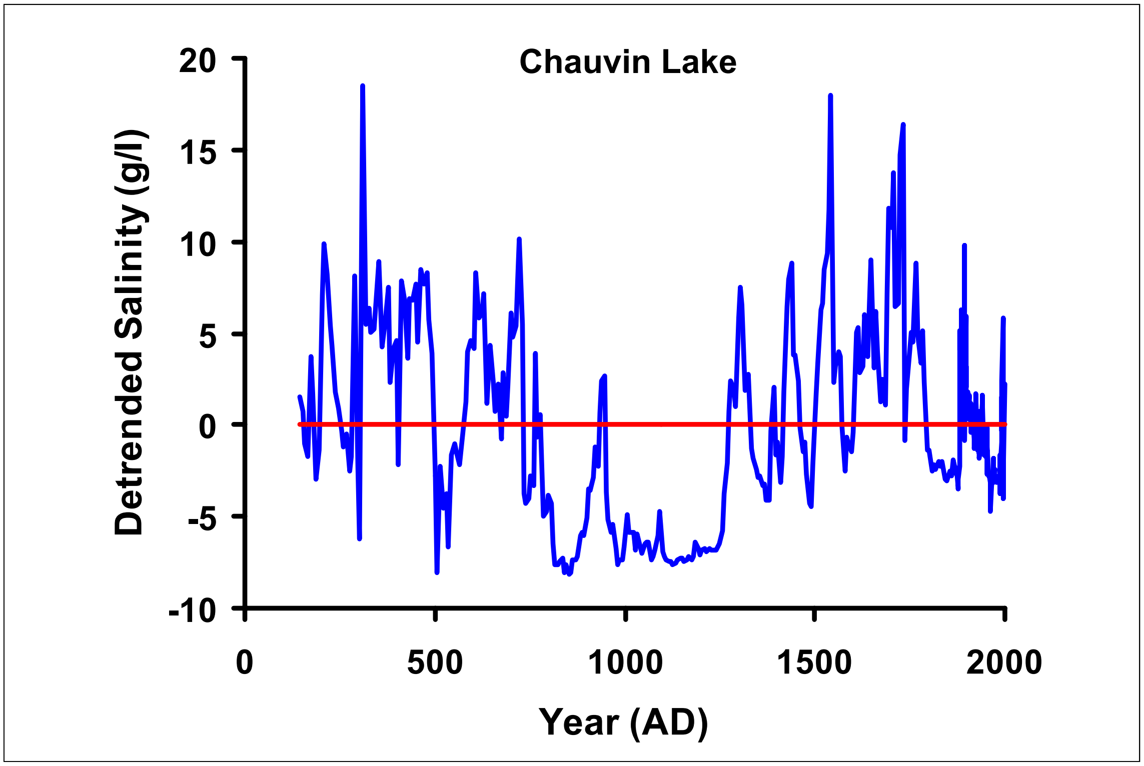
Chauvin Lake is ideally suited for climatic research because it is located within a very small effective drainage (see above) that is tightly linked to past climatic variability. Analysis of aerial photographs between 1940 and the present demonstrate that lake levels have varied in accordance with historical changes in precipitation. Cores of lake sediments were collected from the western basin of the lake using standard procedures and sediments were cut into fine interval sections (2.5 mm thick). Each interval was equivalent to 3-4 years of lake history.



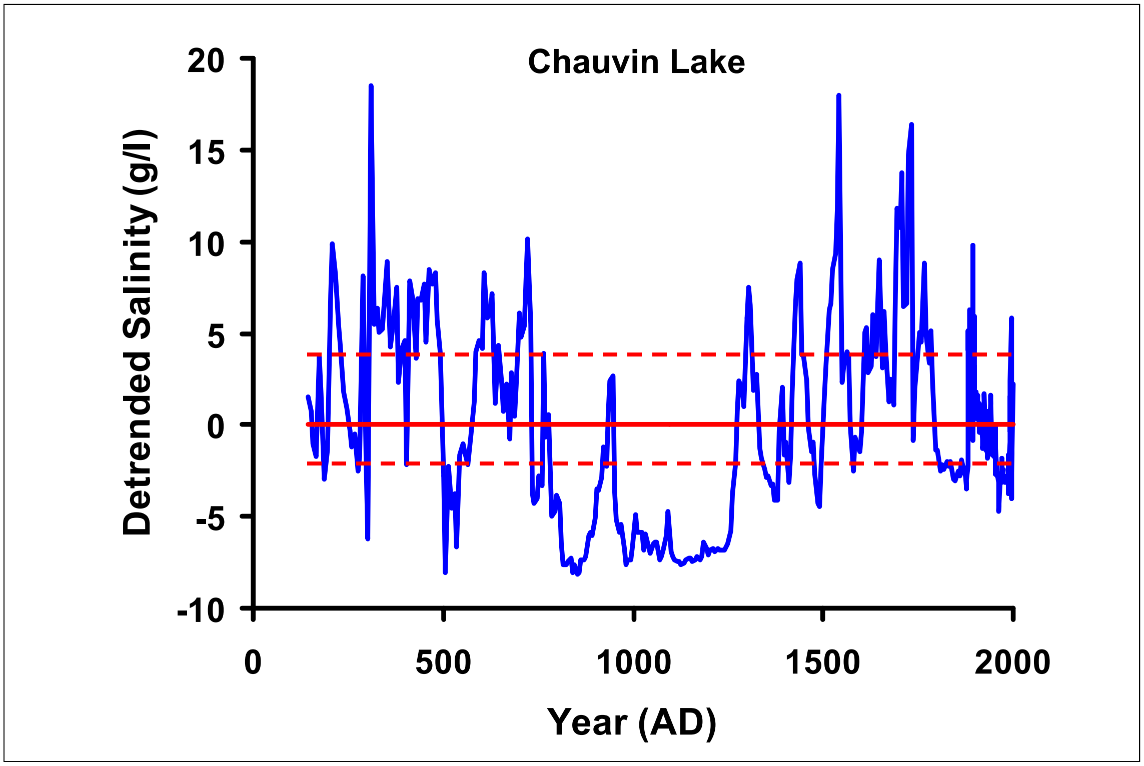
Fossil diatoms were analyzed in each sediment level and changes in species composition were used to reconstruct past changes in lake water chemistry (blue line above) and lake depth (not shown; see final report). Analysis of past changes in chemistry show that the lake water saltiness has varied from virtually pure freshwater to salinities almost as concentrated as those found in the world's oceans (i.e., 33 g/L). In our analysis, very salty conditions represent past drought-like climatic conditions, whereas very fresh waters suggest an excess of precipitation. In all cases, sediment age was determined by analysis of several naturally-occurring radioisotopes, including 210-Pb and 14-C.



