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A statistical procedure to determine recent climate change of extreme daily meteorological data as applied at two locations in Northwestern North America

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Abstract An iterative chi-square method is applied to determine recent climate change of extremes of daily minimum temperature at two locations between an 18-year recent period and a 36-year prior period. The method determines for each of two locations in northwestern North America, Bozeman, Montana, USA and Coldstream, British Columbia, Canada, which values of the extreme daily weather elements are most significantly different between the prior years and the recent years and gives a measure of the weekly significance of that difference. Determination was made of the average percent of each recent year date (plotted weekly) that was impacted by extreme weather due to climate change as well as the percentage change in the frequency of the number of extreme days for each period of contiguous significant weeks. During the recent period at both locations, most weeks experienced a greater number of days of extreme high minimum temperature and a fewer number of days of extreme low minimum temperature. The weekly percentage changes indicate that extreme high minimum temperatures at both Bozeman and Coldstream are increasing at the rate of about 10% per decade, with a close corresponding decrease of extreme low minimum temperatures. The major changes in climate were very similar at both locations, with greatest warming occurring during the late winter and early spring and during the late July to August period.

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1 Introduction

Numerous analyses of historical weather records have been made to determine recent climate change. Those studies typically analyzed mean monthly or mean annual weather data to detect change of temperature and/or precipitation over the period of study. Although monthly resolution is usually sufficient to indicate general seasonal patterns, the approach may miss "natural" seasons whose intervals or break points do not coincide with monthly boundaries. Also, while monthly anomalies are important, it is the daily extremes of weather that often have the greater impact on plants, animals and on human health and activities.

Climate change analyses of extreme daily temperature and/or precipitation can be found in the literature. One such study was made by De Gaetano (1996) who did an analysis of the trend of a selected number of extreme high and extreme low daily maximum and minimum temperatures at 22 locations in northeastern United States. De Gaetano analyzed three extreme high and three extreme low daily occurrences of both maximum and minimum temperature. He applied Monte Carlo techniques to assess the statistical significance applied to Students *t*-tests that were used to evaluate standardized time series. This approach differs from De Gaetano's in that this statistical method determines for each week of the year which particular extreme of daily temperature are significantly different in the recent period of years compared to the prior period of years.

Caprio (1966) first described the conceptual bases and the procedure for the iterative chi-square statistical method. The technique was subsequently applied to identify periods of weather that critically impacted small grain and rangeland production in Montana (Caprio and Williams 1973) and the conditions that contribute to winterkill of winter wheat (Caprio and Snyder 1984; Kalma et al. 1992). The statistical procedure was also adapted to determine the association of daily weather occurrences with fruit production in British Columbia (Caprio and Quamme 1999, 2002, 2006) and with tree ring growth in Arizona (Caprio et al. 2003). The iterative chi-square statistical method was used in the grape study (Caprio and Quamme 2002) to determine changes in daily maximum and minimum temperatures and precipitation over a 56-year period in the Okanagan Valley of British Columbia (Caprio and Quamme 2002). These research studies have demonstrated that the iterative chi-square method is a useful procedure for determining critical threshold values and for generating measures of significance. Here we further extend the use of the iterative chi-square method in climate change analyses to include percent change in extreme daily weather events by demonstrating its application in the analyses of daily extremes of minimum temperature at two sites.

The lowest temperature recorded during a 24-h period is referred to as the minimum daily temperature. Relative to the normal (or average) minimum daily temperature for a particular day, the daily minimum temperature can be extremely high or extremely low. This study considers the occurrence of both extreme high and extreme low daily minimum temperatures. The analytical procedure determined the weekly significance of the difference between the number of extreme high or extreme low daily minimum temperature occurrences between a 36-year prior period and an 18-year recent period for Bozeman, Montana and for Coldstream, British Columbia. The study also determined the average percent or fraction of each day within each week of the year that is attributable to climate change due to extreme high or extreme low daily minimum temperatures.

For many activities it is important to know which particular extremes of daily temperature and/or daily precipitation have become more or less frequent and when during the year such changes had occurred. Of particular interest in the results of this study is the close correspondence of the derived climate changes between the two locations, even though they are 800 km apart and on opposite sides of the Continental Divide

2 Methods

The data for the study were for the climate stations at Bozeman, Montana, (45° 40′ N, 111° 03′ W, elevation 1,480 m) and Coldstream, British Columbia (50° 14′ N, 119° 12′ W, elevation 482 m). The analysis was made of daily minimum temperatures for the 54-year periods, 1947–2000 at Bozeman and 1938–1991 at Coldstream. The weather station at Coldstream remained at the same location during the length of this study. It is ideally situated for climate change study, being located in a rural ranch setting. Weather observations for all 54 years of the Bozeman study were made at one site on the Montana State University campus except for 5 years, when parts or all of those years were made at two other sites on the university campus. Both the Coldstream observation site and the principle Bozeman observation site possess attributes consistent with providing homogeneous daily minimum temperature records, including long periods of daily weather observations at the sites, unchanged open exposures and non-urban environments. Computer analysis for the Coldstream station used in this work had already been generated for three previous studies (Caprio and Quamme 1999, 2002, 2006) to determine weather impacts on fruit production in the Okanagan Valley of British Columbia and to evaluate the potential impact of climatic change. The 54-year period (1947–2000) was chosen for the Bozeman study since it included the most recent period available for analysis that covers the same number of years as in the Coldstream study.

In this study the iterative chi-square analysis was applied to determine climatic differences at Bozeman between the 18 recent years (1983–2000) and the climate during the 36 prior years (1947–1982). The analysis for Coldstream compared the difference in climate between the 18 recent years (1974–1991) and the climate during the 36 prior years (1938–1973).

This analysis determined the climatic change from the early period to the recent period for both the extreme high minimum temperatures and for the extreme low minimum temperatures. The iterative chi-square statistical method used in this study is the same as that applied in several research papers (Caprio and Quamme 1999, 2002, 2006; Caprio et al. 2003). While those papers dealt with fruit production and tree-ring growth in which the weather during both the good and the poor years was compared with the weather during the normal years, this study determines changes in extremes of daily minimum temperatures between the 18 recent years and the 36 preceding years.

