AN APPROACH TO DETERMINE THE EFFECT OF EL NINO ON EXTREME DAILY WEATHER OCCURRENCE

Joseph M. Caprio, Professor Emeritus, Department of Land Resources and Environmental Sciences, 334 Leon Johnson Hall, Montana State University, Bozeman, Montana, 59717-3120
Perry R. Miller, Department of Land Resources and Environmental Sciences, 334 Leon Johnson Hall, Montana State University, Bozeman, Montana, 59717-3120
Jon M. Wraith[1], Department of Land Resources and Environmental Sciences, 334 Leon Johnson Hall, Montana State University, Bozeman, Montana, 59717-3120

ABSTRACT

We developed a procedure using the chi-square statistic to determine the effect of El Nino-Southern Oscillation on the frequency of extreme daily weather occurrence. Its application is demonstrated for a site in southwestern Montana, located east of the Continental Divide 970 km from the Pacific Ocean. The study used daily weather data focused on a 29-wk period from 3 Dec to 23 Jun in a 100-yr weather record at Montana State University (Bozeman) and compared this weather in relation to November-March sea-surface temperature anomalies in an area of the eastern tropical Pacific Ocean. Daily weather extremes were compared between 25 El Nino years and 50 'normal' years. During El Nino years, December-June weather at Bozeman was characterized by more days of extreme high maximum temperatures, fewer days of extreme low minimum temperatures, fewer days of high precipitation amounts, and fewer days with small diurnal temperature ranges. For the 29-wk period, we determined the difference between El Nino years and normal years to be about 20 percent for each of these four extreme daily weather conditions. An increase or decrease of extreme daily weather occurrences can impact natural resources and a wide range of human activities including agriculture, forestry, recreation, construction, and other businesses.

Keywords: El Nino, extreme daily weather, Northwestern United States, iterative Chi-square

INTRODUCTION

The variability of the El Nino-Southard Oscillation (ENSO) sea-surface temperature anomalies affect extremes of climate over much of the world with important consequences for natural resources and a wide range of human activities (McPhaden et al. 2006). Since El Nino sea surface temperature anomalies tend to persist for many months and have predictable climatic associations, it is prudent to undertake research to understand how El Nino affects extremes of weather for individual locations in order to provide useful information for decision makers.

Numerous studies of the El Nino effect have compared the monthly mean temperatures and/or precipitation at given locations during El Nino years with so-called 'normal' years (Shabbar et al. 1997, Wang and Fir 2000, Twine et al. 2005). Researchers have also studied extremes of daily weather events associated with the El Nino in which given values of extreme daily weather occurrences are selected for analysis or the daily extremes are determined as percentages of occurrences, such as being beyond the 95-percent probability level (Gershunov et al. 1998, Cayan et al. 1999).

Caprio (1966) first described the conceptual basis and details of the statistical procedure used in this study, known as the iterative chi-square method. Caprio and Quamme (2002) applied this methodology in previous research to determine daily weather effects on grape production, and to determine climate change of daily maximum and minimum temperature and precipitation

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[1] Associate Dean of Agriculture and Associate Director of New Hampshire Agricultural Experiment Station, College of Life Sciences and Agriculture, G15 Rudman Hall, 46 College Road, Durham, New Hampshire 03824

over a 56-yr period in the Okanagan Valley of British Columbia, Canada. It has also been applied in research to determine the impact of daily weather on growth of tree rings in Arizona (Caprio et al. 2003) and to determine recent climate change of extreme daily temperatures at two locations in northwestern North America (Caprio et al. 2009). Our research objective was to develop a procedure to determine the effect of El Nino on frequency of extreme daily occurrence of several climatic elements. This was achieved by applying the iterative chi-square approach that considered climate differences between El Nino years and 'normal years.' We demonstrated the technique by using daily weather data for a 100-yr period at the Montana State University Weather Station, Bozeman, Montana, which is located in the Rocky Mountain foothills east of the Continental Divide 970 km from the Pacific Ocean.

METHODS

Year Characterization

The ENSO Index chosen for use in this study is based on the Japanese Meteorological Agency (JMA) estimate of sea-surface temperature (SST) anomalies, known as the JMA ENSO Index (Sittel 1994, Green 1995). The Index is based on SST anomalies in the tropical Pacific Ocean in an area bounded by 4o S to 4o N latitude and 150o W to 90o W longitude. When we initiated this study the JMA ENSO Index was the only century-long El Nino index available. The National Oceanic and Atmospheric Administration (NOAA) identified several El Nino areas in the eastern Pacific Ocean. The JMA ENSO Index is based on ocean temperatures in a rectangle area that is the same as NOAA NCEP/NCAB El Nino Region 3 Index area except the NOAA Index extends 5 degrees north and south of the equator rather than 4 degrees. (Trenberth 1997, Trenberth and Stepaniak 2001).

The JMA mean normal SST for the period 1961-1990 is as follows: Jan (25.4 °C), Feb (26.2 °C), Mar (26.9 °C), Apr (27.1 °C), May (26.6 °C), Jun (26.1 °C), July (25.2 °C), Aug (24.6 °C), Sep (24.6 °C), Oct (24.6 °C), Nov (24.6 °C), and Dec (24.9 °C). We determined the JMA Index for each month by computing a 5-mo running mean (labeled as the central month) of the monthly SST anomalies (Sittel 1994, Green 1995). Thus, a given monthly JMA Index includes information for each of the five monthly SST anomaly values in order to smooth out possible intra-seasonal variations. The annual values used in this analysis to identify an El Nino year were chosen to be the mean of the five JMA Index values for the 5-mo period, Nov-Mar, which includes weather data from Sep-May. The year of the El Nino is identified here as the year of the Jan-Mar period. The 100 annual values of the JMA Index were ordered from low to high and divided into quartiles. The highest quartile years were considered the El Nino years and the lowest quartile years were considered the La Nina years. The central two quartiles constituted the 'normal years'.

