TREE-RING RESEARCH, *Vol. 59(2), 2003, pp. 99–113*

A CHI-SQUARE TEST FOR THE ASSOCIATION AND TIMING OF TREE RING-DAILY WEATHER RELATIONSHIPS: A NEW TECHNIQUE FOR DENDROCLIMATOLOGY

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ABSTRACT

This study introduces a new analytical procedure based on the chi-square (χ^2) statistic to evaluate tree-ring weather relationships. An iterative χ^2 method, developed previously for relating annual crop production to daily values of meteorological measurements, is applied to tree-ring data and compared to results obtained from correlation and bootstrapped response function analyses. All three analytical procedures use a southern Arizona chronology (*Pinus arizonica* Engelm.) and the latter two use monthly average meteorological data. The χ^2 analysis revealed most of the relationships exhibited by the correlation and response function analyses as well as new linear and nonlinear associations. In addition, cardinal values were obtained that define daily thresholds of the meteorological variables at which the limitation to growth becomes significant. Some of the associations are plausible from the physical system but require more study to confirm or refute a real cause and effect. A few associations appear to be too late in the season or too early in the previous year to affect ring width. We recommend that this χ^2 technique be added to the existing dendroclimatic procedures because it reveals many more possible cause and effect relationships.

Keywords: dendroclimatology, tree rings, chi-square, daily weather, response function analysis.

INTRODUCTION

Identification of the meteorological variables that influence tree-ring width is usually one of the early steps in the dendroclimatic reconstruction process. Two widely used statistical approaches to such identification are correlation and response function analyses, typically on monthly meteorological data (Fritts 1976; Gray *et al.* 1981; Fritts and Wu 1986; Guiot 1991). The tree-ring response to climate is assumed to be time-invariant in these approaches, but the Kalman filter is available for identifying responses that evolve through time (*e.g.* Van Deusen 1987; Visser and Molenaar 1990).

An important assumption in these methods is linearity of response. In terms of a simple bivariate relationship, an implication of linearity is that the tree-ring departures from normal are scaled proportional to the climatic anomalies from normal, and that the relationship is applicable across the full range of the climatic variable. Caprio and Quamme (1999, 2002) make no such assumption of linearity in an iterative chi-square (χ^2) method that they applied to identify the meteorological variables important to crop production. Weather anomalies over a few days or weeks at a critical time of the growing season are recognized as critical to the success or failure of a crop. The method relies on daily rather than monthly weather data. Threshold phenomena (*e.g.* critical low temperature) are specifically addressed by the method, and it is possible to identify asymmetric responses—for example, growth reduced in response to anomalously high temperature but unaffected by anomalously low temperature.

Caprio (1966) described the conceptual basis and details of the iterative χ^2 technique. The technique was developed to identify periods of weather that critically impact small grain crops and rangeland in Montana (Caprio and Williams 1973) and was used to identify critical daily weather conditions that contribute to the winterkill of wheat (Caprio and Snyder 1984; Kalma *et al.* 1992). The analytical methods used in this study were described in two recent papers on critical daily weather events that impact the production of apples and grapes in the Okanagan Valley of British Columbia (Caprio and Quamme 1999, 2002).

It is reasonable to assume that nonlinear relationships and threshold responses might be present in the tree-ring response to weather. Plant physiological responses to the atmospheric environment are typically curvilinear (Grace *et al.* 1981; Jones 1983). Tree-growth sensitivity to weather anomalies could plausibly be amplified at times depending on the phenology of the tree. With the exception of work on event years or pointer years (Schweingruber 1996), little quantitative information is available on how daily weather affects tree growth. Brief weather occurrences that are critical for ring growth, such as one or more days of a severe freeze or a short period of extremely hot desiccating winds, are unlikely to be detected in analyses that use monthly mean meteorological data. This paper describes the application of the iterative χ^2 method to the analysis of tree-ring chronologies. We apply this method to the interpretation of an Arizona pine (*Pinus arizonica* Engelm.) chronology from the Santa Catalina Mountains of southern Arizona. For comparative purposes, we also report the results of correlation and response function analyses.

METHODS

A 104-year standardized chronology, 1895–1998, derived from nine trees (four cores per tree) was used as the dependent tree-ring data. The ring widths were dated by conventional methods, the dating checked by program COFECHA (Holmes 1983; Grissino-Mayer 2001), and standardization accomplished using program ARSTAN (Cook 1985). The meteorological data for this test consist of daily measurements for the Palisades Ranger Station (32°25′N, 110°43′W, 2,422 m). This station is located within 2 km of the tree-ring site and at approximately the same elevation. Missing weather data were estimated from neighboring stations to obtain a continuous meteorological record from 1895–1998 (Fritts *et al.* 2002).

Correlation analysis and bootstrapped response functions were run using program PRECON (Fritts *et al.* 1991). The simple correlations between ring-width indices and monthly average maximum meteorological data are based on the period 1900–1998. For the response functions, the correlations among the 14 monthly temperature and precipitation series (previous year's July through current year's August) were calculated for 1900–1998, and the correlation matrix was rotated to obtain new orthogonal principal components (Fritts 1976). An unbiased "best fit" between the principal components of the meteorological variables and standardized indices was obtained by a bootstrap regression procedure (Efron 1976). These regression estimates are rotated back into the domain of the original meteorological variables to obtain the response function weights (Guiot 1991). The χ^2 analysis includes both the year prior to ring growth and the year of ring growth.

For the χ^2 analysis, the 104 annual growth indexes are ranked from smallest to largest and divided into quartiles. The χ^2 test is then used to compare the daily weather occurrences during the 26 widest (good) and the 26 narrowest (poor) ring-width years with the daily weather occurrences during the 52 "normal" ring-width years (mid-quartiles). A sliding window of three weeks is used with each period in succession, adding a new week and dropping the first week as the three-week time frame advanced. The first period includes days 1–21 of the year prior to the year of ring growth. The second period includes days 8–28, *etc.*, continuing to the end of the year of tree-ring growth.