In the first step of this analysis, daily minimum temperatures were sorted from low to high for data sets of both periods of years, i.e. the prior and recent years.

The temperatures, which were recorded in Imperial Units, were broken down into contiguous classes of two degrees Fahrenheit and tallies were made of the frequency with which the variable fell into each class for each of the two data sets. For each 3-week period the chi-square test was applied to the total number of days accumulating in each class in succession ordered from highest to lowest classes (high to low scan) and from lowest to highest classes (low to high scan) generating a chi-square value for each class for both the high-low and low-high scans. For each climatic category of recent years the total number of daily occurrences for each three-week period is 378 (21 days $\times$ 18 years). The total number of days in the extreme category of the prior years is 756 (21 days $\times$ 36 years). The chi-square (χ^2) test is applied to the total number of days accumulating in each class in succession ordered high to low (high-low scan) or low to high (low-high scan) generating chi-square values for each class in both scans. The first chi-square value in the high to low scan is for the data in the first (highest) class, the second for data in the first plus the second (next highest) class, etc. The low to high scan starts with the first (lowest) class.

A sliding window of 3 weeks was used in the analysis, with each period in succession adding a new week and dropping the first week as the 3-week time frame advanced. The χ^2 test thus determines the significance of the difference in frequency of days in the classes between the two data sets. The results were converted to metric units to the nearest degree Celsius.

If the daily minimum temperature count of the 18 recent years deviated from the expected one-half that of the 36 preceding years, the χ^2 values that are generated in each of the two scans increased and then decreased. The temperature at which the χ^2 reached a maximum (or turning) point is referred to as the "cardinal" temperature (CT).

The largest χ^2 value in the iterative scan from lowest to higher minimum temperatures determined which extreme low (equal and less than) most distinguished the climate difference between the early and the recent periods designated by the temperature at the point of maximum χ^2 which was then identified as the threshold temperature, hereafter referred to as the cardinal temperature (CT). The largest χ^2 value in the iterative scan from highest to lower minimum temperatures determined which extreme high (equal and greater than) most distinguished the climate difference between the two periods. Chi-square values are statistically significant at 0.01 ($df = 1$) when the actual value is 6.63. Temperatures in this study are considered significant when the chi-square values are equal and greater than 7 (rounded up from the actual value of 6.63). Chi-square values equal to and greater than the significant level indicate that the sample has less than 0.01 probability of occurring by chance. The hypothesis that the climate is the same during the prior years and the normal years is then rejected. The larger the χ^2 value, the greater the probability that there is a real climate difference between the number of extreme days of the prior years and of the recent years. Highs and lows in the chi-square values, when plotted against time of year, indicate those periods when and at which scale these differences are significant.

The χ^2 measures of probability levels may not be strictly applicable when counts are small (Snedecor 1946), however, χ^2 values encountered at the beginning of the scans tend to be insignificant and superceded by more significant levels further up (or down) in the scan.

The iterative chi-square method determines whether the number of daily occurrences of extreme climate element during the recent period differs significantly from the expected number of occurrences of the extreme climatic element during the prior period. If there is no difference in the expected number of extreme climatic elements, there will be half as many occurrences in the 18 recent years as in the 36 prior years. If the departure of occurrences varies from this 1:2 ratio, it may be random and not indicate a climatic difference. However, if the departure is large, the number of extreme occurrences may differ significantly between recent years and prior years.

To illustrate how the χ^2 value is computed, consider following two examples of high to low scan for extreme minimum temperature of recent versus prior years. The data are presented in Table 1.

In the equation below, A and E represent the actual and expected number of occurrences, respectively. The letters r and p are for recent and prior years, respectively.

$$\chi^2 = \frac{(A_\mathrm{r} - E_\mathrm{r})^2}{E_\mathrm{r}} + \frac{\left(A_\mathrm{p} - E_\mathrm{p}\right)^2}{E_\mathrm{p}}$$

For the first 3-week period in Table 1,

$$\chi^2 = \frac{(110 - 84)^2}{84} + \frac{(143 - 169)^2}{169} = 12$$

For the second 3-week period in Table 1,

$$\chi^2 = \frac{(102 - 133)^2}{133} + \frac{(297 - 266)^2}{266} = 11.$$

The total number of extreme high daily minimum temperature occurrences in the first sample is $110 + 143 = 253$ and in the second sample $102 + 297 = 399$ (Table 1). The 253 occurrences in the first sample are expected to be proportional to a ratio of 1 to 2 or 84 for recent years and 169 for prior years. In the first sample, the occurrences during the recent years exceed the 84 expected occurrences, resulting in the large significant chi-square value of 12 (excess).

In the second sample, the 102 occurrences during the recent years are less than the 133 expected occurrences, resulting in the large significant χ^2 value of 11 (deficit). The cardinal temperatures in the two samples are $\geq -4°$C (25°F) in excess and $\geq -6°$C (21°F) in deficit, respectively.

For each overlapping 3-week period and scan the computer output includes the maximum chi-square, the accumulated counts of daily weather occurrences and the associated cardinal values. The χ^2 value of each 3-week sliding window is assigned to

Table 1 Counts, cardinal temperatures and chi-squares for recent vs. prior years for two 3-week periods centered on January 10 and December 19 using the high to low scans for extreme high minimum temperature

3-Week center date	Scan direction	Recent years' count	Prior years' count	Cardinal temperature	Chi square
1/10	High–low	110	143	$\geq -4°$C (25°F)	12 (excess)
12/19	High–low	102	297	$\geq -6°$C (21°F)	11 (deficit)