According to this classification, all those years where the mean Nov-Mar JMA Index was ≥ +0.46 °C were considered El Nino years. For the La Nina years, the mean Nov-Mar JMA index was ≤ -0.50 °C. This study considers only the relation between the 25 El Nino yr, sometimes referred to as the 'Warm Phase' and the two central quartile, i.e., 50 yrs, 'normal' years. According to this classification the 25 El Nino years were: 1903, 1905, 1906, 1912, 1914, 1919, 1920, 1926, 1928, 1930, 1931, 1941, 1952, 1958, 1966, 1969, 1970, 1973, 1977, 1983, 1987, 1988, 1992, 1995, and 1998. The 25 La Nina years were: 1904, 1909-11, 1917, 1918, 1923, 1939, 1943, 1945, 1946, 1950, 1955, 1956, 1965, 1968, 1971, 1974-76, 1985, 1989, 1996, 1999, and 2000. This classification method was highly consistent with a report spanning from 1951 to 2008 (National Weather Service 2008). All other years during 1901-2000 not listed as El Nino or La Nina were considered the 50 'normal' years. The average monthly JMA Index SST anomaly for Nov-Mar was +1.01 °C during the 25 El Nino yrs and the two most extreme values were +2.58 °C and

+2.82 °C in 1983 and 1998, respectively. During the 25 La Nina yrs, the average monthly JMA Index SST anomaly for Nov-Mar was -0.93 °C and the two most extreme values were -1.74 °C and -1.34 °C in 1917 and 1971, respectively.

Chi-Square Analyses

Weather data at the Bozeman, Montana, site (45º 40'N, 111º 03'W, elevation 1480 m) were measured and analyzed in Imperial units and the results were converted to metric units. Daily meteorological data were recorded to the nearest whole °F (temperature) or 0.01 in (precipitation) from 26 Nov to 30 Jun each year. For chi-square analyses, we used a sliding window of 3 wks, adding a new week and dropping the first week as the overlapping 3-wk time frame advanced. For example, the first 3-wk period included days 1-21, i.e., 26 Nov-16 Dec, with all associated daily weather values and was labeled as the central or 11th day, i.e., 6 Dec. The second 3-wk period included days 8-28, i.e., 3 -23 Dec, and was labeled as 13 Dec, etc., continuing until 29 successive 3-wk periods, spanning 31 wks, i.e., 26 Nov-30 Jun), were recorded within each 'year.' A 3-wk span of daily weather data was used in this study since previous studies found this smoothing process to provide reasonable conclusions about the occurrence of extreme weather.

Within each 3-wk period, temperature was broken down into classes of 2 °F in order to have an adequate number of observations in most classes and precipitation was broken down into classes of 0.05 in. The climate variables, maximum and minimum temperature, precipitation, and diurnal temperature range, were each sorted from low to high values, separately within the 25 El Nino and 50 'normal' years. The terms maximum and daytime temperature and the terms minimum and nighttime temperature were used interchangeably in this study. For each overlapping 3-wk period for the four climate variables, the chi-square statistic was used to test the significance of the difference from an expected 1:2 ratio of the frequency of days between the 25 El Nino years and the 50 'normal' years in cumulative scans in both increasing and decreasing directions, explained below. For the test of each class of a given climatic variable, the total number of daily occurrences in each 3-wk period was 525 (21 days x 25 yr). The total number of days in the normal category was 1050 (21 days x 50 yr). The chi-square test is made, iteratively, of the total number of days accumulating in each class of the given variable in succession ordered from high to low values (high-low scan) or from low to high values (low-high scan). The first chi-square value in the high to low scan includes data in the highest class only, the second for cumulative data in the first plus the second (next highest) class, the third for cumulative data in the first plus the second plus the third class, etc. The low to high scan is performed identically, but starting with the lowest class.

When the counts for the El Nino years deviate from the expected 1:2 ratio with the 'normal' years the chi-square values in the scan increase to a maximum and then decrease beyond the point in which the relationship no longer exists, i.e., final cumulative data analysis for each 3-wk period must, by definition, contain 525 El Nino counts and 1050 'normal' counts. The maximum chi-square point in the scan identifies the "cardinal value" of the climatic element. The "cardinal value" is that point which defines the beginning of the extreme values above or below, depending on the scan direction. In this way, the iterative chi-square method provides a way to determine whether the number of extreme daily occurrences during ENSO years differs significantly from the expected number of occurrences during normal years.

Chi-square values for temperature were taken as statistically significant at $P = 0.01$ ($df = 1$); when the actual value was ≥ 6.63. For efficient data analysis, we considered temperature differences in this study significant when $\chi^2 \geq 7$ (rounded up from the actual valued of 6.63), so the significance was slightly more conservative than $P = 0.01$. Chi-square values for precipitation were taken as statistically significant at $P = 0.05$ ($df = 1$); when χ^2 was ≥ 3.84. Similarly, we rounded 3.84 up to '4' for efficient computation. Previous studies have used this level of significance for precipitation because a large percentage of days are without precipitation and in view of the large spatial variability of precipitation (Caprio and Quamme 2002, Caprio et al. 2003). When the relation is significant, the hypothesis that the extreme climate during El Nino years is the same as during normal years is rejected. The larger the value of chi-square, the higher the probability that there is a real extreme climatic effect of the El Nino. We performed high-low and low-high scans for each of the four climatic elements.

A minus sign is given to the chi-square value when the extreme climatic occurrence in the El Nino years is less than in the normal years (inverse relationship). Positive and negative values in the chi-square values plotted against time of year reveal those periods when the El Nino affects extreme climate. Chi-square probability levels are not strictly applicable when counts of the daily weather elements are small (Snedecor 1946). However, chi-square values based on low counts tend to be insignificant and superseded by larger chi-square values in the classes further up (or down) in the scan.