The weather data were recorded in Imperial units. Thus, the program was run with tables and graphs produced in those units. The meteorological data were recorded in whole °F (temperature) or 0.01 inches (precipitation). To allow for a number of observations in most contiguous classes, temperature was broken down into classes of two degrees Fahrenheit and precipitation into classes of one-tenth of an inch. The data for each climatic variable were sorted from high to low. Tallies were made of the frequency with which the data fell into each class. For a given three-week period and for a given climatic variable, the χ^2 statistic was used to test the significance of the difference in frequency of days between an extreme tree-ring quartile and the two combined mid-quartiles (a two-category chi-square table with one degree of freedom).

For each extreme class of widest or narrowest rings, the total number of daily occurrences for each three-week period is 546 (21 days × 26 years). The total number of days in the normal production category is 1,092 (21 days × 52 years). The χ^2 test is applied to the total number of days accumulating in each class of a variable in succession ordered high to low (high-low scan) or low to high (low-high scan) generating χ^2 values for each class in both scans. The first χ^2 value in the high to low scan, for example, is for the data in the first (highest) class, the second for the data in the first plus the second (next highest) class, *etc.* The low to high scan starts with the first (lowest) class.

If the counts during each of the extreme quartiles deviated from the expected 1:2 ratio from the combined mid quartiles, the χ^2 values generated in the scan increase in periods when there is a direct relationship between ring width and climate, reach a maximum, then decrease beyond the point where the direct relationship ceases to exist. At the maximum χ^2 (or turning) point in a given scan, the precipitation or temperature at that point is referred to as the "cardinal" value. When the χ^2 value peaks in a contiguous sequence of weekly significant χ^2 values, the cardinal value at that point is taken as the critical level at which the meteorological element most likely impacts on the plant. Chi-square probability levels are not strictly applicable when counts of the daily weather elements are small (Snedecor 1946). However, χ^2 values based on low counts tend to be insignificant and superseded by larger χ^2 values in the classes further up (or down) in the scan. Cardinal values for temperature and precipitation are abbreviated CT and CP, respectively. For each overlapping three-week period, scan, and extreme class, the computer generates the maximum χ^2, the accumulated counts of daily weather occurrences, and the associated cardinal value of the climatic element being scanned.

A minus sign is assigned to the χ^2 value when the occurrences in the extreme quartiles are less than expected (inverse relationship). Scans in both directions are necessary to reveal the direction of the impact of the critical level. In high-low scans, cardinal values represent thresholds at and above which growth is impacted, whereas in low-high scans the cardinal value represents a threshold at and below which growth is impacted. For example, if freezing air temperature is limiting to growth, the low to high scan will show that all temperatures at 32°F (0°C) and lower will be associated with low growth. On the other hand, if growth is limited at and above a particular high temperature, the high to low scan will reveal it.

The iterative χ^2 method provides a way to determine whether the number of daily occurrences of the climatic element during good (or poor) years differs significantly from the expected number of occurrences of the climatic element during normal years. If there is no difference in the expected number of climatic events, then there will be half as many occurrences in the 26 good (or poor) years as in the 52 normal years. If the departure of the occurrences from this 1:2 ratio is small, it may be random and not indicative of a climatic difference. However, if the departure is large, there is a possibility that the number of daily climatic occurrences differs significantly during the good (poor) years relative to the normal years.

The χ^2 values for temperature are considered significant when they are equal or greater than 7. A χ^2 value of 7 (rounded up from the actual value of 6.63) is statistically significant at $p < 0.01$ (df $= 1$). The significance value of χ^2 for precipitation is 4 (rounded up from the actual value of 3.84, $p < 0.05$, df $= 1$) because a large percentage of days are without precipitation and in view of the large spatial variability of precipitation. A χ^2 value equal to and larger than the significance level denotes that the sample has less than 0.01 probability for temperature and 0.05 probability for precipitation of occurring by chance. The hypothesis that the effects of climate are the same during the good (or poor) years relative to normal years is then rejected. The larger the χ^2 value, the higher the probability that there is a real climatic effect on ring-width growth. Peaks and troughs in the χ^2 values plotted against time of year reveal those periods when, and at which level, each climatic element is likely to have affected growth.

As an example, consider the freezing point (0°C) as the temperature at which a plant is killed, keeping in mind that temperatures below that will also kill the plant. As the χ^2s are computed for each succeeding class (in the low to high scan), accumulating more climatic occurrences in the scanning process, the χ^2 values initially will be small but will increase towards the class that includes the 0°C. The initial χ^2s in the scan are typically less because fewer climatic occurrences are included in the χ^2 computation than in the further accumulation of occurrences at higher temperatures. After the class that includes temperatures above 0°C is added into the accumulation of occurrences, the χ^2 will begin to decrease. This decrease in χ^2 occurs because the departures from the one to two ratio further up on the scan will be small. The conclusion to be reached from the scan of low to high is that minimum temperatures equal and less than 0°C are critical and 0°C is designated as the cardinal temperature.

Table 1. Counts, cardinal temperatures, and χ^2s for poor *vs.* normal tree-ring width years for the three-week period centered on February 22 of the year prior to growth using the low to high and high to low scans of daily minimum temperature.