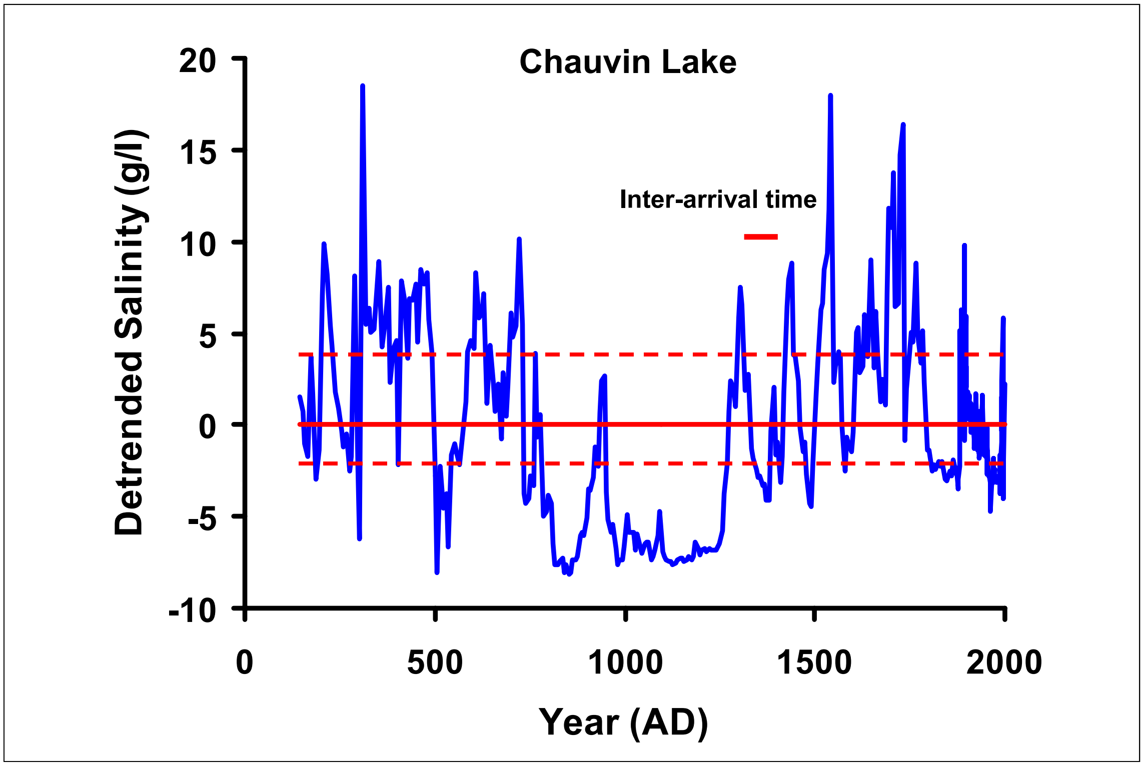
In order to measure the occurrence of past droughts, and to determine their past frequency to forecast future drought occurrence, we first removed long-term trends in lake chemistry data which did not relate to the extreme events of interest (droughts or floods). The first step in this ‘detrending’ procedure was to fit a linear regression, then remove the regression trend from the series of observations.



The detrended data was then examined for the presence of extreme events.



In our project, drought conditions were assumed to occur whenever lake saltiness exceeded that recorded during 1988-1989 (marked with the upper red dashed line), the last widespread drought on the Prairies. Agricultural losses exceeded 50 billion US dollars during that drought. Consequently, salinities which exceeded this critical level represent periods of major financial loss, with significant social consequences. Similar criteria were used to calculate critical salinities characteristic of potential flooding conditions (lower red dashed line).



Of the many drought characteristics measured, the time between droughts (called an *inter-arrival time*) was the most important for quantifying past drought behaviour and for forecasting future risks of severe droughts. In particular, we sought to describe the distribution of past inter-arrival times, in order to predict the next occurrence of a severe drought.

Weibull Model

$$f(x;\alpha,\beta) = (\beta/\alpha)(x/\alpha)^{\beta-1}\exp\{-(x/\alpha)^{\beta}\},$$

$$0 < x, 0 < \alpha, 0 < \beta.$$

α = scale parameter

β = shape parameter

x = inter-arrival time

Maximum likelihood parameter fit

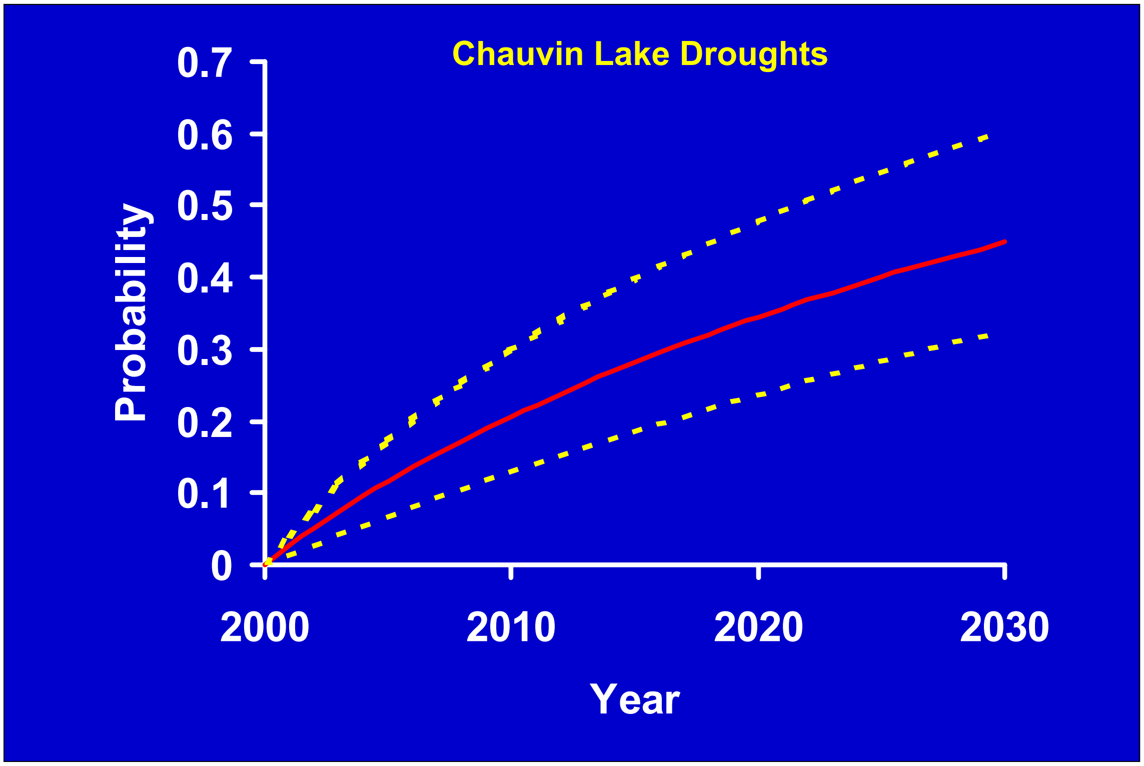
The statistical characteristics of past droughts and their inter-arrival times were measured using a Weibull model, a standard model developed in the manufacturing industry and which is often used to measure flood behaviour (e.g., to determine flood frequencies, such as 1-in-100 year events).