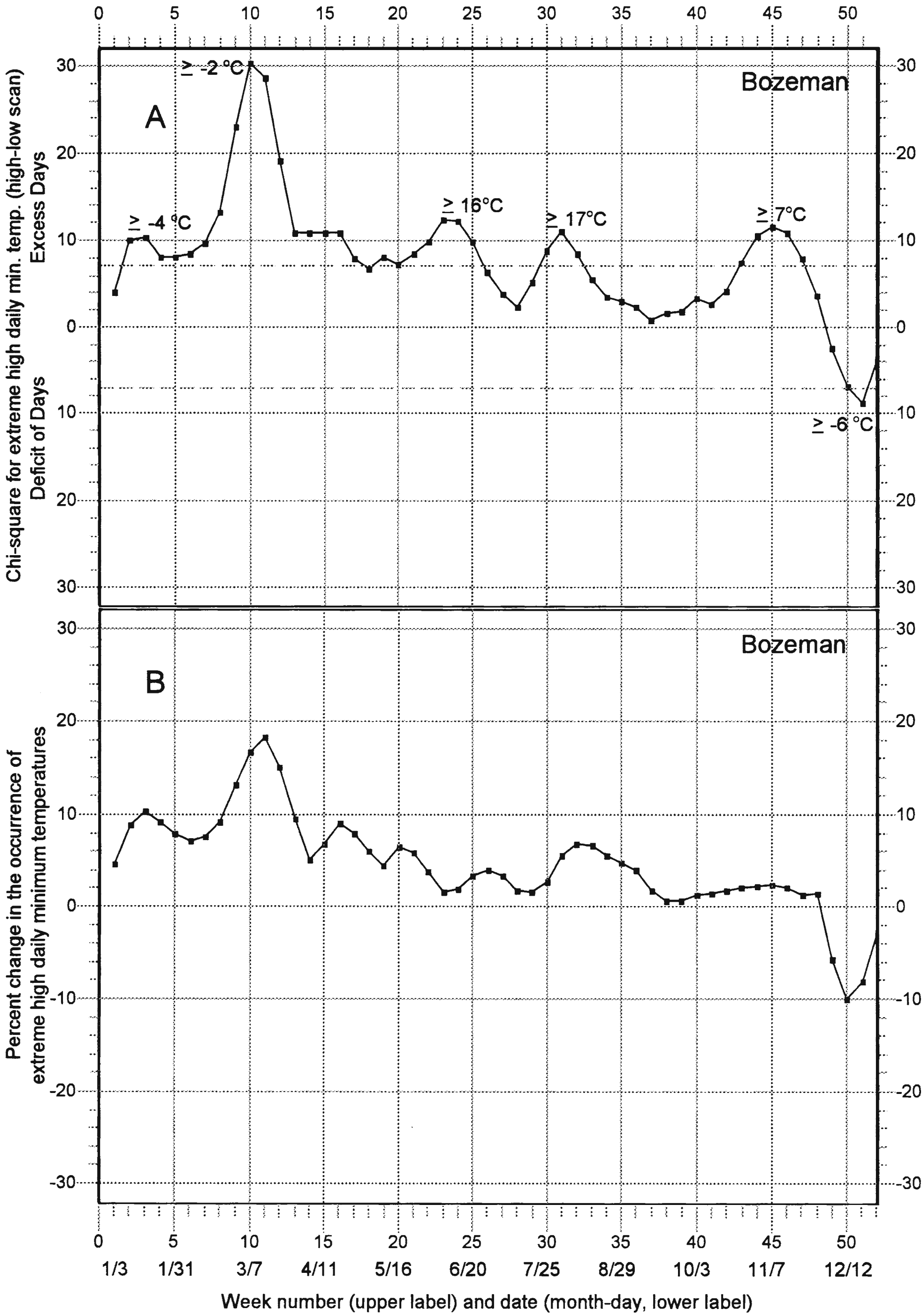

Fig. 1 **a** Bozeman: Significance of the difference in the number of days of extreme high daily minimum temperature during the 18 recent years (1982–2000) compared to the 36 prior years (1947–1981) at Bozeman, Montana. Cardinal values (the weather value at the maximum χ^2) are indicated on the graph. Chi square values = 7 (indicated by *dotted lines*) are the critical values for significance ($p \geq 0.01$, 1 *df*). **b** Bozeman: For each date (plotted weekly) in a recent year, the average percent that had an extreme high minimum temperature occurrence due to climate change