Scan Direction	Poor Count	Normal Count	Cardinal Temperature	χ^2
High–Low	308	741	≥ -4°C	10 (deficit)
Low–High	177	219	≤ -6°C	25 (excess)

To illustrate how the χ^2 value is computed, consider a low to high scan for minimum daily temperature for poor versus normal ring-width years. In the equation below, *A* and *E* represent actual and expected number of occurrences, respectively. The letters *p* and *n* are for poor and normal years, respectively.

$$\chi^2 = \frac{(Ap - Ep)^2}{Ep} + \frac{(An - En)^2}{En}$$

$$= \frac{(177 - 132)^2}{132} + \frac{(219 - 264)^2}{264} = 25$$

The total number of daily minimum temperature occurrences in this example is 177 + 219 or 396 (Table 1). The 396 occurrences are expected to be proportioned in a ratio of one to two or 132 for poor years and 264 for normal years. The 177 occurrences during poor years exceed the 132 expected occurrences, resulting in the large significant χ^2 value of 25. In this example, a low-high scan revealed that an excess of daily minimum temperatures ≤ -6°C was significantly associated with narrow rings. In the high to low scan, a deficit of daily minimum temperature ≥ -4°C was also significantly associated with narrow rings (Table 1). However, the lower chi-square value denotes a lower probability that it is as significant as the excess of daily minimum temperature ≤ -6°C. Here, the cardinal minimum temperature is -6°C rather than 0°C used in the hypothetical example above.

Precipitation can limit plant growth at any time of the year related to drought or periods of excessive precipitation. The high to low scans for precipitation are generally most useful. The low to high scans for precipitation include many days with no precipitation, so these χ^2 tests rarely reach statistical significance (Caprio and Snyder 1984). Diurnal temperature range, in itself, is usually not a limiting factor in crop yield, but scans of diurnal temperature range are included in the computer output. They are not included here to save space, as they contributed little to the understanding of the impact of the daily weather events on this ring-width chronology.

The technique uses four different scans for each climatic element, *i.e.* the high-low and low-high scans for both the narrow and wide rings. For each of the four scans, the maximum χ^2 value is generated for each weekly time step. Significant differences in scans using wide compared to narrow rings indicate the presence of nonlinear relationships. Running averages of three contiguous three-week running average χ^2 values are calculated and plotted. Given the large annual variability of both the weather and the timing of phenological events (Cayan *et al.* 2001), it may be expected that plant-weather associations will follow a smooth pattern of change from week to week. This running average smoothing procedure was found to generate a more reasonable pattern of plant-weather associations (Caprio and Quamme 1999, 2002). The running average χ^2 value for each week represents a sample over five weeks weighted 1-2-3-2-1. Reference to associations is usually made only if the running average χ^2 is statistically significant for two or more contiguous weeks.

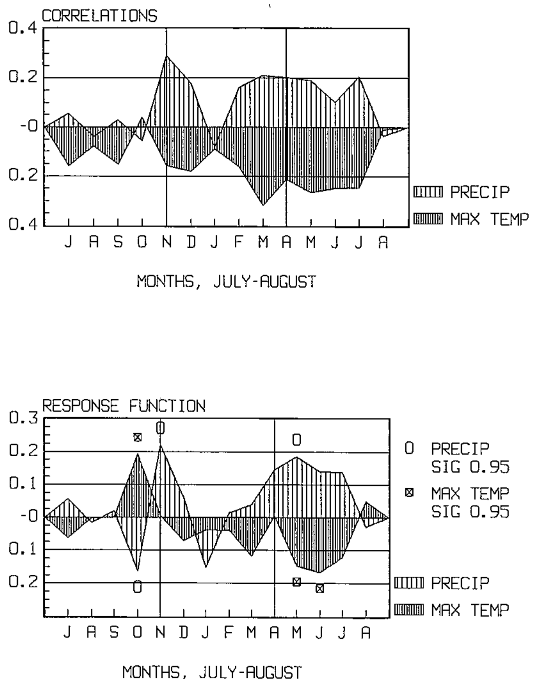

Figure 1. Correlation (top) and bootstrapped response function (bottom) results of mean monthly maximum temperature and total monthly precipitation with annual indices from *Pinus arizonica* in the Santa Catalina Mountains of Arizona. Correlations ≥ |0.2| are significant ($p < 0.05$).

RESULTS AND INTERPRETATIONS

Response Function and Correlation Analyses

The correlations reflect significant direct relationships between precipitation and tree-ring width for previous (P) November and current (C) March, April, and July, and an inverse relationship between maximum temperature and ring width from March through July (C) (Figure 1, top). The response function reflects a significant inverse relationship between precipitation and direct relationship with maximum temperature in October (P) (Figure 1, bottom). This is a time when the growth processes for the prior year are becoming dormant but photosynthesis persists into the autumn periods, when clear cloudless days are associated with high maximum temperatures that favor photosynthate accumulation for the next year's growth. By November (P), the temperature is usually too low for high rates of photosynthesis but precipitation becomes directly and significantly related to growth. In spring, maximum temperature becomes significantly inversely related to ring width in May and June (C), while precipitation becomes significant directly related to ring width in May (C). Correlations and a response function were also obtained for maximum temperatures including the entire 24 months for comparison with the χ^2 results. Plots are not included here, but important results are discussed below.