Conditional Probability Analysis

$$P(X \leq y^{*}X \geq y_0) = \frac{\exp\{-(y_0/\hat{\alpha})^{\beta}\} - \exp\{-(y/\hat{\alpha})^{\beta}\}}{\exp\{-(y_0/\hat{\alpha})^{\beta}\}}$$

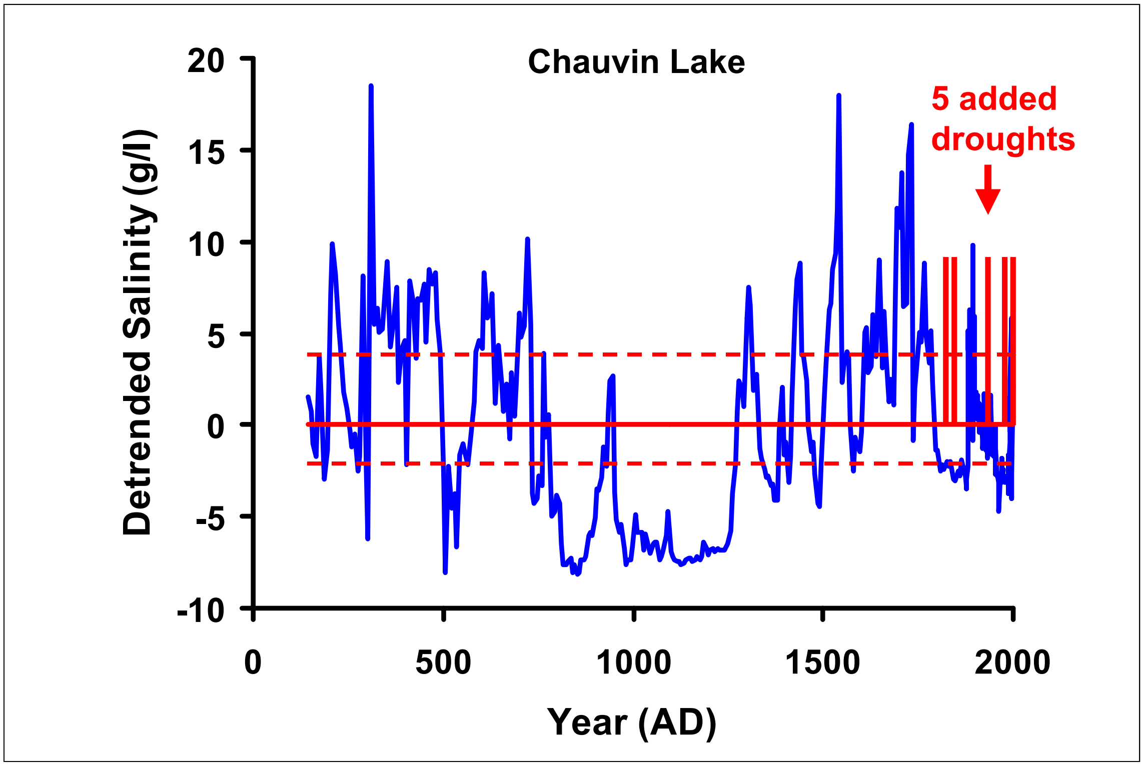
- no droughts since 1988

Once the behaviour of past droughts was described with a Weibull model, the probability of a future event (*P* above) was calculated using a conditional probability analysis. In our example, the ‘condition’ is that there has not been a drought since 1988-89. Once the behaviour of past droughts was described with a Weibull model, the probability of a future event (*P* above) was calculated using a conditional probability analysis. In our example, the ‘condition’ is that there has not been a drought since 1988-89.



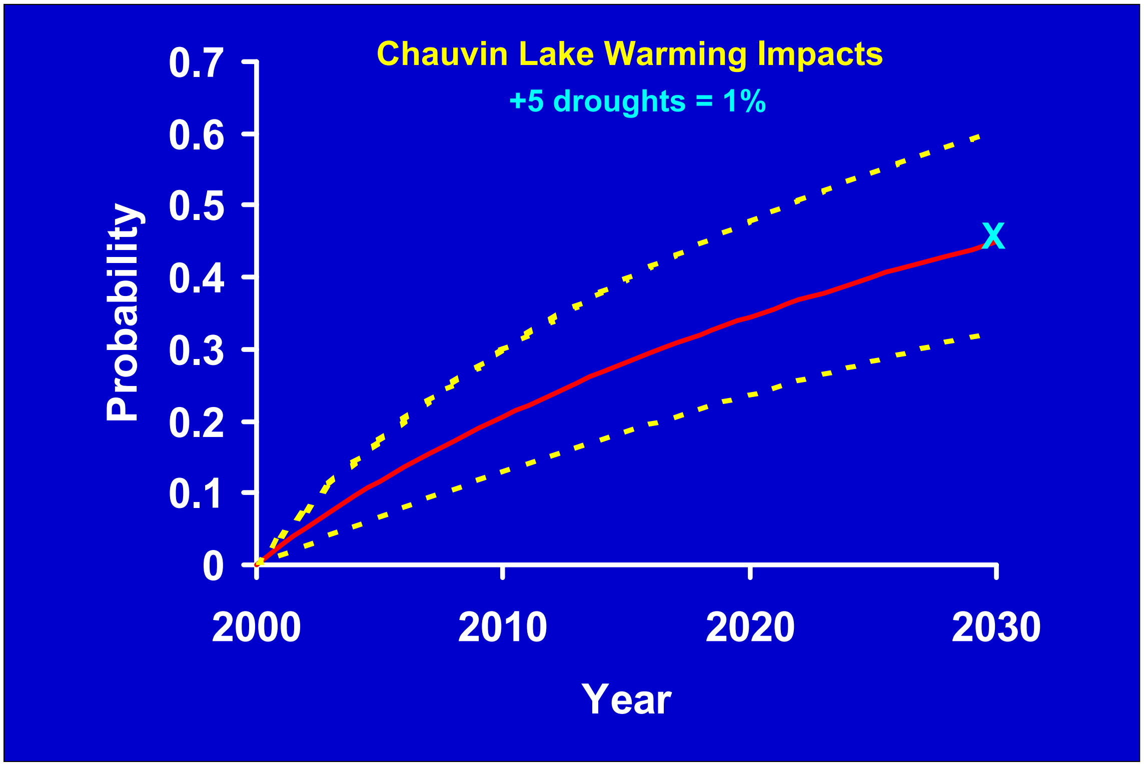
Risks of future droughts as bad or worse than that of 1988 were estimated for each of the next 30 years from 2001 AD until 2030 AD (red line above). In addition, we randomized our time series (history) 1000 times and recalculated the risk of future droughts for each new sequence to determine whether our observed risk could have arisen by chance. This analysis also provides a 95% confidence interval for each years' prediction (yellow dashed lines above). While the true probability of a future drought can never be known perfectly, this analysis allows us to determine that the true risk lies between the upper and lower dashed lines 95 times out of 100.

Our analysis shows that droughts can occur in any given year. As time progresses, the likelihood of their occurring increases, such that by 2030 AD, there is a 45% chance that a drought will occur which costs Canada over $1.5 billion dollars. This probability might be as high as 67% but is no lower than 33%.