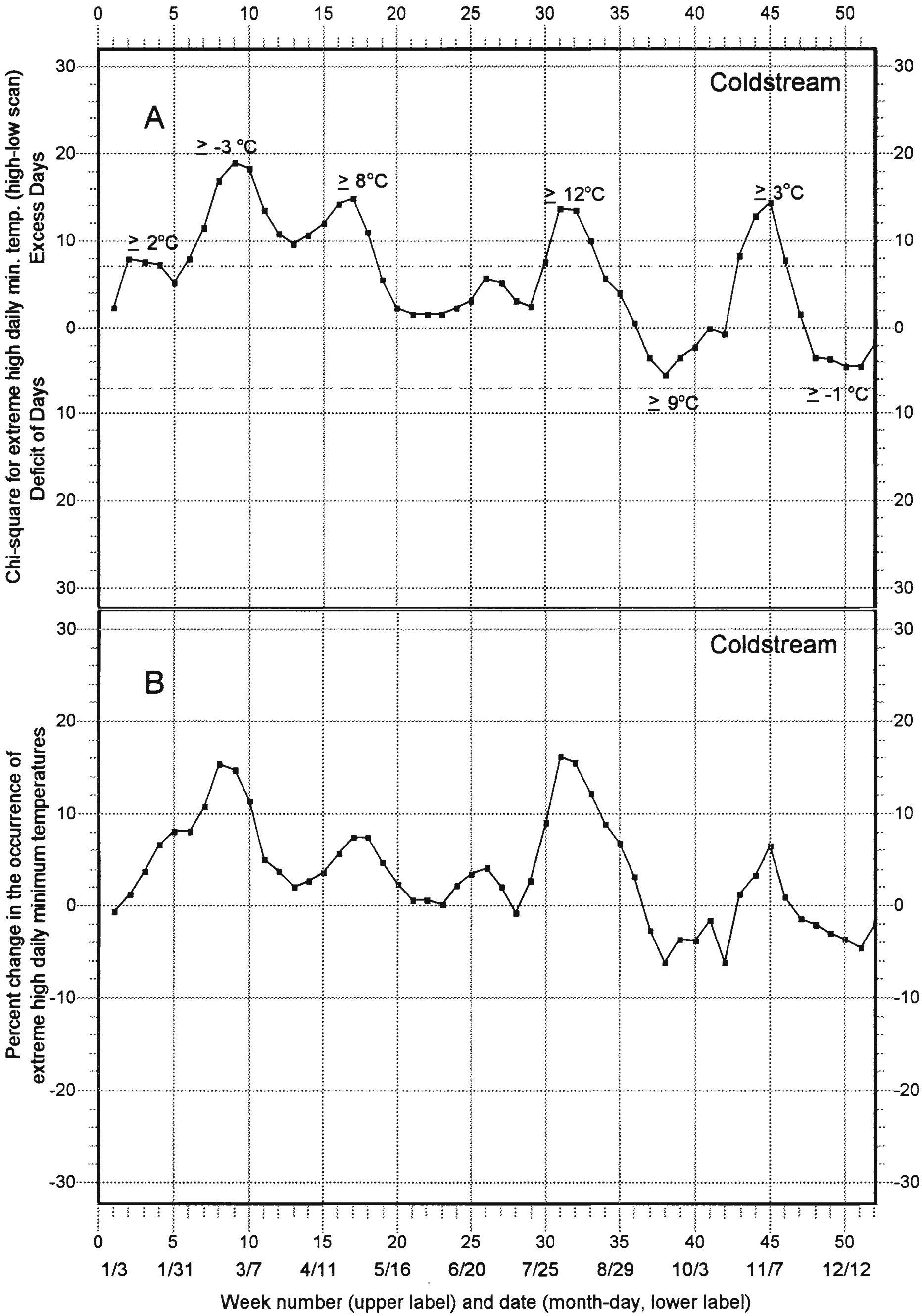

Fig. 2 **a** Coldstream: Significance of the difference in the number of days of extreme high daily minimum temperatures during the 18 recent years (1982–2000) compared to the 36 prior years (1947–1981) at Coldstream, British Columbia. Cardinal values (the weather value at the maximum χ^2) are indicated on the graph. Chi square values = 7 (indicated by *dotted lines*) are the critical values for significance ($p \geq 0.01$, 1 *df*). **b** Coldstream: For each date (plotted weekly) in a recent year, the average percent that had an extreme high minimum temperature occurrence due to climate change

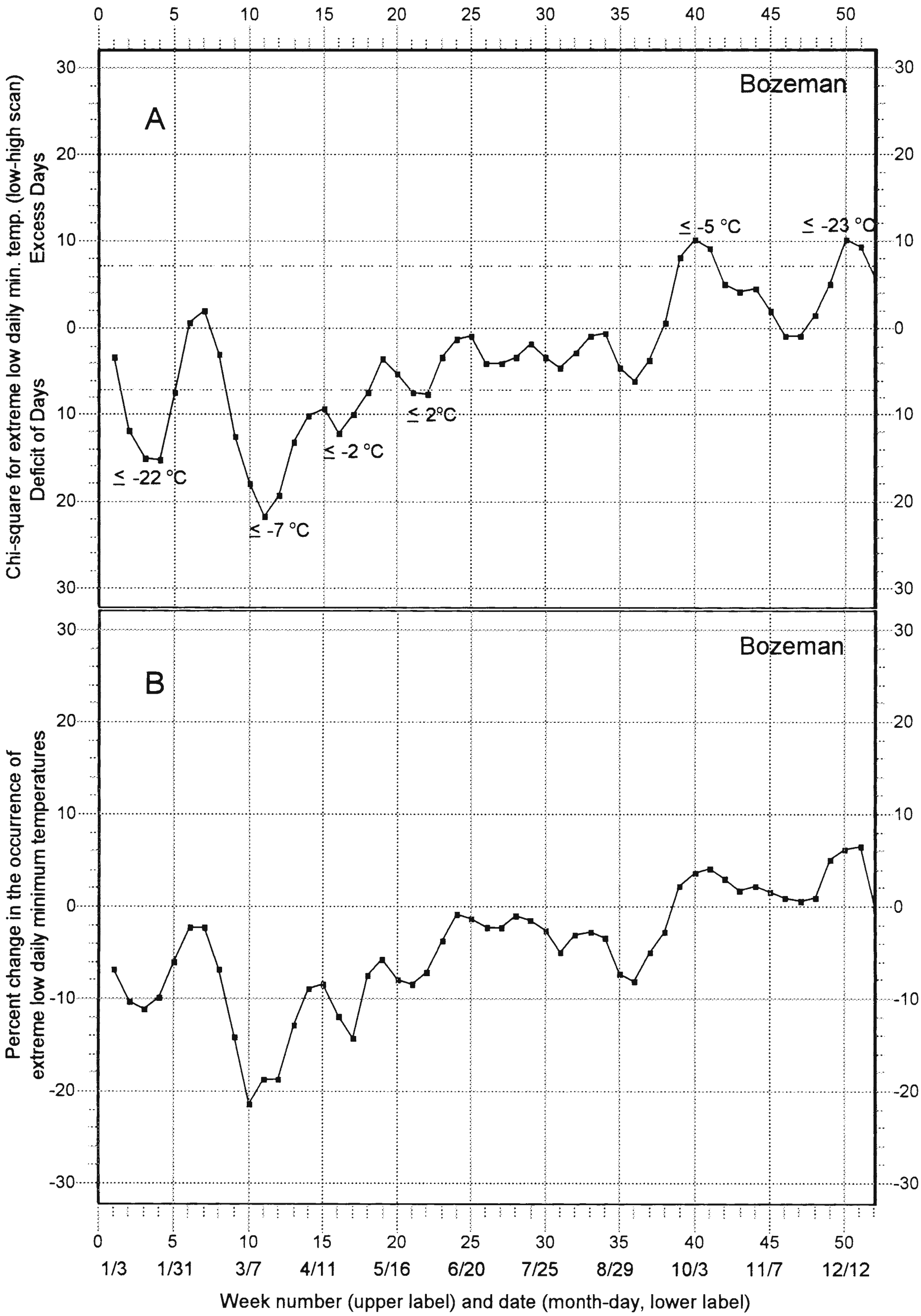

Fig. 3 **a** Bozeman: Significance of the difference in the number of days of extreme low daily minimum temperatures during the 18 recent years (1982–2000) compared to the 36 prior years (1947–1981) at Bozeman, Montana. Cardinal values (the weather value at the maximum χ^2) are indicated on the graph. Chi-square values = 7 (indicated by *dotted lines*) are the critical values for significance ($p \leq 0.01$, 1 *df*). **b** Bozeman: For each date (plotted weekly) in a recent year, the average percent that had an extreme low minimum temperature occurrence due to climate change