χ^2 Analysis using Daily Meteorological Variables

In Figures 2 through 5, the three-week running averages of the weekly χ^2 values are plotted, and cardinal values are usually given only if the as-

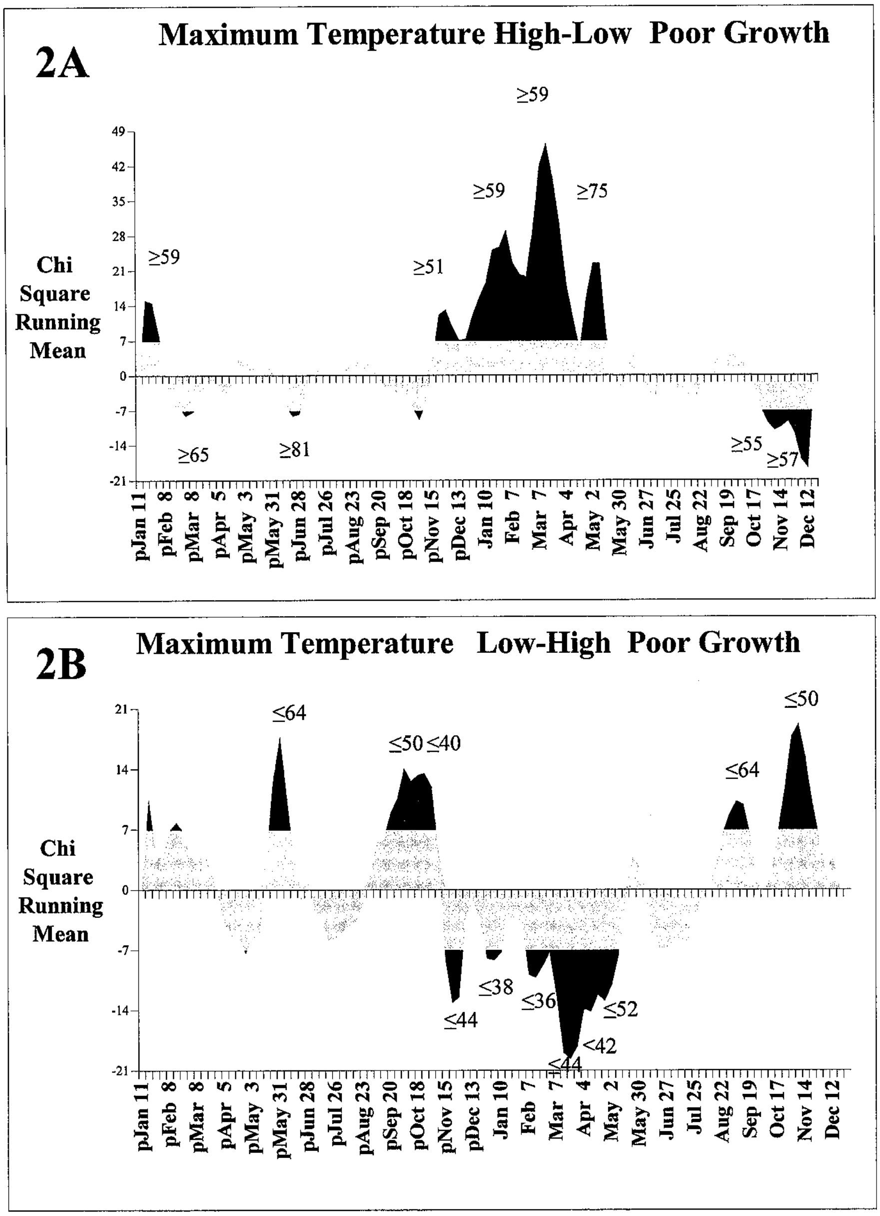

Figure 2. Three-week running average of the weekly χ^2 values for maximum temperature, narrow ring years versus normal growth years, high-low (A) and (B) low-high scans. Numbers above and below significant peaks are temperature (°F). Negative peaks indicate deficiency, positive peaks indicate excess.

sociation was statistically significant for a period of more than one week. The dates on the x-axis refer to the central day of the central week of each period. The peak weekly cardinal value for a given significant period is usually associated with a peak 3-week running χ^2 value, but if not, the cardinal value of the most statistically significant original week within each significant period is entered near the appropriate peak shown in the figures (Caprio and Quamme 1999, 2002).