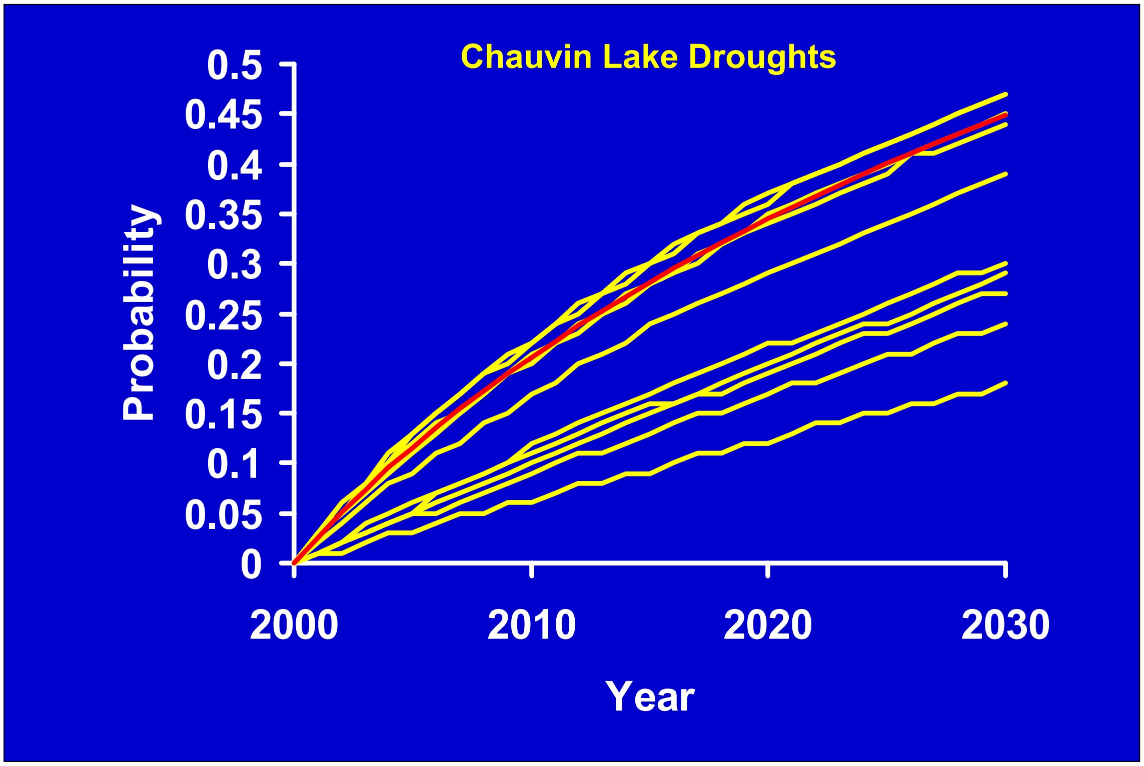


Our analysis are conservative because we have detrended the historical record, and because we cannot directly account for the possible impacts of future global warming. However, it is also possible to mimic the *effects* of increased drought frequency arising from such warming by adding artificial droughts to the observed record.

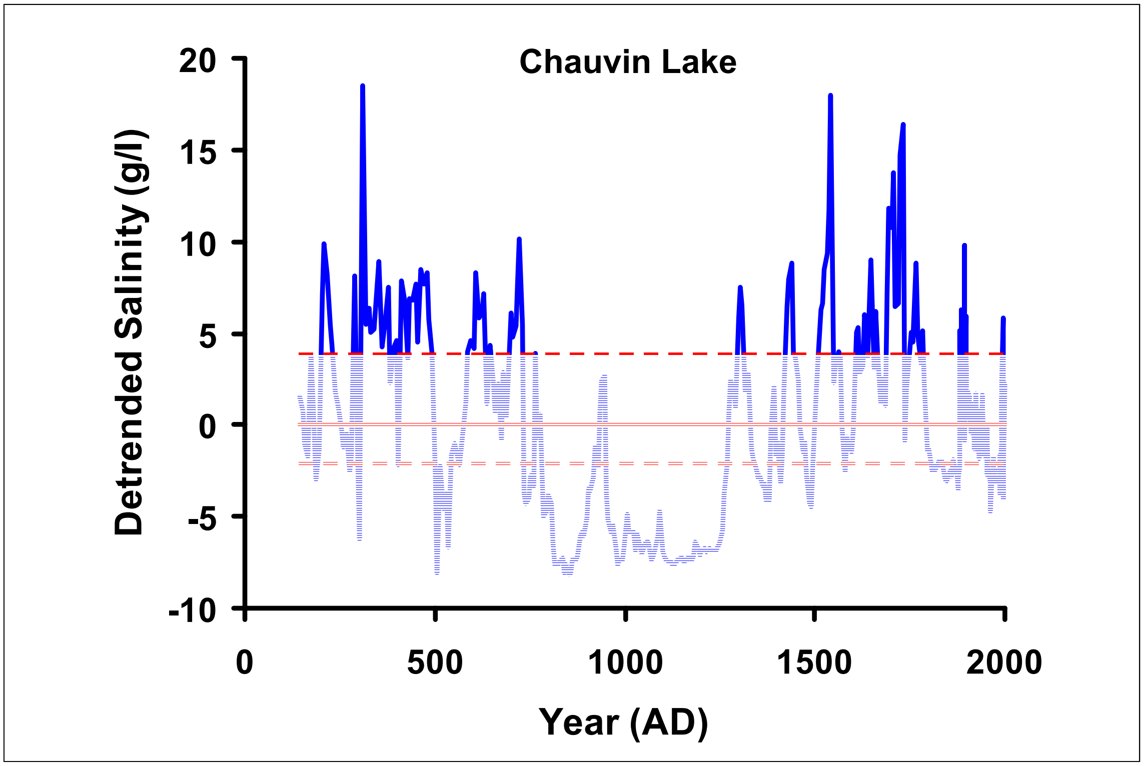
For example, the addition of 5 droughts to the past 150 years was used to model an extreme instance of increased drought frequency. This addition represents at least a doubling of the highest observed natural drought frequency, and represents a likely 'worst case scenario' for near-future changes in climate. We then recalculated the risk of future critical droughts for the year 2030 AD.