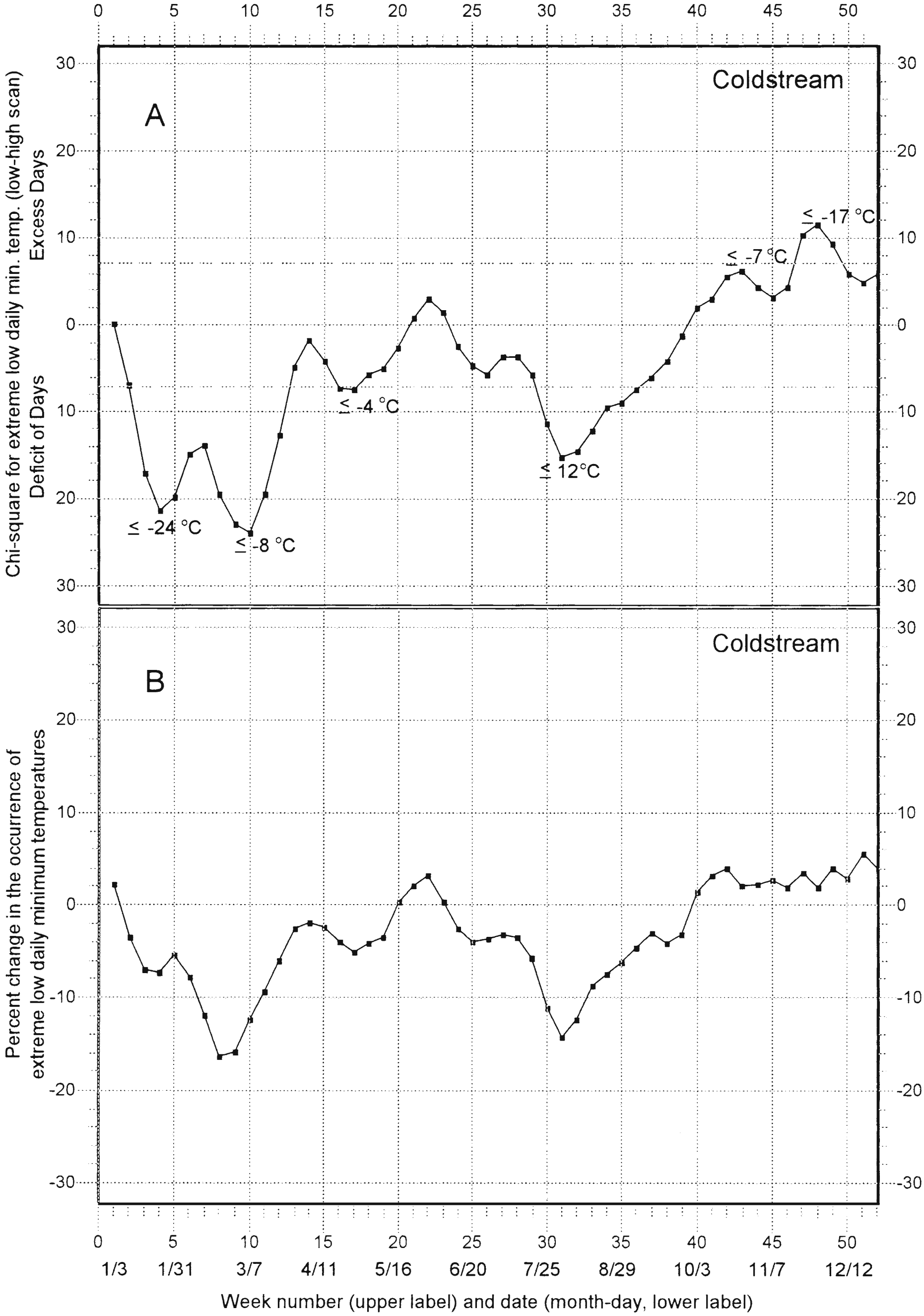

Fig. 4 **a** Coldstream: Significance of the difference in the number of days of extreme low daily minimum temperatures during the 18 recent years (1982–2000) compared to the 36 prior years (1947–1981) at Coldstream. Cardinal values (the weather value at the maximum χ^2) are indicated on the graph. Chi-square values = 7 (indicated by *dotted lines*) are the critical values for significance ($p \leq 0.01$, 1 *df*). **b** Coldstream: For each date (plotted weekly) in a recent year, the average percent that had an extreme low minimum temperature occurrence due to climate change

the center week. Thus, the entire 3-week period of the window must test significant in order to attribute significance to the center week. The χ^2 values of each iterative 3-week window in a scan, when plotted, appear as a curve and the computer selects the largest of the plotted χ^2 values.

The 3-week running averages of these weekly values were calculated for Bozeman and Coldstream for extreme low (low-high scan) and extreme high (high-low scan) minimum temperature. The use of running averages as a smoothing procedure when applying the iterative chi-square method, in this analysis and in previous studies (Caprio and Quamme 1999, 2002, 2006; Caprio et al. 2003), was found to generate more reasonable patterns of variation from week to week. This smoothing procedure effect should be expected in view of the large variability of annual weather. These 3-week running averages of χ^2 values for each week represent samples over 5 weeks weighted 1–2–3–2–1 and are plotted in section a of Figs. 1, 2, 3 and 4. The cardinal value of the original most statistically significant week within each significant period was entered near the appropriate peak in section a of Figs. 1, 2, 3 and 4. Reference in the text to an association is usually made only if the association is statistically significant for a period of more than 2 weeks.

For each overlapping 3-week period, we calculated the difference in the numbers of extreme days in the 18 recent years compared with one half the number of extreme days in the 36 prior years. That value divided by 18 (number of years) gives the difference in the number of extreme days per year. That value divided by three (number of weeks) yields the difference in the number of extreme days per week. Three week running averages of these weekly values were calculated. These smooth weekly values of the difference in the number of extreme days per week were then divided by seven (days per week) giving the average number (in fractions of a day) of extreme occurrences per day. That value multiplied by 100 yields the average daily percent climate change. These daily values are plotted weekly in the b-sections of Figs. 1, 2, 3 and 4 and referred to in the text as the percent change in the occurrence of extreme daily weather conditions during the recent year due to climate change. This value is referred to here as the percent climate change of the extreme occurrences.