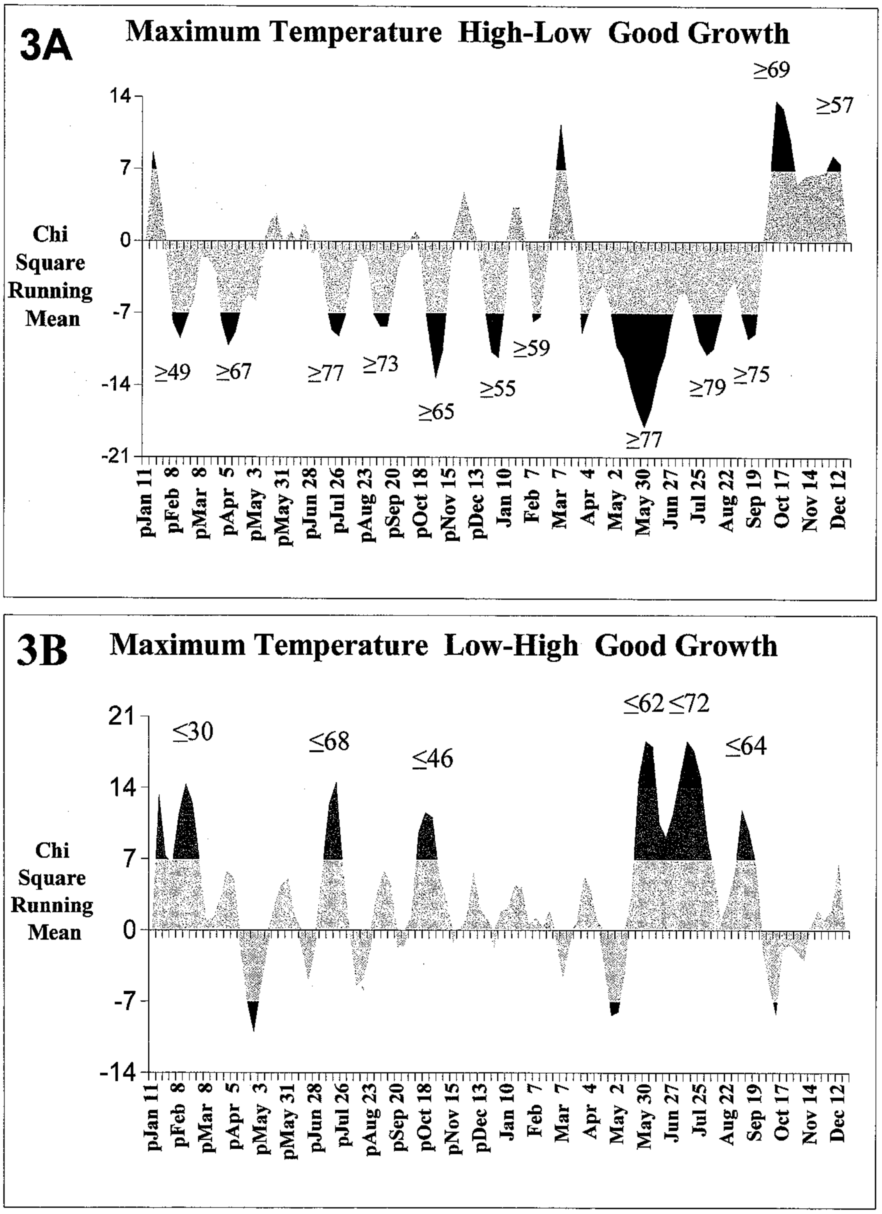

Figure 3. Same as Figure 2 except for maximum temperature and wide-ring years versus normal growth years.

(a) Narrow vs. Normal Ring, Maximum Temperature, High to Low Scan

This relationship is dominated by significant and positive χ^2 values from mid-November (P) to mid-May (C), a six-month period preceding the beginning of growth in late April (C) and the first full month of the growing season (Figure 2A). Several χ^2 peaks occur within this period, with the maximum χ^2 on March 14 (C). Poor growth is associated with cardinal maximum temperatures ≥51°F (11°C) starting late in the autumn, rising to cardinal temperatures of ≥59°F (15°C) in February–April (C) and even higher temperatures of

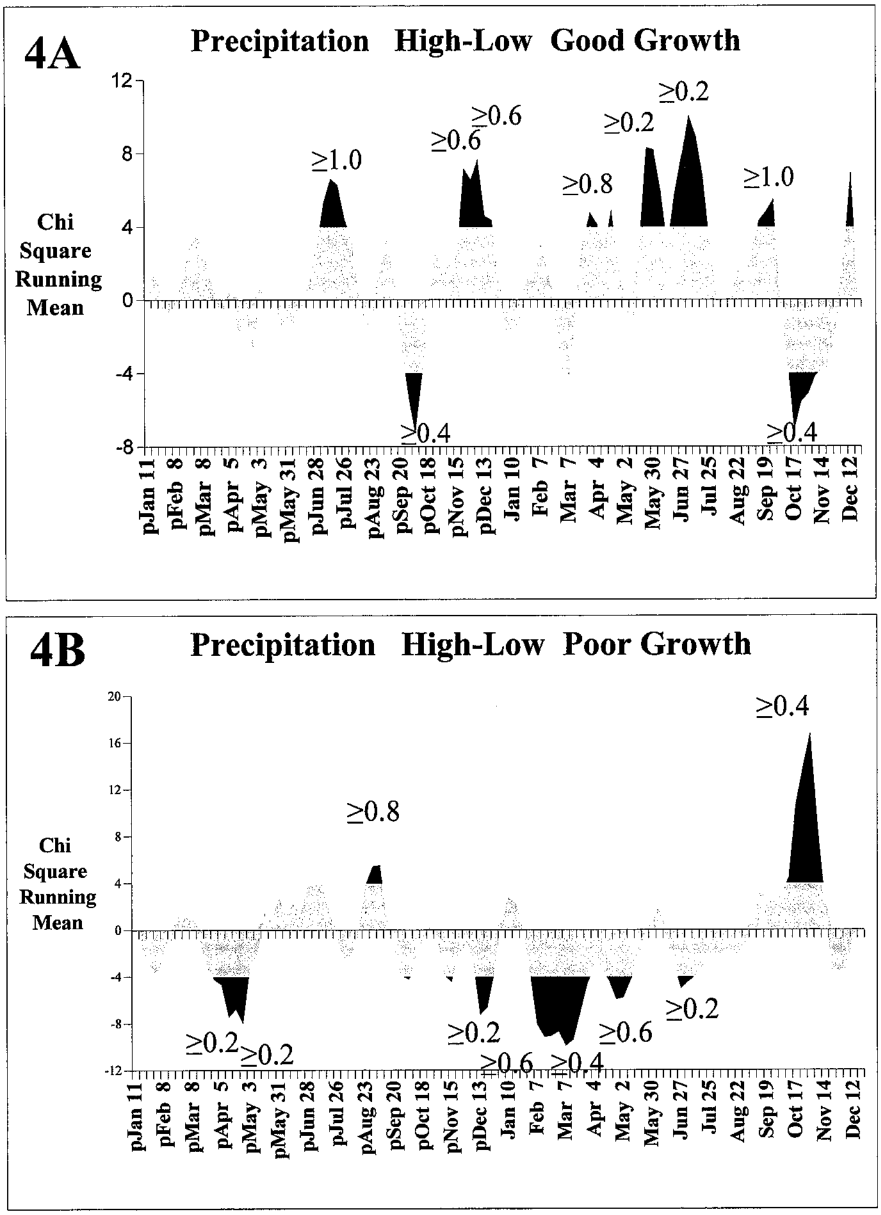

Figure 4. Same as Figure 2 except for precipitation. (A) high-low scan for wide rings versus normal growth years. (B) high-low scan for narrow rings versus normal growth years.