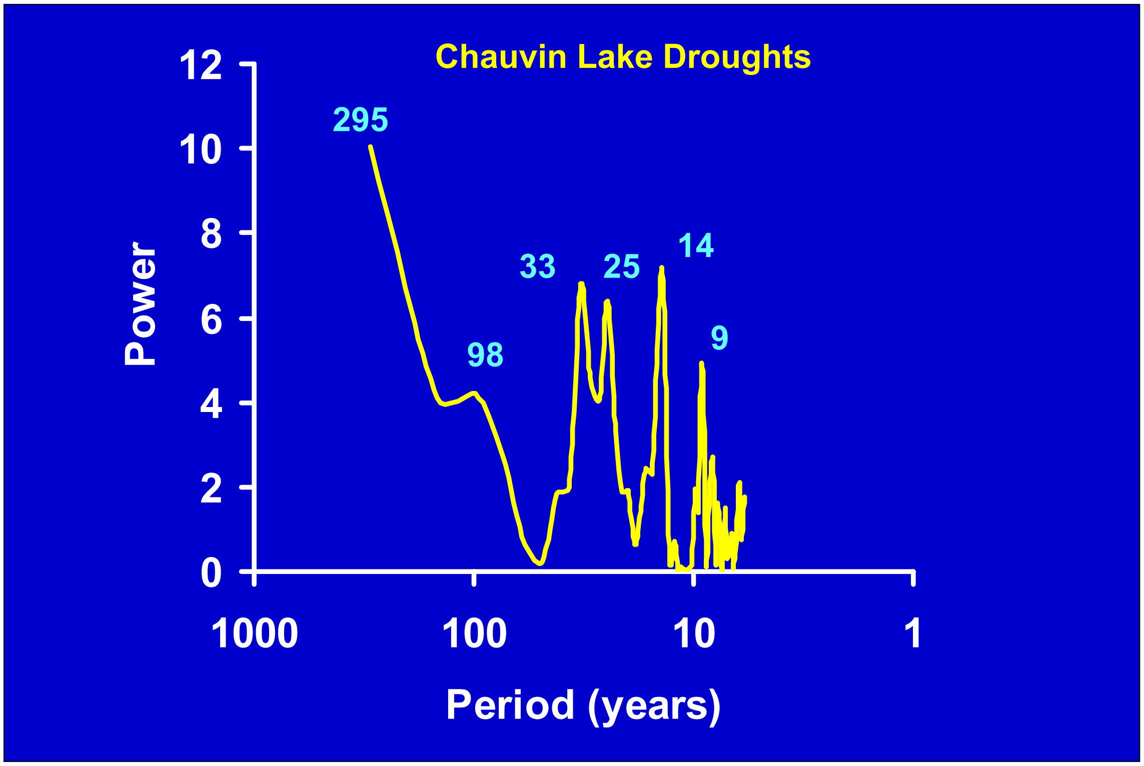
This analysis shows that the likelihood of a severe drought will increase only 1% over 30 years as a result of a doubling drought frequency arising from global warming. This does *not* mean that global warming is unimportant, rather *it means that the variability of drought occurrence is so naturally high that we may be unable to detect the effects of global warming within the next 30 years.* This result arises because drought occurrence is highly variable; hence accurate predictions for any given year will be difficult to achieve.



We also modeled a family of risk curves for droughts of different severity. Overall, we found that the droughts of 1988 (red) and the 1930s (curve below that) were among the *mildest* on record and hence the most likely to occur in the future. In addition, we found that the *most* severe drought on record (40 years long, more severe than the 1930s) had over a 15% probability of occurring within the next 30 years. Presently, Canada has no adaptation plan suitable for dealing with such an extreme event.



Finally, we sought to determine whether these extreme droughts exhibited any cycles that might be useful in predicting their recurrence. To model this periodicity, we first *censored* the historical data to eliminate all observations that were below the critical drought salinity (matted white area). In their place, we substituted values equal to the critical salinity itself (upper red dashed line). Thus, our analysis focused only on the behaviour of the extremely high salinity events (i.e., droughts), and did not consider cycles that may arise from different causes.



This analysis of cycles (Fourier Spectral Analysis) demonstrated that significant periodicity did exist in past drought behaviour. Further visual analysis (above) suggested that several cycles might be present, including those potentially arising from lunar, solar, oceanic and other, longer-term, forcing functions (causes).

Chauvin Lake Drought Statistics

Mean inter-arrival time	**60.5 yr**
Std deviation	112.7
Mode	None
Maximum	569
Minimum	1
Number of droughts	**25**
Duration	**11.8 yr**
Std deviation	13.2
Mode	1
Maximum	45
Minimum	1
Period	**98 yr, 295 yr** $P < 0.001$

Basic statistical analysis revealed that droughts lasted almost 12 years on average, but that ~60 years elapsed between major events. During the past 2000 years, 25 major droughts were recorded in eastern Alberta, the longest of which was ~45 years in duration.