Data for two examples are presented in Table 1 to show how the χ^2 value is computed considering extreme low daily minimum temperature for El Nino years versus normal years. In Equation 1 below, 'A' and 'E' represent actual and expected number of occurrences, respectively. The letters 'e' and 'n' are for El Nino and normal years, respectively.

Eq. 1

$$\chi^2 = \frac{(Ae - Ee)^2}{Ee} + \frac{(An - En)^2}{En}$$

For the first 3-wk period:

$$\chi^2 = \frac{(43 - 81)^2}{81} + \frac{(200 - 162)^2}{162} = 27$$

For the second 3-wk period:

$$\chi^2 = \frac{(150 - 121)^2}{121} + \frac{(212 - 241)^2}{241} = 10.$$

The total number of extreme low daily minimum temperature in the first sample was 43 + 200 = 243 and in the second sample 150 + 212 = 362 (Table 1). We expected the 243 occurrences in the first sample to be proportional in a ratio of 1:2, or 81 for El Nino years and 162 for normal years. In the first sample, the 43 occurrences during El Nino years was less than the 81 expected occurrences, resulting in the large significant χ^2 value of 27 (deficit). In the second sample, the 150 occurrences during El Nino years were greater than the 121 expected occurrences, resulting in the large significant χ^2 value of 10 (excess). The cardinal temperatures in the two samples were ≤ –19 ºC (-3 ºF) in deficit and ≤ –12 ºC (+11 ºF) in excess, respectively.

For each overlapping 3-wk period and scan, our computer output included the maximum χ^2, the accumulated counts of daily weather occurrences, and associated cardinal values. we assigned the χ^2 value of each 3-wk sliding window to the center week. Section A of Figures 1-4 gives 3-wk running averages of the weekly χ^2 values. The cardinal value of the most statistically significant week within each significant period was entered near the appropriate peak shown in Figures 1 to 4. Reference in the text to an association is usually made only if the association was significant for a period of > 2 consecutive weeks.

Table 1. Counts, cardinal temperatures, and chi-square for El Nino vs. 'normal' years for the 3-wk periods centered on 7 Jan and 7 Mar using the low to high scans of extreme low daily minimum temperature

3-wk center date	Scan direction	El Nino year's count	Normal year's count	Cardinal temperature	Chi-square
7 Jan	Low-high	43	200	≤ -19ºC (-3 ºF)	27 (deficit)
7 Mar	Low-high	150	212	≤ -12ºC (+11 ºF)	10 (excess)

Determination of Size of Departure from Normal

Applying the iterative chi-square method offers a number of advantages. The method requires no limiting assumptions as to linearity. In addition, the method provides measures of significance and gives threshold values ≥ and ≤ when there are significant responses of the climatic elements to the El Nino effect. Also, use of daily weather provides 1-wk resolution to determine the effect of El Nino on occurrence of extreme daily weather elements. Caprio et al. (2003) provide a more detailed description of the iterative chi-square method with examples of the interpretation of computer output in a paper on tree ring weather relations, along with comparisons with some other statistical methods.

For each overlapping 3-wk period during 31 wk from 26 Nov to 30 Jun, i.e., 29, 3-wk periods, we calculated the difference in the number of extreme days in the 25 El Nino yrs compared to one half the number of extreme days in the 50 ‘normal’ yrs. This value divided by 25 (number of yrs) gives the difference in number of days/year during that 3-wk period. In turn, this value divided by three (number of wks) gives the difference in the mean number of extreme days/week. We calculated 3-wk running averages of these weekly values. Thus, smoothed weekly values of the difference in number of extreme days/week were then divided by 7 (days/wk) and multiplied by 100 to yield the average daily percent of an extreme daily weather due to the El Nino. These daily percentage values were plotted for each week in the B- sections of Figures 1-4. For example, if each day within a particular week during an El Nino year had an average of one-tenth (or 10%) of a day greater extreme daily occurrence due to the El Nino effect, this was referred to as a 10-percent climate change. Since one day represents 14.3 percent of a week, percentages shown in the B-section of the graphs indicates one day of climatic change/week for each 14 percent. Thus, seven percent on the graph represents 0.5 day of climatic change/week.

Percentages in the tables and in part B of the graphs indicate the increase or decrease in percent of a day within each particular week of an El Nino year having an extreme daily weather occurrence due to the El Nino effect. For example, if the percentage for a particular week is indicated in a table or in the B section of the graph as 10 percent, it indicates that each day within that week of an El Nino year had an extra 0.1 day of an extreme weather event due to the El Nino effect.

RESULTS AND DISCUSSION

Chi-Square Test for Extreme High Daily Maximum Temperature (High-Low Scan)

Our data indicated an excess of days of extreme high maximum temperature during 15 of the 29 wks of the study, whereas no weeks had a deficit of days of extreme high maximum temperature (Fig. 1). The excess of extreme high daily maximum temperature was most numerous during two periods (Table 2).

Maximum χ^2 of 23 occurred during weeks 22-23 (27 May-9 Jun) with a CT of

Table 2. Data on two periods that had a significant increase in the number of days of extreme high minimum temperatures due to El Nino.

Weeks	Dates	Max weekly χ^2	Daily average period change*	Dates of Max χ^2 wks	Daily average change of Max χ^2 wks*	Cardinal temp of Max χ^2 wks
3 - 8	14 Jan – 24 Feb	15	+8.6%	28 Jan – 3 Feb	+16%	≥ 1°C (+33°F)
17 - 25	22 Apr – 2 June	23	+5.7%	27 May – 9 June	+8%	≥ 27°C (+81°F)

* Positive signs indicate the average fraction of a day (in percent) increase in extreme high daily minimum temperatures during the two intervals that were attributable to El Nino.