≥75°F (24°C) in early May. During this November (P) to May (C) interval, photosynthesis can occur, building up stored food reserves for the subsequent season's growth. This result would support the hypothesis that when atmospheric temperatures are unusually high at this time, while soil temperatures are low, water loss may exceed water uptake causing leaf water stress, diminishing photosynthesis with less accumulation of food and poor growth. In addition, during high temperatures, respiration in the crowns would also be high, reducing the sucrose being stored. This result is reflect-

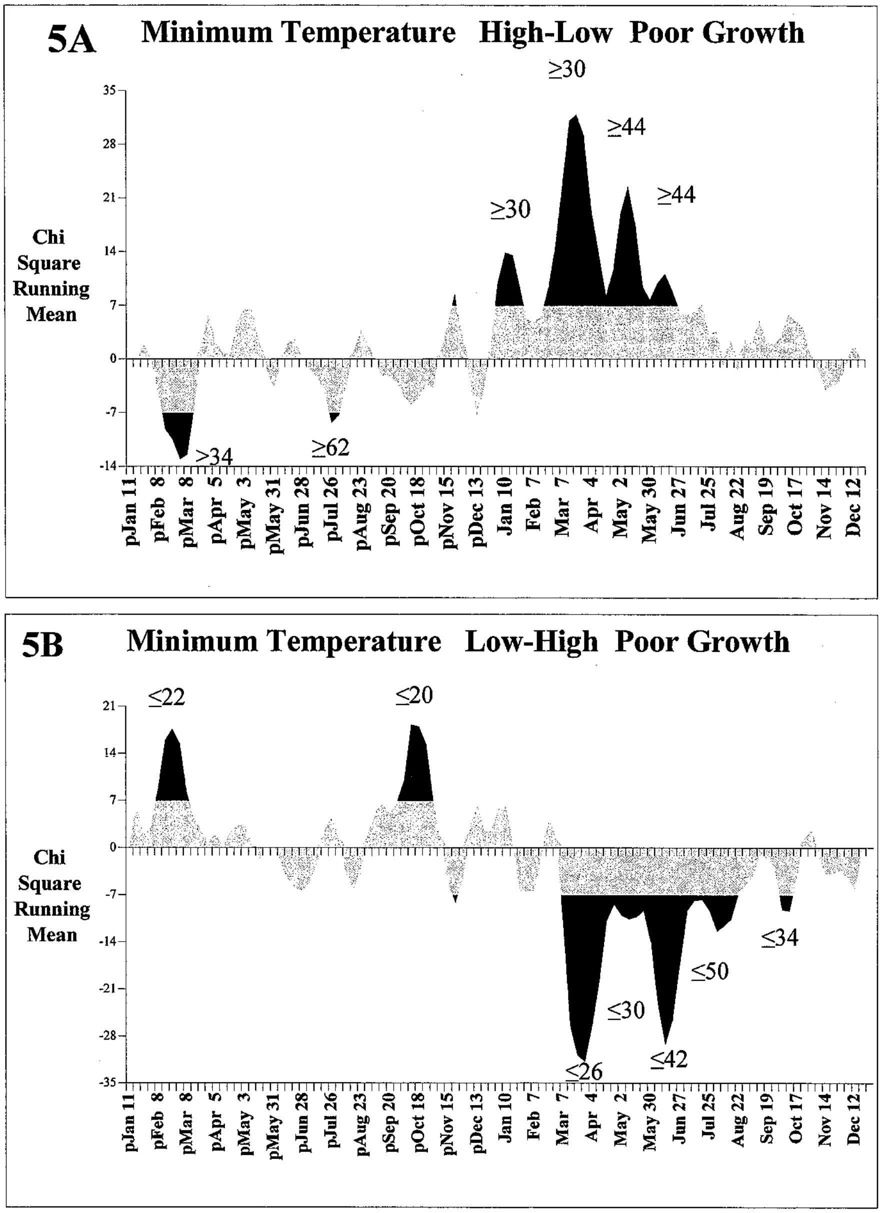

Figure 5. Same as Figure 2 except for minimum temperature and narrow ring years versus normal growth years.

ed only as insignificant negative temperature coefficients for November (P) through February (C) in the correlation analysis and December (P) through March (C) in the response function analysis (Figure 1). Later in the season, negative maximum temperature coefficients become significant in both the correlation and response function analyses. The χ^2 analysis indicates a corresponding relation (deficit of low maximum temperatures) that is near the significant level during June (C) and July (C) (Figure 2B).

The χ^2 analyses indicates a significant association also occurring from late October (C) to December (C), which is well after we have observed stem size increase using dendrograph measurements (Fritts and Fritts 1955). However, these observations on nearby *Pinus ponderosa* and *P. arizonica* trees lasted for only six years, which is a limited sample of years to be conclusive. Only non-significant departures were present for months of October (C) and November (C) for the correlations and the response function of maximum temperatures. It is possible that, during some unusually warm autumn periods not reflected in monthly mean data of these analyses, growth continues and could be limited by low temperatures from late October through December.

Three minor peaks in the χ^2 analysis occur in January (P), February–March (P) and June (P). No significant months were noted in the correlation and response function analyses during these periods. The χ^2 results could reflect unknown phenomena or may represent random responses in the data set.

(b) Narrow vs. Normal Ring, Maximum Temperature, Low to High Scan

During the entire two-year period of analysis, there are four major intervals when an excess of low maximum temperatures are significantly associated with poor growth (χ^2s are positive) (Figure 2B). The first (previous May) and last two are relatively short, single-peaked, and outside the interval usually considered likely to affect ring width. The second has two significant peaks for October 4 (P) and October 25 (P) with maximum χ^2s of 14 (CT $\leq$ 50°F (10°C) and $\leq$40°F (4°C)). These results suggest that when maximum temperatures are at or below 50°F (10°C) and 40°F (4°C), poor growth occurs. It also implies that when temperatures are higher, normal growth occurs. Hence, a positive relationship between growth and maximum temperature exists, which is consistent with the significant positive relationship in the response function with October (P) temperature (Figure 1) but not shown in the correlation results.