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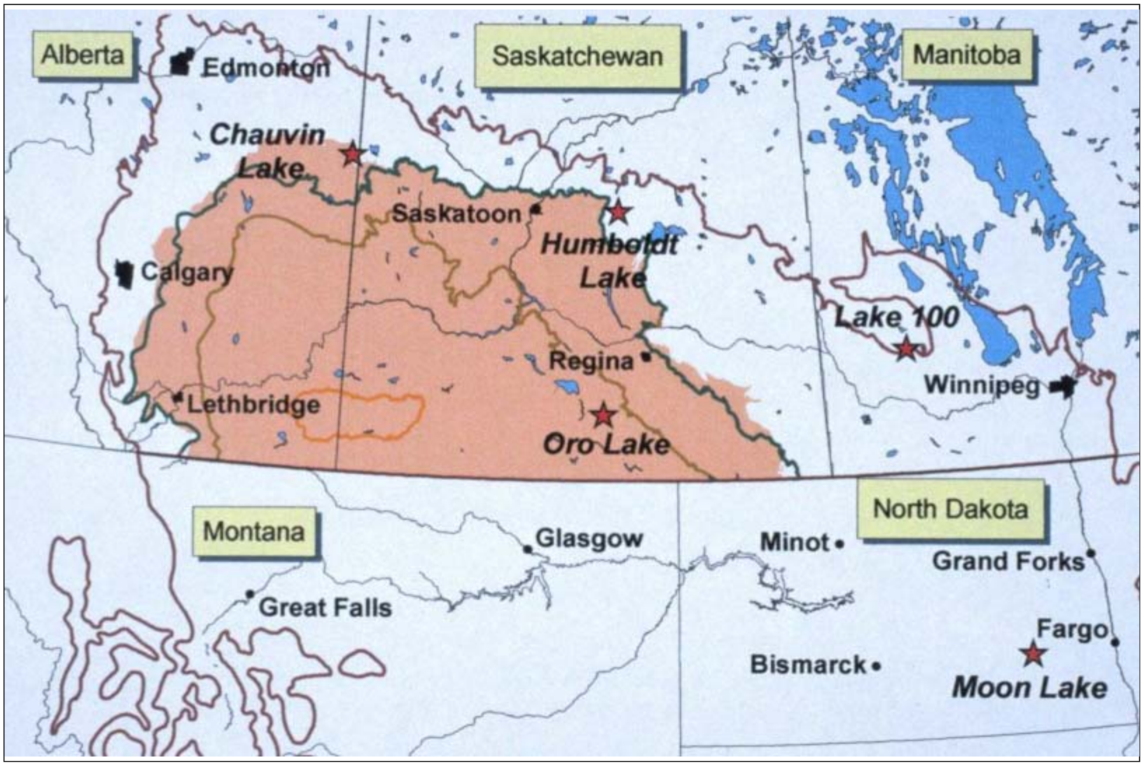
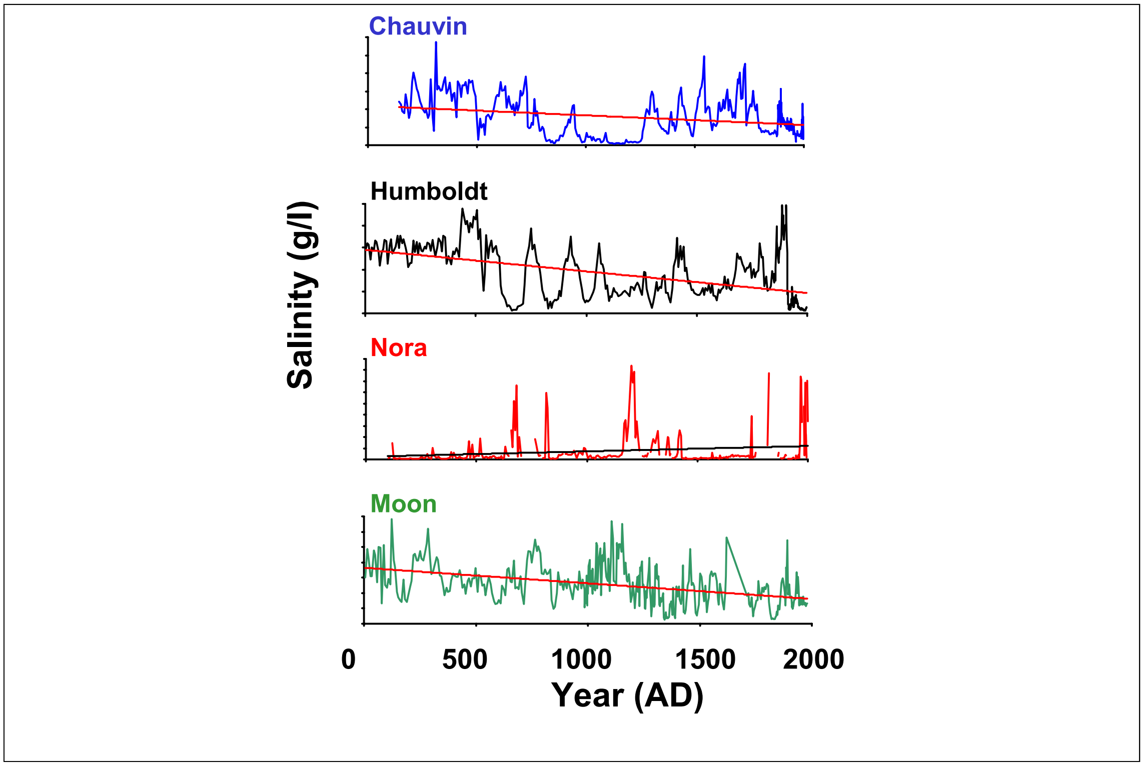
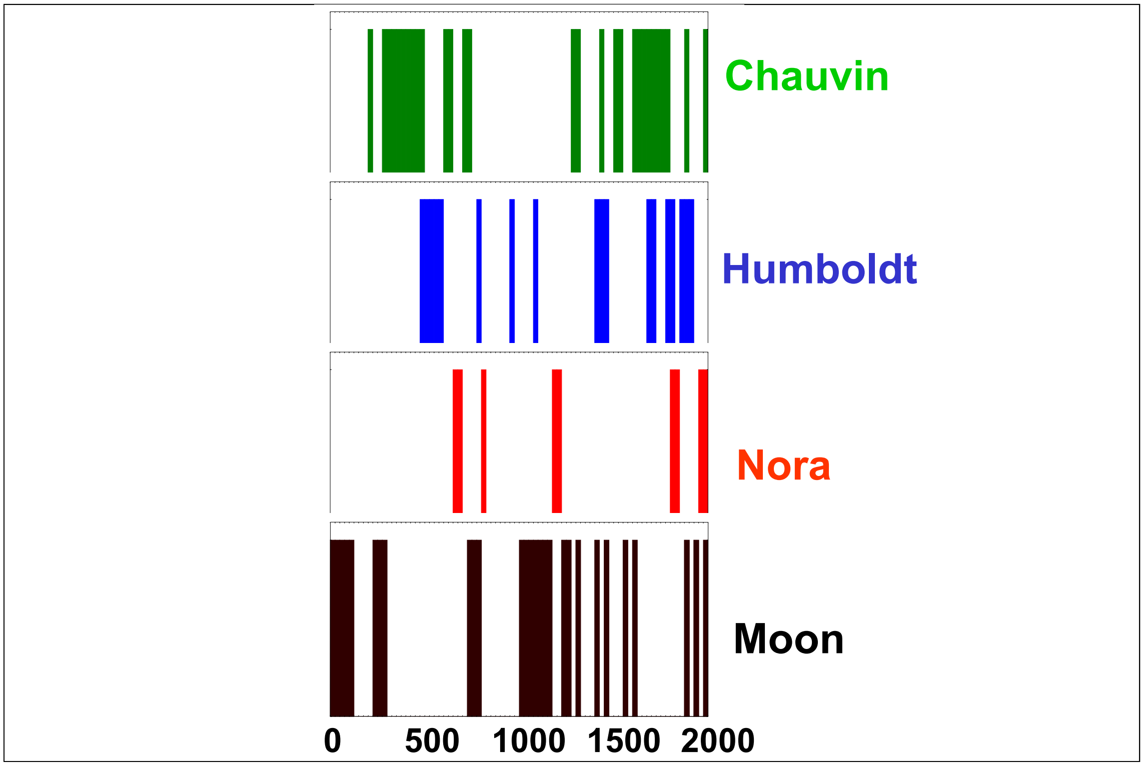
Analyses at any given site provide insights on the history past droughts and on the risk of of their recurrence. However, to gain a better perspective of the potential impacts of droughts on the Prairies, we compared the results of our risk assessments among our four main analytical sites.



Drought reconstructions were attempted at Chauvin Lake (AB), Humboldt Lake (SK), Nora Lake (MB) and Moon Lake (ND). In addition, we plan on extending our analyses to Oro Lake, Saskatchewan. All primary sites (red stars) lie near the margin of the northern Great Plains in regions where agricultural production is subject to periodic shortages of precipitation. These sites were selected from an initial survey of ~100 lakes as those with the best combination of demonstrated climatic sensitivity and preservation of an undisturbed fossil record.