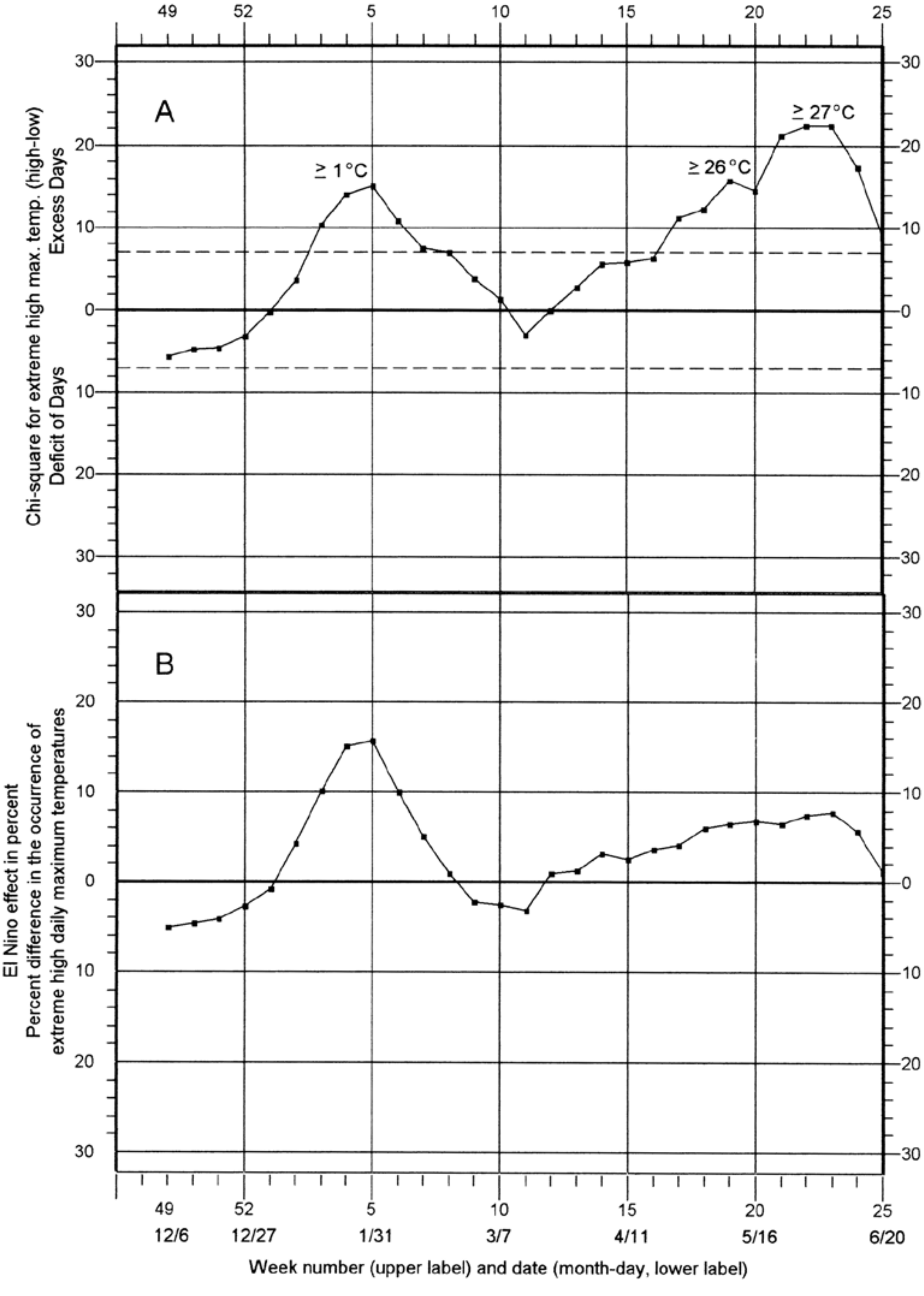

Figure 1. (A) Significance of the difference in the number of extreme high maximum temperature days during the 25 El Nino years compared to the 50 normal years. Cardinal values (the extreme high maximum temperature occurrence during the week of maximum χ^2) are indicated on the graph. Chi-square values =7 (indicated by the dotted lines) are the critical values for significance (P=0.01, 1df).

(B) For each date (plotted weekly) in an El Nino year, the average percent that had an extreme high maximum temperature occurrence due to the El Nino effect.

≥ 27 ºC (81 ºF). Departure from normal during this period was an increase of 8 percent. However, the maximum percentage departure from normal occurred during week 5 (28 Jan-3 Feb) with an increase of 16 percent associated with a χ^2 of 15 and a CT of ≥ 1 ºC (33 ºF). Considering seven percent as the level for 0.5 day/wk as the El Nino effect and 14 percent as the level for 1 day/wk, we can make the following interpretations:

1. For extreme high maximum temperatures there were 8 wks with at ≥ 1 day increase associated with the El Nino and 2 wks that had at ≥ 1 day/wk increase associated with the El Nino.

2. We observed no weeks with low maximum temperature cooling associated with the El Nino.

3. The greatest percentage increase in extreme maximum temperatures occurred during week 5 (28 Jan-3 Feb) when we detected a 16 percent increase. Whereas the biggest departure from normal occurred during winter (14 Jan-24 Feb), a greater number of days of extreme high maximum temperatures occurred during weeks 17-25 (22 Apr-23 Jun), as indicated by the large chi-square values, but with a percentage increase consistently < 8 percent. This was consistent with earlier onset of spring, which has been reported previously for this region (Cutforth et al. 1999, Cayan et al. 2001).

4. During the first significant departure period (14 Jan-24 Feb), peak response occurred during week five (28 Jan-3 Feb) when an excess of extreme daily maximum temperatures ≥ +1 ºC (+33 ºF) occurred. During this 6-wk period, occurrence of extreme maximum daily temperatures averaged 26 percent more frequently, i.e., 249.5 vs. 198, during El Nino years than during normal years.