The same significant six-month interval as in the H-L scan appears in the L-H scan but with six significant χ^2s with negative signs in the L-H scan. Here, the interpretation is consistent in that poor growth is associated with a deficit of maximum temperatures $\leq$ 36°F (2°C) to $\leq$ 52°F (11°C). This implies that low maximum temperatures favor more normal growth.

(c) Wide vs. Normal Ring, Maximum Temperature, High to Low Scan

From February (P) through February (C), seven short intervals with significant χ^2s were found, all with negative signs (Figure 3A). Cardinal temperatures range from $\geq$49°F (9°C) to $\geq$67°F (19°C) in winter (P) and early spring (P), from $\geq$73°F (23°C) to $\geq$77°F (25°C) in summer (P), and from $\geq$55°F (13°C) to $\geq$59°F (15°C) in late autumn (P) and winter (C). From April (C) to the end of September (C), χ^2s with negative signs are consistently significant. Most significant was the week of May 30 (C) with a χ^2 value of -18. Cardinal values from April (C) to September (C) ranged from $\geq$75°F (24°C) to $\geq$79°F (26°C). This result indicates that deficits of days with maximum temperatures at or above the cardinal values are significantly associated with good growth. In other words, low maximum temperatures throughout the entire two-year period nearly always favor good growth.

These results support the generally inverse relationship between growth and maximum temperature shown in the correlation and response function analyses (Figure 1). The only χ^2 values that have a significant positive sign are in October (C) and December (C) (CT $\geq$ 69°F (21°C) and $\geq$57°F (14°C)). Although this result suggests that ring growth may continue late into autumn, the correlation, response function and dendrograph evidence do not support this finding. This relation might be spurious, but may be valid because unusually warm sunny weather this late in the growing season might contribute to cell enlargement, if indeed the enlargement growth process can remain active this late in the growing season.

(d) Wide vs. Normal Ring, Maximum Temperature, Low to High Scan

We found six peaks with significant positive χ^2s for this relationship (Figure 3B). No significant negative values appear. The largest and most consistent values occurred in the growing season during the interval from late May (C) through September (C). The cardinal values during the growing season ranged from ≤62°F (17°C) to ≤72°F (22°C). An excess number of days with maximum temperatures equal or less than 62°F (17°C) to 72°F (22°C) are associated with good growth. This implied inverse association of maximum temperature with good growth is consistent with the correlation and response function results. The three intervals with significant χ^2s before the growing season are consistent with the results from the high-low scan (Figure 3A) comparing maximum temperature with good growth.

Differences in results as shown in Figures 2 and 3 imply the presence of nonlinearity in the relationship of ring width with maximum temperature. Figure 2 shows poor growth years as opposed to normal growth years and indicates a considerably different response than is shown in Figure 3, which shows good growth versus normal growth years. Comparisons between poor growth and normal years (Figure 2) support a direct relationship between poor growth and the presence of warm winter and early spring temperatures that likely reduce net photosynthesis and starch storage. In contrast, a similar response is absent from Figure 3. This nonlinear effect is not captured in either the correlation or response function results. On the other hand, the positive relationship with October (P) temperature is present for both good and poor growth (Figure 3). The linear relationship is well-defined in the response function results, but not in the correlation results. In addition, maximum temperatures later in the spring and summer appear significant (Figures 2 and 3) and this is consistent with the inverse relationship seen with maximum temperature during the growing season reflected in the correlation and response function analyses (Figure 1).

(e) Wide vs. Normal Ring, Precipitation, High to Low Scan

Except for two cases, the precipitation-growth relationship is direct (Figure 4A). The earliest direct effect marks the beginning of the monsoon rains in July (P) with a maximum χ^2 of 7 (CP ≥ 1.0″ (25 mm)). In the correlation and response function analyses, this interval is not significant but the trend is apparent (Figure 1). This result could also reflect a weak positive first-order autocorrelation often present in tree-ring growth.

The interval from November (P) through September (C) is punctuated by six significant peak χ^2 values, November 22 (P), December 6 (P), March 28 (C) May 30 (C), July 4 (C) and September 26 (C) (cardinal values range from ≥0.2″ (5 mm) to ≥1.0″ (25 mm)). This result indicates the importance of precipitation during the following periods: early winter, before growth begins in late April (C) and May (C), the onset of monsoon rains in July, and the prolonged monsoon rains in September. These results are similar to results from the correlation and response function analyses (Figure 1).

We found two intervals with significant inverse χ^2 peaks, one centered at October 4 (P) (Figure 4A) and the other at October 17 (C) (CP ≥ 0.4″ (10 mm)). The first of these associations appears in the response function analysis but not the correlation analysis (Figure 1). The second association occurred after the July (P) to August (C) period considered in the correlation and response function precipitation analyses and therefore can not be directly compared in these results. Note that temperature in late September (P) to early October (P) is inversely related to the next year's ring width (Figures 1 and 2). Putting the two results together, both the response function results and the χ^2 tests suggest that cool and rainy weather from late September (P) to early October (P) appear unfavorable. For next year's growth alternatively, dry warm weather during this period appears favorable to growth.