Since one day represents one-seventh of a week, which calculates to 14.29% of a week, the percentages shown in the b-section of the graphs indicates one day of climatic change per week for each 14%. Thus, 7% on the graph represents a half day of climatic change per week, 28% 2 days of climatic change per week, etc.

A detailed description of the iterative chi-square method with examples of the interpretation of computer output are given in a paper on tree-ring weather relations along with comparisons with some other statistical methods (Caprio et al. 2003).

3 Results

3.1 Bozeman: change in the days of extreme high minimum temperatures

The results of the analyses for Bozeman and Coldstream are presented for significant periods for both days of extreme high minimum temperatures and for days of extreme low minimum temperatures.

Figure 1 indicates that at Bozeman there were more days of extreme high minimum temperatures in recent years compared to the prior years during all months except December. The occurrences of extreme high daily minimum temperature were significantly more numerous during three periods. The corresponding data are presented in Table 2.

Table 2 and Fig. 1 show that the maximum χ^2 of 30 occurred during week 10 (3/5–3/11) with a CT of ≥ −2°C (29°F). Considering 7% as the level for one-half day per week climate warming (or cooling) and 14% as the level for one day per week climate warming (or cooling), we can make the following interpretations. For extreme high minimum temperature there were 16 weeks that had at least one-half week of climatic warming and three weeks that had at least one whole week of climatic warming. There were only 2 weeks that had at least one-half week of climatic cooling.

The greatest percentage change in climate occurred during week 11 (3/12–3/18) when a 17% increase of extreme high minimum temperatures was detected. While there was a significantly greater number of days of extreme high minimum temperature during weeks 43–47 (10/22–11/25), which is indicated by the large chi-square values, the number of days of climate change was relatively few, which resulted in a climate change of only 2%.

It was determined that the occurrence of extreme high daily minimum temperatures during the three significant periods (1/8–6/24) (7/23–8/12) (10/22–11/25) averaged more frequent during the recent period compared to the prior period by 40% and 56%, respectively. The small sample during weeks 43–47 (10/22–11/25) did not allow for a percentage comparison between the numbers of extreme days in the recent period relative to the prior period. Additional comparisons can be made for each significant period using information from the associated table and text. An example is presented below for the significant period covering weeks 2 through 25 (1/8–6/24) for extreme high daily nighttime temperature at Bozeman.

Since the 0.08 fraction of extreme days in recent years (from Table 2) represents a 40% increase of the fraction of extreme days in prior years (from paragraph above), the fraction of extreme days in prior years equates to 0.20 and the total fraction of extreme days in recent years is 0.20 plus 0.08 which equals the daily fraction of 0.28. That is, 0.08 divided by 40% is equal to X divided by 100% which equates to X = 0.20, where X is a fraction of a day with extreme high minimum temperatures in prior years leaving 0.80 as the fraction of non extreme days in prior years. Given that the percent of extreme days in prior years is 20% while the percent of extreme days in recent years is 28%, the percent of non-extreme days in prior and recent years is the difference, or 80% and 72% respectively.

Table 2 Data on three periods that had a significant increase in the number of days of high minimum temperatures at Bozeman

Week number	Dates	Max weekly χ^2	Daily[a] average period change (%)	Dates of Max χ^2 week(s)	Daily[a] average change of Max χ^2 week(s), (%)	Cardinal temp of Max χ^2 week(s)
2–25	1/8–6/24	30	+8	3/5–3/11	+17	≥ −2°C (29°F)
30–32	7/23–8/12	11	+5	7/30–8/5	+6	≥ 17°C (63°F)
43–47	10/22–11/25	12	+2	11/5–11/11	+2	≥ 7°C (45°F)

[a]Positive signs indicate the average fraction of a day (in percent) increase in extreme high daily minimum temperatures during the two intervals that are attributable to climate change at Bozeman.

Based on the sums of all 52 weeks of extreme days, it was determined that the recent years averaged 27% more extreme high nighttime temperatures than the prior years, an increase from 59.0 to 74.9 days/year.

Figure 1 indicates that there were significantly fewer daily occurrences of extreme high minimum temperatures during the recent years compared to the early years only during weeks 50–51 (12/10–12/23). Maximum λ^2 of 9 occurred during week 51 (12/17–12/23) with a CT of ≥ −6°C (21°F). The greatest percent climate change during this significant period was 10% during week 50 (12/10–12/16).

In summary, the longest period of significant warming at Bozeman as indicated by the increase in the number of days of extreme high minimum temperatures occurred during the first 6 months of the year, January to June, with greatest warming during this period occurring from late February to late March. Significant periods of warming also occurred during parts of July to August and October to November. Significantly fewer number of days of extreme high minimum temperatures occurred only during the month of December.

3.2 Coldstream: changes in the days of extreme high minimum temperatures

Figure 2 indicates that at Coldstream there was a greater occurrence of days of extreme high minimum temperature during recent years compared to the prior years for all months except for two short periods centered on September and December. The occurrence of extreme high minimum temperature was significantly more numerous during four periods. The corresponding data are presented in Table 3.

Table 3 and Fig. 2 show that the maximum λ^2 of 19 occurred during week 9 (2/26–3/4) with a CT of ≥ −3°C (26°F). The percent change during this week was an increase of 15% on week 8 (2/19–2/25). For extreme high minimum temperature there were 15 weeks that had at least one-half week of climate warming and 4 weeks that had at least one whole week of climate warming. There were no weeks that had at least one-half week of climate cooling. The greatest percentage change in climate occurred during weeks 8 and 9 (2/19–3/4) when a 15% increase of extreme high minimum temperatures was detected and during weeks 31 and 32 (7/30–8/12) when 16% increase was detected. It was determined that extreme high daily minimum temperatures during the four significant periods (1/8–1/28) (2/5–5/6) (7/23–8/19) (10/22–11/18) average more frequent during the recent period compared to the prior by 32%, 64%, 35% and 46%, respectively.