Additional comparisons can be made for each significant departure period using information from the associated table and text. An example is given below for the significant departure period covering weeks 3-8 (14 Jan-24 Feb) for extreme high daily maximum temperature at Bozeman. Since the 0.086 fraction of extreme days from Table 2 represents a 26-percent increase of the fraction of extreme days compared with ‘normal’ years, i.e., 249.5/198 x 100 = 26 percent, the fraction of extreme days in normal years equates to 0.331, i.e., 0.086/0.26 = 0.331, and the total fraction of extreme days in El Nino years is 0.331 plus 0.086 which equals 0.417. Given that the percent of extreme days in normal years is 33.1 percent while the percent of extreme days in El Nino years is 41.7 percent, the percent of non-extreme days in normal and El Nino years is 66.9 and 58.3 percent, respectively.

During the second significant period (22 Apr-23 Jun) peak response occurred during weeks 22-23 (27 May-9 Jun) when an excess of daily maximum temperatures ≥ +27 ºC (+81 ºF) occurred. During this 9-wk period the occurrence of extreme maximum daily temperatures averaged 67 percent more frequent during El Nino years than during normal years. We determined for all 29 wks combined that El Nino years averaged 20 percent more days, i.e., 119.9 vs. 100.2, with extreme high maximum temperature than normal years.

Chi-Square Test for Extreme Low Minimum Temperature (Low-High Scan)

We detected a deficit of days of extreme low minimum temperatures during the El Nino years during 7 of the 29 wks of the study (Fig. 2). The deficit of days extended from 7 Jan to 24 Feb. Alternatively, there was an excess of days of extreme low minimum temperatures during only 2 of the 29 wks, from 4 to 17 Mar (Table 3). Maximum χ^2 of 32 occurred during week 5 (28 Jan-3 Feb) with a CT of ≤ -19 ºC (-3 ºF). The percent change during this week was a decrease of 12 percent.

For extreme low minimum temperatures there were 5 wks that had ≥ 0.5 day decrease associated with the El Nino and 2 wks that had nearly 1 day/week decrease associated with the El Nino (Fig. 2). The greatest percentage decrease in extreme low minimum temperature occurred during weeks 4 and 5 (21 Jan-3 Feb) when we

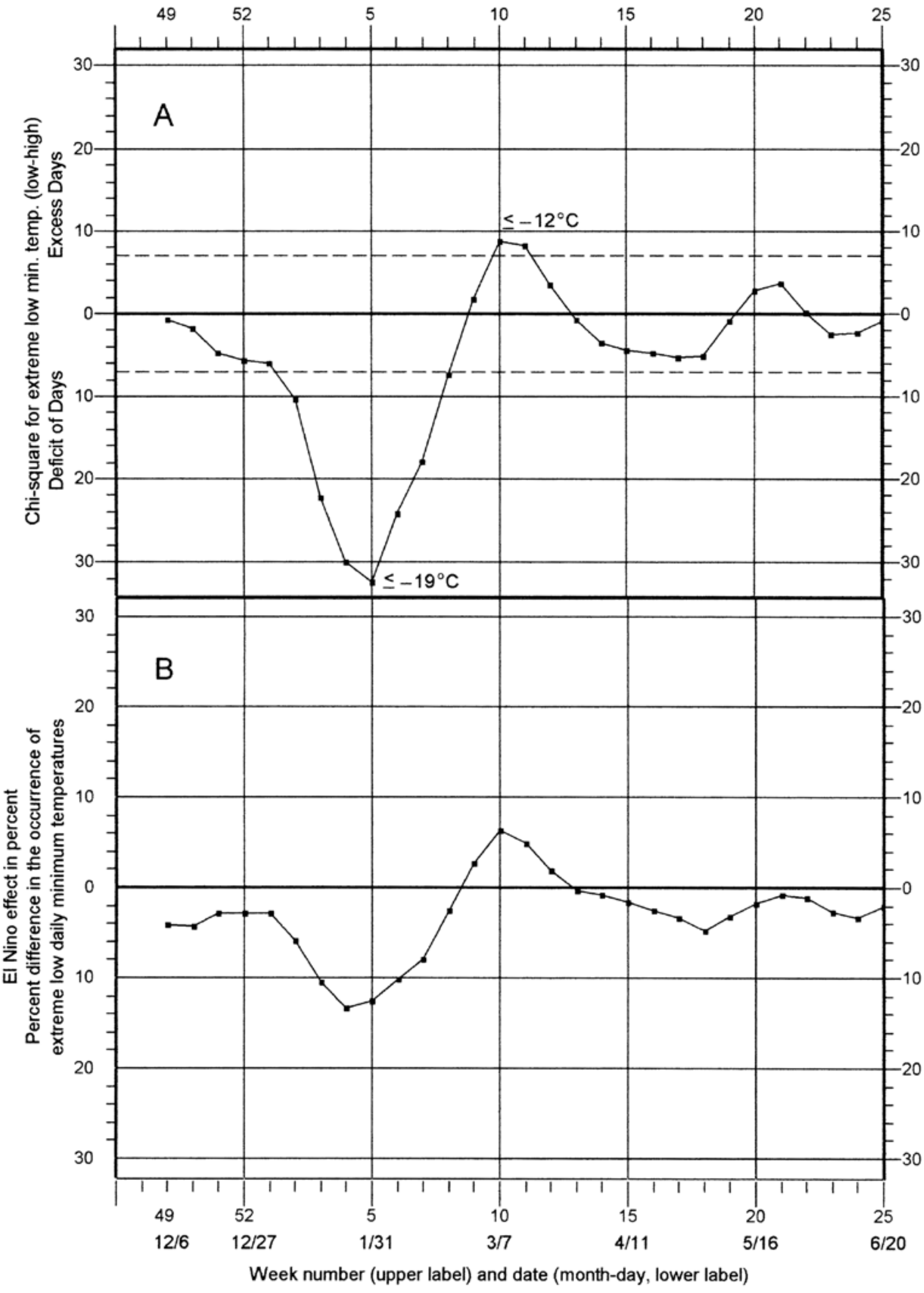

Figure 2. (A) Significance of the difference in the number of extreme low minimum temperature days during the 25 El Nino years compared to the 50 normal years. Cardinal values (the extreme low minimum temperature occurrence during the week of maximum χ^2) are indicated on the graph. Chi-square values =7 (indicated by the dotted lines) are the critical values for significance (P=0.01, 1df).