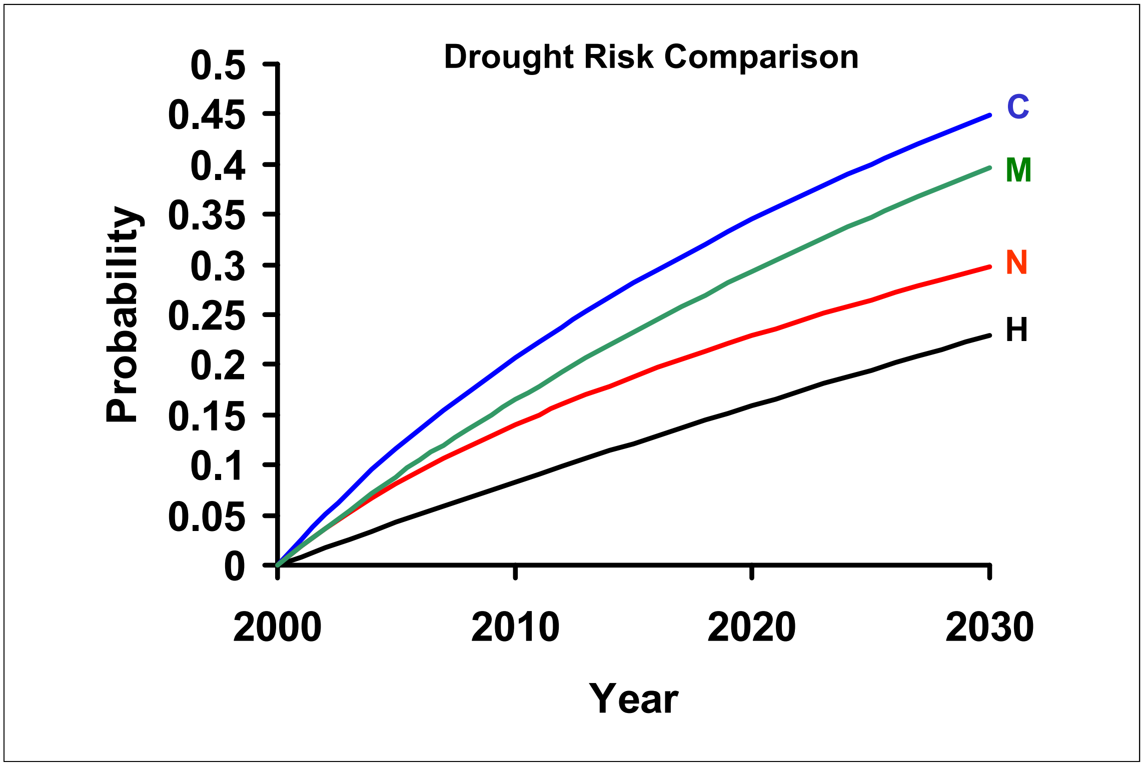


Comparison of historical changes in lake salinity among sites reveals striking differences in past lake chemistry and drought events. Three of four sites were characterized by high salinities in the distant past, and relatively benign present-day conditions (Moon, Humboldt, Chauvin). In contrast, Nora Lake MB was historically a freshwater system, which has only occasionally experienced water shortfall. Interestingly, recent lake conditions in Manitoba are indicative of low water availability since 1960 consistent with modern climatic observations.

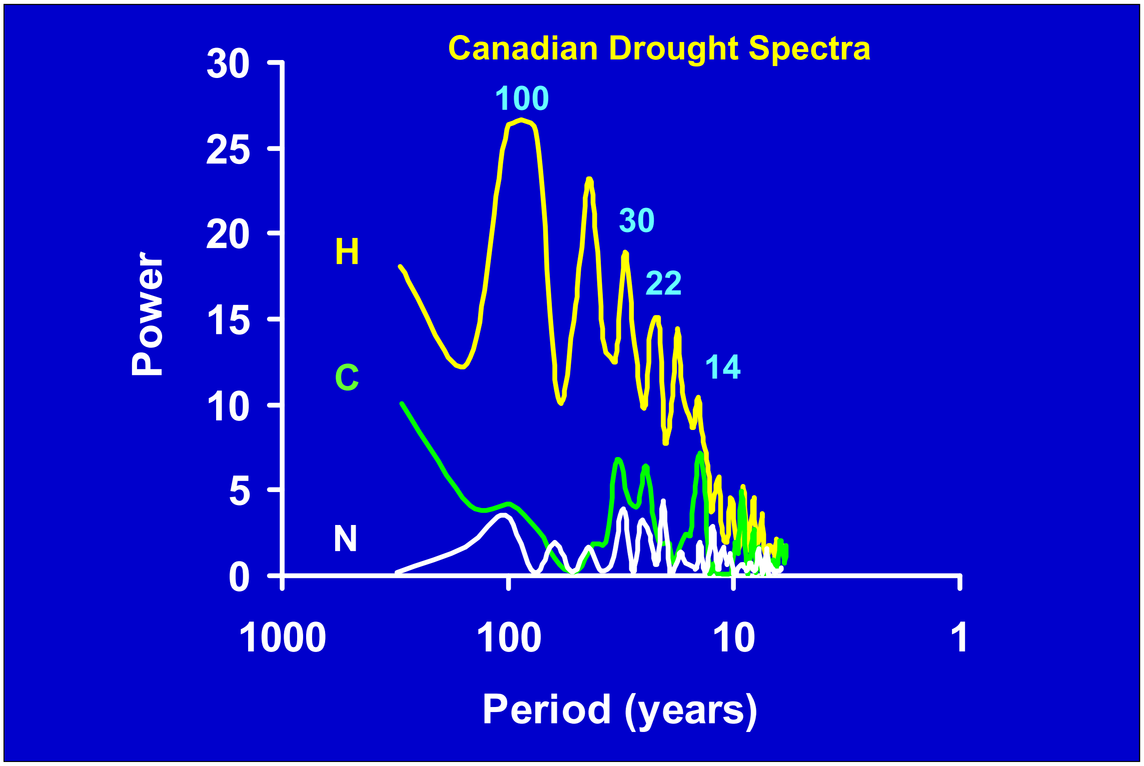


In order to better visualize the relationship among droughts at different locales, we converted the time series into a series of ‘bar codes’ which are easier for the human mind to interpret. For this analysis, the past 2000 years was divided into 25 year intervals. If a significant drought as bad or worse than that of 1988-1989 occurred in an interval, it was heavily coloured. If no drought occurred, the interval was left blank.

Comparison of drought occurrence among lakes shows that while some droughts seem to occur simultaneously at most locations (e.g., 1860-1890s), most droughts are characterized by patchy distributions (occur at some sites, but not all). Thus while prairie-wide droughts can occur, most events usually exhibit high variation in intensity among regions.



When risks of future droughts are compared among sites, we see that eastern Alberta and North Dakota are much more likely to experience severe droughts than are central Saskatchewan and western Manitoba. However, we point out that even in the case of the least drought-prone site (Humboldt Lake, SK), there remains at least a 23% (+/-15%) probability that a economically-significant drought will hit by 2030 AD. Further, our statistical analysis shows that such droughts could occur in *any year* with serious economic consequences (>$1 billion in losses in Canada).