Table 3 Data on four periods that had a significant increase in the number of days of extreme high minimum temperatures at Coldstream

Week number	Dates	Max weekly χ^2	Daily[a] average period change (%)	Dates of Max χ^2 week(s)	Daily[a] average change of Max χ^2 week (s), (%)	Cardinal temp of Max χ^2 week (s)
2–4	1/8–1/28	8	+4	1/8–1/21	+7	≥ 2°C (36°F)
6–18	2/5–5/6	19	+8	2/26–3/4	+15	≥ −3°C (26°F)
30–33	7/23–8/19	14	+13	7/30–8/12	+16	≥ 12°C (54°F)
43–46	10/22–11/18	14	+4	11/5–11/11	+7	≥ 3°C (38°F)

[a]Positive signs indicate the average fraction of a day (in percent) increase in extreme high daily minimum temperatures during the two intervals that are attributable to climate change at Coldstream.

Based on the sums of all 52 weeks of extreme days, it was determined that the recent years averaged 23% more extreme high nighttime temperatures than the prior years, an increase from 61.5 days/year to 75.6 days/year.

There were no significant periods with fewer numbers of occurrences of extreme high minimum temperatures.

In summary, the greatest warming at Coldstream, as indicated by the increase in the number of days of extreme high minimum temperature, occurred mostly during the periods from January to early May, late July to mid-August and late October to mid-November.

3.3 Bozeman: changes in the days of extreme low minimum temperatures

Figure 3 indicates that at Bozeman there was a deficit of days of extreme low minimum temperature from January through August in recent years compared to the early years for all but 2 weeks in early February. The deficit of occurrence of extreme low minimum temperatures was statistically significant during three periods. The corresponding data are presented in Table 4.

Table 4 and Fig. 3 show that the maximum χ^2 of 22 occurred during week 11 (3/12–3/18) with a CT of ≤ -7°C (19°F). The percent change during this week was a decrease of 19%. For extreme low minimum temperature there were 20 weeks that had at least one-half week of climate warming and 5 weeks that had at least one whole week of climate warming. There were no weeks that had at least one-half week of climate cooling. The greatest percentage change in climate occurred during week 10 (3/5–3/11) when a 21% decrease of extreme low minimum temperatures was detected. It was determined that extreme low daily minimum temperatures during the three significant periods (1/8–2/4) (2/26–5/6) (5/21–6/3) average less frequent during the recent period compared to the prior period by 41%, 31%, and 60%, respectively.

Based on the sums of all 52 weeks of extreme days it was determined that the recent years averaged 20% fewer number of extreme low nighttime temperatures than the prior years, a decrease from 76.8 to 61.4 days/year.

Figure 3 indicates that during the entire four and one-half month period from early mid September through December only weeks 46 and 47 (11/12–11/25) did not experience an excess of extreme low minimum temperatures. The greater number of days of extreme low minimum temperatures during this period was statistically significant during two periods. The corresponding data are presented in Table 5.

Table 4 Data on three periods that had a significant decrease in the number of days of low minimum temperatures at Bozeman

Week number	Dates	Max weekly χ^2	Daily[a] average period change (%)	Dates of Max χ^2 week(s)	Daily[a] average change of Max χ^2 week(s), (%)	Cardinal temp of Max χ^2 week(s)
2–5	1/8–2/4	15	−7	1/15–1/21	−11	≤ -22°C (-7°F)
9–18	2/26–5/6	22	−14	3/12–3/18	−19	≤ -7°C (19°F)
21–22	5/21–6/3	8	−8	5/28–6/3	−8	≤ 2°C (35°F)

[a]Negative signs indicate the average fraction of a day (in percent) decrease in extreme low daily minimum temperatures during the two intervals that are attributable to climate change at Bozeman.

Table 5 Data on two periods that had a significant increase in the number of days of extreme low minimum temperatures at Bozeman

Week number	Dates	Max weekly χ^2	Daily[a] average period change (%)	Dates of Max χ^2 week(s)	Daily[a] average change of Max χ^2 week(s), (%)	Cardinal temp of Max χ^2 week(s)
39–41	9/24–10/14	10	+3	10/1–10/7	+4	≤ −5°C (23°F)
50–51	12/10–12/23	10	+6	12/17–12/23	+6	≤ −9°C (15°F)

[a]Positive signs indicate the average fraction of a day (in percent) increase in extreme low daily low minimum temperatures during the two intervals that are attributable to climate change at Bozeman.

Table 5 and Fig. 3 indicate that during weeks 39–41 (9/24–10/14) the maximum χ^2 of 10 occurred during week 40 (10/1–10/7) with CT of ≤ −5°C (23°F). The greatest percentage change in climate during this period was an increase of 5% of extreme minimum temperatures during week 40 (10/1–7). The small sample during weeks 39–41 (9/24–10/14) did not allow for a percentage comparison between the numbers of extreme days in the recent period relative to the prior period. During weeks 50–51 the maximum χ^2 of 10 occurred during week 50 (12/12–12/16) with CT ≤ −23°C (−9°F). The percent change during the period was 8%. It was determined that extreme low daily minimum temperature during weeks 50 to 51 (12/10–12/23) averaged 41% more frequent during the recent period compared to the prior period.

In summary, the greatest warming at Bozeman occurred from January to mid-September as indicated by the fewer number of days of extreme low minimum temperatures. Significantly greater number of occurrences of low minimum temperatures occurred only from late September to early October and during the month of December. These two significant periods were influenced by climate change only to the extent of 4% and 6%, respectively, during their peak weekly periods.

3.4 Coldstream: changes in the days of extreme low minimum temperatures

Figure 4 indicates that at Coldstream there was a deficit of days of extreme low minimum temperatures in recent years compared to the early years from January to late September with the exception of a 3-week period from late May to early June. The deficit of occurrence of extreme low minimum temperatures was statistically significant during three periods. The corresponding data are presented in Table 6.

Table 6 Data on three periods that had a significant decrease in the number of days of extreme low minimum temperatures at Coldstream

Week number	Dates	Max weekly χ^2	Daily[a] average period change (%)	Dates of Max χ^2 week(s)	Daily[a] average change of Max χ^2 week(s), (%)	Cardinal temp of Max χ^2 week(s)
2–12	1/8–3/25	22	−9	3/5–3/11	−12	≤ −8°C (17° F)
16–17	4/16–4/29	7	−5	4/16–4/29	−5	≤ −4°C (25°F)
30–36	7/23–9/9	15	−9	7/30–8/12	−14	≤ 12°C (53°F)

[a]Negative signs indicate the average fraction of a day (in percent) decrease in extreme low daily minimum temperatures during the two intervals that are attributable to climate change at Coldstream.