(B) For each date (plotted weekly) in an El Nino year, the average percent that had an extreme low minimum temperature occurrence due to the El Nino effect.

Table 3. Data on the seven-week period that had a significant decrease in the number of days of extreme low minimum temperatures due to El Nino.

Weeks	Dates	Max weekly χ^2	Daily average period change*	Dates of Max χ^2 wks	Daily average change of Max χ^2 wks*	Cardinal temp of Max χ^2 wks
2 - 8	7 Jan – 24 Feb	32	-9.0%	28 Jan – 3 Feb	-12%	< -19°C (-3°F)

* Negative sign indicates the average fraction of a day (in percent) decrease in extreme low daily minimum temperatures during the interval that was attributable to El Nino.

detected a 13-percent decrease. Peak response during 7 Jan-24 Feb occurred during week 5 (28 Jan-3 Feb) when a deficit of extreme daily minimum temperatures ≤ -19 ºC (-3 ºF) occurred. During this 6-wk period, occurrence of extreme daily minimum temperatures averaged 50 percent less frequent during El Nino years than during normal years. El Nino years averaged 18 percent fewer days, i.e., 71.6 vs. 87.6, for all 29 wks combined with extreme low daily minimum temperature than normal years.

Chi-Square Test for Extreme High Precipitation (High-Low Scan)

We detected a deficit of days of high precipitation during El Nino years during 13 of 29 wks of the study (Fig. 3). Only during weeks 14-15 (1-14 Apr, 21.6 mm) the analysis indicated that high precipitation days were more frequent during the December-June period of the 25 El Nino years. Ten of 12 total days that had precipitation amounts of ≥ 12.7 mm (0.50 in) occurring during weeks 14-15 (1-14 Apr) coincided with unusually warm January SSTA of ≥ +1.00 °C. These 10 days with large precipitation amounts occurred during eight different El Nino years.

The deficit of days with heavy precipitation was significant during two periods (Table 4). Maximum χ^2 of 7 occurred during week 6 (4-10 Feb) and χ^2 of 8 for week 23 (3-9 Jun) both with a CT of 1.3 mm (0.05 in; Table 4). For high precipitation there were only 2 wks that had ≥ 0.5 day of decrease of high precipitation (Fig. 3). The greatest percentage decrease in high precipitation amounts occurred during week 23 (3-6 Jun) when we detected an 8-percent decrease. This study did not compare total accumulated precipitation during El Nino years with that during normal years. However, a previous report by the National Weather Service indicated that the South-central Crop District of Montana received only 74 percent of normal precipitation during El Nino years (National Weather Service 2003).

Peak response during the first significant period (4 Feb-17 Mar) occurred during week 7 (4-10 Feb) when a deficit of high precipitation days ≥ 1.3mm (0.05 in) occurred. During this 6-wk period, high precipitation days averaged 41 percent fewer during El Nino years than during normal years. Peak response during the second significant period occurred during weeks

Table 4. Data on two periods that had a significant decrease in the number of days of extreme high precipitation days due to El Nino.

Weeks	Dates	Max weekly χ^2	Daily average period change*	Dates of Max χ^2 wks	Daily average change of Max χ^2 wks*	Cardinal temp of Max χ^2 wks
5 - 11	4 Feb – 17 Mar	7	-2.1%	28 Jan – 10 Feb	-3%	≥ 1.3 mm (0.05 in)
22 - 23	27 May – 9 June	8	-6.6%	27 May – 9 Jun	-8%	≥ 1.3 mm (0.05 in)

* Negative signs indicate the average fraction of a day (in percent) increase in extreme high daily precipitation during the two intervals that were attributable to El Nino.