Comparison of time series analyses among sites also shows that there are some common cycles of droughts at all Canadian sites, although not all cycles were statistically significant. For example, cycles characteristic of solar, lunar, oceanic and other, longer-term, factors are present in our drought records. Regardless of the precise control mechanisms causing the cycles, it is important to recognize that relatively little of the total variation in past drought occurrence can be explained by the presence of such cycles (<10% of total variance). Instead, we emphasize that past droughts are characterized by extremely unpredictable behaviour, and that devastating droughts could occur in any given year. Consequently, we believe that drought behaviour is best modeled as a probabilistic (i.e. chance) event, rather than as an event that exhibits strong cycles

Drought Statistics

	Chauvin	Humboldt	Nora	Moon
Mean inter-arrival	**60.5**	**117.0**	**161.1**	**63.4**
Std deviation	112.7	109.0	220.3	95.9
Mode	None	14	None	10
Maximum	569	342	610	442
Minimum	1	14	5	5
Number of events	**25**	**11**	**8**	**29**
Duration	**11.8**	**13.3**	**5.3**	**5.5**
Std deviation	13.2	23.2	6.5	7.9
Mode	1	1	1	1
Maximum	45	71	20	31
Minimum	1	1	1	1
Period	**98, 295***	**44, 103, 302***	30, 101	**63, 158***

Comparison of drought statistics among sites shows a strong west-to-east gradient within the Canadian Prairies. For example, average inter-arrival time increases, while the number of significant droughts declines as we move from dry Alberta into more humid Manitoba. Similarly, the duration of these events declines from over a decade to ~5 years in length. Interestingly, there are significant long-period cycles of droughts present at all Canadian sites (e.g., 100 years) suggesting the possible presence of a common forcing mechanism. When combined with state-of-the-art models of atmospheric circulation, the presence of these cycles may provide an important clue to the factors ultimately responsible for past and future droughts.

Conclusions

1. **Severe droughts are a natural feature of the Prairies. Extreme droughts (e.g., 1930s) occur every 60-100 years, with 23-45% probability of occurring by 2030.**

2. **Most droughts are long-lasting (5-10 year duration).**

3. **Extreme events have *some* periodicity. Droughts have 14, 22, 30 and 100 year cycles. Floods have 25, 50 and 300 year cycles.**

4. **Future climatic warming will increase drought likelihood. However, given variable drought frequency, risk of occurrence will change little over the next 30 years.**

Overall, our analyses demonstrated that severe droughts are a natural feature of the Prairies. Extreme droughts, such as those of the 1930s, seem to occur every 60-100 years, with 23-45% probability of occurring again by 2030 AD. Economic losses associated with such an event are expected to greatly exceed $50 billion US dollars in North America. By contrast, this is equivalent to 10 times the total annual value of all west coast North American fisheries (e.g., salmon, shellfish, etc.).

Although past droughts have exhibited some cycles characteristic of solar, lunar and atmospheric-ocean causal mechanisms, very little of the total historical variance in drought occurrence is directly linked to these cycles. Consequently, we feel that adaptation strategies should focus on the probability of future droughts, and less effort should be invested in determining the phase of the drought cycle.

Finally, we point out that, while it is likely future global warming may lead to an intensification of drought cycles, the high inherent variability of natural droughts may well mask this effect for at least 30 years.

What does the future hold? Based on the results of the Prairie drought project, we have attempted to summarize our main findings, and to point out their implications for life on the Prairies.

Implications

1. **Strong correlation between reconstructed climate and crop production shows that risk forecasts are most relevant to the Prairie agricultural sector.**

2. **Common drought and flood cycles suggest continental-scale causal mechanisms. Cycle periods indicate lunar (14-18 y), solar (20-25 y), Pacific Ocean (60-75 y) and other (300 y) participation, but not ENSO (4-7 y).**

3. **Similar geographic gradients of drought risk and modern climate suggests that basic climate controls have varied little through last 2000 y.**

First, it seems evident that our risk analyses are directly relevant to Prairie agriculture and overall societal organization. Strong and consistent correlations between fossils, climate and crop production at all sites confirm that our study lakes are recording historical changes in climate that can influence farm economy. This economy remains the basis for regional economic development in western Canada.

Second, our analysis points to the possible presence of common large-scale factors that help start or reinforce droughts. In particular the presence of characteristic cycles at all Canadian sites suggests the influence of solar, lunar and oceanic control mechanisms. Although El Nino (ENSO) signals were not detected in our analysis, they lie near the limit of our temporal resolution, and hence may not be as easily detected as some of the other cycles.

Third, the fact that future drought risk is higher in the presently-dry western Canadian sites than in the presently-humid eastern sites suggests that the basic factors controlling overall climate have not varied much during the past 2000 years. This observation is consistent with the role of the Rocky Mountains in blocking the flow of moist Pacific air into the continental interior and reflects the geographic structure of western North America.

Implications (continued)

4. **20^{th} century climate was benign. Global warming may return the Prairies to past, higher drought frequency. Severe droughts of the 19^{th} century may be the best model for expected impacts.**

5. **Coherent prairie-wide droughts can occur (e.g., 1890s), but intensity varies with locale. Network adaptation strategies are recommended (e.g., inter-provincial crop insurance, PFRA *et al*).**

6. **Drought onset is usually rapid and may prevent effective *ad hoc* adaptation to prolonged events (e.g., 1930s).**

A critical finding of our analysis is that 20^{th} century climate was relative humid. Extrapolation of this result therefore suggests that global warming may return the Prairies to past, higher drought frequencies. Consequently, we suggest that the severe droughts of the 19^{th} century (1860-1890s) may be the best model for expected impacts for future droughts. Availability of accurate models of climate impacts may be a critical step in determining Canada's ability to adapt to future climatic change.

One aspect of this adaptation is the formation of infrastructure that is appropriate to severe drought events. We propose that two approaches should be considered. First, because droughts are naturally patchy, we suggest network adaptation strategies will be more effective than site-by-site adaptation or management strategies. For example, the formation of a prairie-wide crop insurance program might be the most effective way to disperse risk of severe drought impacts over a wide, but economically relevant, base. Such strategies are commonly used by reinsurance companies used to dealing with catastrophic losses (e.g., Hurricane Andrew and Miami), and may be appropriate for prairie agriculture. Similarly, we feel that there should be reduced reliance on *ad hoc* relief measures, mainly because such programs cannot be sustained for the duration of a decade-long (i.e., average) drought. Instead, we feel more effort needs to be expended on identifying the cause of droughts, and possible means of reducing their long-term impacts on economy and society.

Implications (continued)

7. **Droughts can last decades. Adaptation should be to multi-year events.**

8. **Droughts will reduce both the quantity and quality of surface waters.**

9. **Despite high probabilities of future droughts (45% by 2030), risk assessments may be conservative because of peripheral location of sites.**

Adaptation measures must be carefully tuned to the environmental conditions that will occur during the prolonged drought events. For example, because most historical droughts lasted over a decade, adaptation plans need to consider the effects of permanent loss of income on prairie farmers. Similarly, counteraction measures must consider the possibility that both the amount and quality of surface waters will decline during these droughts, and that water storage technologies (dams, dugouts, etc.) may not be viable management options.

Finally, despite the high probabilities of future droughts (up to 45% by 2030), our risk assessments may actually underestimate drought risks on many areas of the southern Canadian prairies and the northern United States. Our research sites represent a compromise between the highest quality fossil records and our ability to find suitable locations within the time provided by our funding agencies (NSERC, AFIF). As a result, our lakes do not lie in the driest regions of the prairies. In the future, our approach should be expanded to included extremely drought-prone regions of southern Alberta and Saskatchewan, as well as more intermediate sites. Together with the analyses presented above, this network should provide a realistic estimate of the impacts of past and future droughts on the Canadian Prairies.