Table 6 and Fig. 4 show that the maximum χ^2 of 24 occurred during week 10 (3/5–3/11) with CT of $\leq -8°C$ (17°F). The percent change during this week was a decrease of 12%. For extreme low minimum temperature there were 13 weeks that had at least one-half week of climate warming and 3 weeks that had at least one whole week of climate warming. There were no weeks that had at least one-half week of climate cooling. The greatest percentage change in climate came during weeks 8 and 9 (2/19–3/4) when a 16% decrease in the number of days of extreme low minimum temperatures was detected and during week 31 (7/30–8/5) when 14% decrease was detected. It was determined that extreme low daily minimum temperatures during the three significant periods (1/8–3/25) (4/16–4/29) (7/23–9/9) averaged less frequent during the recent period compared to the prior period by 51%, 58%, and 38%, respectively.

Based on the sums of all 52 weeks of extreme days, it was determined that the recent years averaged 24% fewer number of extreme low nighttime temperatures than the prior years, a decrease from 50.8 to 38.6 days/year.

Figure 4 indicates that there were an excess number of days of extreme low minimum temperatures during weeks 20–23 (5/14–6/10) and weeks 40–52 (10/1–12/30). Only weeks 47–49 (11/19–12/9) were significant with maximum χ^2 of 12 occurring during week 48 (11/26–12/2) with CT of $\leq -17°C$ (1°F). The percent climate change of extreme low minimum temperature during this week was an increase of only 2%.

In summary, the greatest warming occurred at Coldstream as indicated by the fewer number of days of extreme low minimum temperatures during the period from January through September. A significant excess number of days of extreme low minimum temperatures occurred only from near mid November to early December.

4 Discussion and conclusions

This study describes climate differences of extreme daily weather occurrences at two locations between a prior period and a recent period. The analysis clearly indicates that the occurrence of extreme high daily minimum temperatures during the recent period were greater compared to the prior period at both Bozeman and Coldstream. Warmer weather occurred at both locations from January through September with predominant warming having taken place from January to mid-April at both the Bozeman and Coldstream locations. Peak warming at both locations occurred during the period from late February to early March. The period from late September through December at both locations included some weeks that had significant increases in extreme low minimum temperatures and some weeks that had significant increases in extreme high minimum temperatures.

There was a very close correspondence between the Bozeman and Coldstream stations in the occurrence of the warming as well as the correspondence in the time of the less significant tendency for cooling in the period from October to December.

The 52-week average increase of extreme high nighttime temperatures attributable to climate change at Bozeman and Coldstream was 27% and 23%, respectively. The 52-week averaged decrease of extreme low nighttime temperatures attributable to climate change at Bozeman and Coldstream was 20% and 24%, respectively. Since the interval from the middle of the prior period to the middle of the recent period is 27 years, these percentages suggest that extreme high nighttime temperatures are becoming more frequent at a rate of about 1% per year or 10% per decade at these two locations, with a close corresponding decrease of extreme nighttime minimum temperatures.

The close correspondence in the warming at both locations, which are about 800 km apart and at opposite sides of the Continental Divide is consistent with several previous studies that indicated a pronounced winter to early spring warm-up in northwestern North America since the mid 1900s (Karl et al. 1993; Dettinger and Cayan 1995; Lettenmaier et al. 1994; Vincent et al. 1999). A discussion of the possible causes of the recent spring warm-up can be found in Cayan et al. (2001) that also reported that the greatest warm-up occurred during the month of March.

The following is a list of information that can be provided by the iterative chi-square method.

1. Weekly significance of the difference between the number of extreme high or extreme low daily minimum temperature occurrences between the prior and recent years (Figs. 1a, 2a, 3a, and 4a).
2. Average percent or fraction of each day within each week of the year that is attributable to climate change due to extreme high or extreme low daily minimum temperature (Figs. 1b, 2b, 3b, and 4b).
3. Average percent or fraction daily change in the frequency of extreme high or extreme low minimum temperature days for each significant period (Tables 2, 3, 4, 5 and 6).
4. Extreme threshold values (cardinal temperatures) for each significant period of high maximum or low minimum temperature that most distinguish the recent years from the prior years (Tables 2, 3, 4, 5 and 6).
5. For each of the significant periods calculations can be made from data in the tables and graphs of the average daily percent or fraction of extreme days attributable to climate change, the average daily percent or fraction of extreme days not attributable to climate change and the average daily percent or fraction is not an extreme day. An example of how this is done was presented for the significant period of weeks 2–25 (1/8–6/24) in the Section 3.1.

The chi-square test determines the significance of the difference in the accumulated days in each two degrees step in the scans between the early and the recent years. Scans are made of sorted daily minimum temperatures in both the high to low and low to high directions. Chi-square values generated in the scans increase in periods where there is a direct relationship between the number of daily occurrences between the prior and recent years, reach a maximum (threshold temperature) and then decrease beyond the point where the direct relationship ceases to exist. The fact that the maximum chi-square in each scan is taken as the significant level of climate change could raise the question as to whether the alpha value should be adjusted upward due to multiple tests in order to reduce the chance of incorrectly declaring statistical significance when non exists. Multiple tests adjustments are intended to achieve greater precision in describing statistical significance. For example, in the presence of multiple tests the conventional alpha levels can be too high (e.g., 0.05 might be equivalent to 0.10) and statistical significance is over estimated. Adjustments of alpha values are not made in this study. This issue might benefit from additional research to determine whether this test can be modified to achieve a more precise significance test for evidence of climate change.

When applying the iterative chi-square method, no limiting assumptions are made as to linearity. In this study the method used daily weather information providing one-week resolution in the determination of climate change of extreme daily minimum temperature. The same procedure can be applied to determine climate change of extreme occurrences of other climate elements.

Information provided by the iterative chi-square analysis can be interpreted in terms of the probable effect of climate change in many areas, such as in agriculture, recreation, engineering requirements, energy needs, etc. Application of this method at many locations that have suitable long term daily weather records could provide planners with useful information to make rational decisions in dealing with the potential impact of climate change.

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