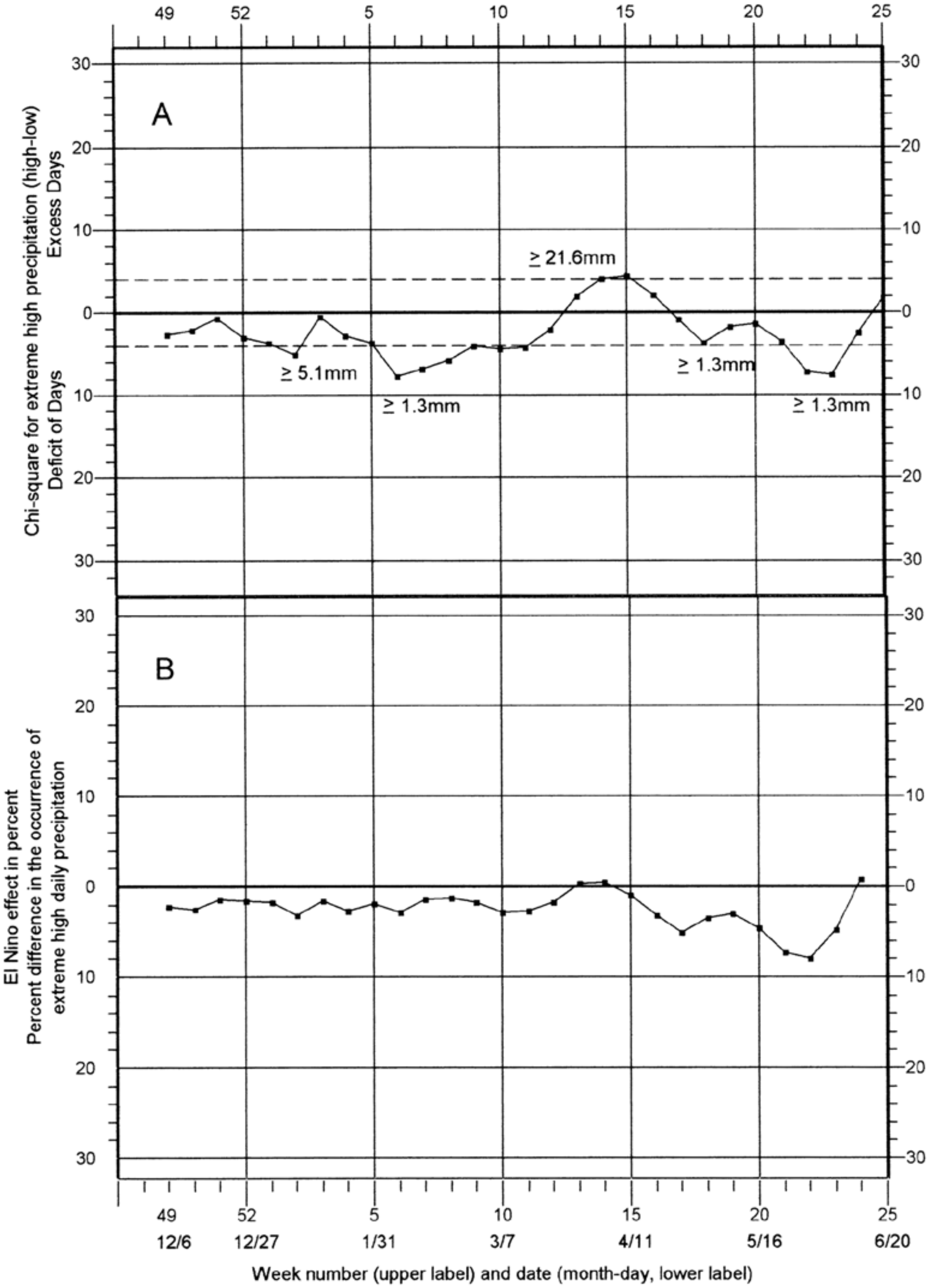

Figure 3. (A) Significance of the difference in the number of high precipitation days during the 25 El Nino years compared to the 50 normal years. Cardinal values (the extreme high precipitation occurrence during the week of maximum χ^2) are indicated on the graph. Chi-square values =7 (indicated by the dotted lines) are the critical values for significance (P=0.05, 1df).

(B) For each date (plotted weekly) in an El Nino year, the average percent that had a high precipitation occurrence due to the El Nino effect.

22-23 (27 May-9 June) when a deficit of high precipitation days > 1.3mm (0.05 in) occurred. During this 2-wk period, high precipitation days averaged 24 percent fewer during El Nino years than during normal years. We determined that for the entire 29-wk study period, El Nino years averaged 21 percent fewer days, i.e., 48.9 vs. 61.7, with high precipitation amounts than normal years.

Chi-Square for Extreme Small Diurnal Temperature Range (Low-High Scan)

There was a deficit of extreme small diurnal temperature ranges during El Nino years during seven of the 29 wks of the study (Fig, 4), with no periods of excess (Table 5).

Maximum χ^2 of 13 occurred during week 22 (27 May-3 Jun) with a CT of 14 ºC (25 ºF), representing a 12-percent decrease during this week. For the deficit of extreme small diurnal temperature ranges there were 4 wks that had ≥ 0.5 day associated with the El Nino and no weeks that had at least one whole day/week decrease associated with the El Nino.

During the first significant period (18 Feb-10 Mar), peak response occurred during weeks 8-10 (18 Feb-10 Mar), when a deficit of small diurnal temperature range days ≤ 8 ºC (15 ºF) occurred (Table 5); this occurrence of extremely small diurnal temperature-range days averaged 29 percent fewer during El Nino years than during normal years. During 13 May-9 Jun, peak response occurred during week 22 (27 May-2 Jun) when a deficit of small diurnal temperature range days ≤ 14 ºC (25 ºF) occurred. During this 4-wk period, occurrence of extreme small diurnal temperature days averaged 26 percent fewer during El Nino years than during normal years. For the entire 29-wk study period, El Nino years averaged 18 percent fewer days, i.e., 86.7 vs. 105.2, with extreme small diurnal temperature ranges than normal years.

SUMMARY AND CONCLUSIONS

These results were consistent with other studies on the effect of El Nino on temperature and precipitation in Montana (Sittel 1994, Green et al. 1997, Bernhardt 2002, NOAA 2003). This analysis indicated that based on 100 yr of climate record, Bozeman's local climate was significantly impacted by the El Nino conditions. The 29-wk study period from 3 Dec to 23 June was characterized by a greater number of extreme high daytime temperatures, a deficit of extreme low nighttime temperatures, a deficit of high precipitation days, and a deficit of days with extremely small diurnal temperature ranges. We determined the difference between El Nino years and normal years to be about 20 percent for each of these four extreme daily weather conditions.

The influence of El Nino on daytime temperatures was most significant during the period from about mid January to mid February and from about mid April to early June, during which time a greater number of extreme high daytime temperatures occurred. Peak percent increase of extreme high daytime temperatures occurred

Table 5. Data on two periods that had a significant decrease in the number of days of extreme small diurnal temperatures due to El Nino.

Weeks	Dates	Max weekly χ^2	Daily average period change*	Dates of Max χ^2 wks	Daily average change of Max χ^2 wks*	Cardinal temp of Max χ^2 wks
8 - 10	18 Feb – 10 Mar	7	-4.7%	18 Feb – 10 Mar	-5%	< 8°C (15°F)
20 - 23	13 May – 9 June	13	-9.8%	27 May – 2 June	-12%	< 14°C (25°F)

* Negative signs indicate the average fraction of a day (in percent) increase in extreme high daily diurnal temperatures during the two intervals that were attributable to El Nino.

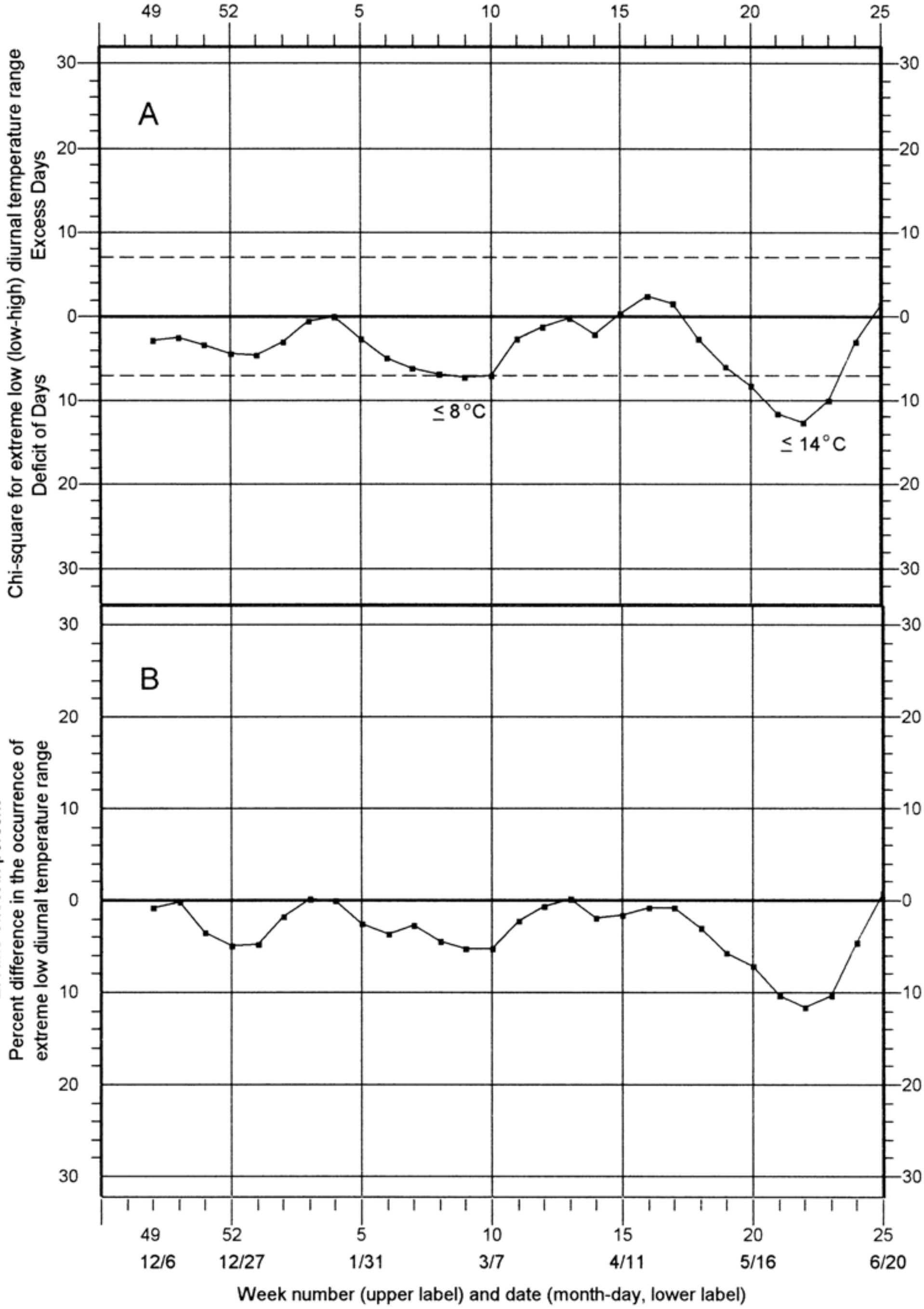

Figure 4. (A) Significance of the difference in the number of low diurnal temperature range days during the 25 El Nino years compared to the 50 normal years. Cardinal values (the extreme low diurnal temperature occurrence during the week of maximum χ^2) are indicated on the graph. Chi-square values =7 (indicated by the dotted lines) are the critical values for significance (P=0.01, 1df).

(B) For each date (plotted weekly) in an El Nino year, the average percent that had a low diurnal temperature range occurrence due to the El Nino effect.

during these two periods at 13 and nine percent, respectively. Extreme high daytime temperatures during the most significant period (22 Apr-23 June) averaged 67 percent more frequent during El Nino years than during normal years.

The influence of El Nino on extreme low nighttime temperatures was most significant during the period from about early January to late February during which time a deficit of extreme low nighttime temperatures was experienced. The greatest decrease in extreme low nighttime temperatures was 12 percent. During the one significant period (7 Jan-24 Feb), extreme low nighttime temperatures averaged 50 percent less frequent during El Nino years than during normal years.

The influence of El Nino on fewer days of high precipitation amounts was most significant during the periods from about early February to mid March and from late May to early June. The greatest percentage decreases of high precipitation amounts observed during these two periods were three and eight percent respectively. High precipitation days during the most extreme precipitation periods, 28 Jan-17 Mar and 20 May-9 Jun, averaged 44 and 24 percent less frequently during El Nino years than during normal years.

The influence of El Nino on the deficit of extreme small diurnal temperature ranges was most significant during the period from about mid February to mid March and from about mid May to early June. Peak percent deficit of extreme small diurnal temperature ranges during these two periods were seven and 13 percent, respectively. Extremely small diurnal temperature range days during the most significant period (13 May-9 Jun) averaged 29 percent less frequently during El Nino years than during normal years.

This approach to determine extreme daily weather associated with the El Nino can be applied at any location for which an uninterrupted long daily weather record is available. The technique provides important information concerning the specific time when El Nino-caused extreme daily weather occurrences may be expected with a time resolution of one week. This procedure revealed extreme high or low thresholds (≥, or ≤) of the most significant climatic elements; thus, the analyst is not required to select arbitrary extreme thresholds for each climate element. Important information is provided on significant levels and percent of extreme daily weather occurrences that can help assess the potential impact of an El Nino event.

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