(f) Narrow vs. Normal Ring, Precipitation, High to Low Scan

In the analysis of narrow rings versus normal rings, the χ^2 values for precipitation are similar but inverse of those for good growth, with some interesting differences. For example, significant χ^2 peaks with negative signs are present for April 12 (P) and April 26 (P) (CP ≥ 0.2″ (5 mm)) (Figure

4B). That is, narrow rings are associated with a deficit of moisture ≥0.2″ (5 mm). This association occurs at a time after bud break when leaf expansion begins, flowers are opening, and the next year's buds are initiated. If it is dry during this period, perhaps the photosynthetic area of the concurrent leaf growth is reduced, leading to a reduction in photosynthesis and a narrow ring during the following year. This relationship is nonlinear, as it is not found in the analysis of wide rings (Figure 4A) nor in the correlation or response function analyses calculated for that interval. A significant χ^2 peak with a positive sign is centered on September 6 (P) (CP ≥ 0.8″ (20 mm)). Although this association occurs a month earlier than the inverse relationship for wide rings, it may be related to the positive October (P) peak in the response function results (Figure 1). A significant negative χ^2 on December 13 (P) (CP ≥ 0.2″ (5 mm)) is consistent with the analysis of wide rings and the correlation and response function results.

However, the two negative peaks that follow on February 14 (C) and March 7 (C) (CP ≥ 0.6″ (15 mm) and ≥0.4″ (10 mm)) are not found in the wide ring or response function results but are present in the correlation results. This result suggests that low precipitation in late winter can lead to the formation of a narrow ring in the following growing season. In contrast, high precipitation does not reliably lead to the formation of a wide ring, supporting the inference that the relationship is nonlinear.

The last two negative χ^2 peaks occur on April 25 (C) and June 27 (C) (CP ≥ 0.6″ (15 mm) and ≥0.2″ (5 mm)) but an absence of significant negative values after that date indicates that a lack of summer rains from July (C) to September (C) does not produce a narrow ring. Thus, narrow rings are more likely the result of deficient winter and early spring moisture rather than deficient summer moisture. However, Meko and Baisan (2001) report both a linear relationship and the potential for summer precipitation at least affecting latewood width if not total ring width. Here both results are consistent with our observations that low winter-spring moisture reduces photosynthetic production and soil moisture, and in turn reduces initial and early-season growth rate. Under extreme conditions, growth may stop or remain low even in the presence of summer rain. If conditions during winter and spring are less extreme, summer rains can stimulate growth and increase late wood width.

A marked peak in χ^2 can be noted on October 30 (C) (CP ≥ 0.4″) (10 mm) indicating that an abundance of precipitation at this time is associated with poor growth. This is in agreement with the results shown in Figure 4A, which indicates that a deficit of precipitation ≥ 0.4″ (10 mm) is associated with good growth. Precipitation this late in the year is not considered likely to have a direct impact on tree-ring growth. However, note in Figure 3A that an abundance of maximum temperatures ≥69°F (21°C) in October (C) is associated with good growth.

(g) Narrow vs. Normal Ring, Minimum Temperature, High to Low Scan

Excesses of high minimum temperatures contribute to poor growth from late December (P) through June (C), covering half the year prior to and including the pre-monsoon growth (Figure 5A). Two pronounced peaks occur on January 10 (C) and March 21 (C) (CT ≥ 30°F (−1°C)) before the beginning of growth. The March 21 peak exhibits highest χ^2 and, as shown in Figure 5B, indicates an inverse relationship between poor growth and minimum temperature in March (C). This association is also shown as an insignificant but prominent peak in the response function results. The January 10 (C) peak may reflect the limitation of minimum temperatures ≥30°F (−1°C) perhaps associated with high nighttime respiration that consumes food reserves and reduces growth (Jones 1983). The peaks on May 9 (C) and June 13 (C) (CT ≥ 44°F (7°C)) suggest that excessively warm minimum temperatures are significant during this interval probably in enhancing respiration and thereby reducing the amount of food available for growth. The two negative peaks for March 1 (P) and July 26 (P) (CT ≥ 34°F (1°C) and ≤62°F (17°C)) are not easily explained in terms of known physiological processes.

(h) Narrow vs. Normal Ring, Minimum Temperature, Low to High Scan

The major feature in this analysis is an extended interval when deficits of low minimum temperature from March (C) through August (C) are associated with poor growth (Figure 5B). The most prominent interval begins in the week of March 7 (C), peaks in the week of March 28 (C), and ends in April 28 (C) (CT ≤ 26°F (−3°C)). This period immediately precedes the initiation of radial growth. At this time, minimum temperatures of ≤26°F (−3°C) favor more normal subsequent growth. If minimum temperatures are higher, growth may be initiated early and the tree could be more vulnerable to late season frost and nighttime respiration may contribute to sucrose loss. A minor peak occurs on May 9 (C) (CT ≤ 30°F (−1°C)), at about the beginning of growth. A second prominent peak begins the week of May 30 (C), peaks on June 13 (C) (CT ≤ 42°F (6°C)), and ends with the onset of the summer monsoons. During this pre-monsoon growth period of increasing temperatures, drought and water stress increase. Low minimum temperatures, *i.e.* ≤26F° (−3°C) to ≤42°F (6°C), will reduce water stress and contribute to more normal ring-width growth.

Two more peaks follow. The first begins the last week in July (C), peaks August 8 (C), and ends late in the month. A cardinal temperature of ≤50°F (10°C) indicates that minimum temperatures above 50°F (10°C) may be associated with less rainfall, reduced soil moisture, greater water stress, and narrow ring growth, whereas cooler temperatures will favor more normal growth. The second peak is observed in the first two weeks of October (C) (CT ≤ 34°F (1°C)). A deficit of low minimum temperatures in early October may indicate cloudy weather accompanied by low maximum temperatures that may be unfavorable for ring growth as indicated in Figures 2B and 4B.

The only two significant periods when an excess of minimum temperatures is associated with poor growth are during the year prior to growth. One is during February (P) (CT ≤ 22°F (−6°C)) which is difficult to explain with our current knowledge of processes that affect tree growth. The second extends through the month of October (P) (CT ≤ 20°F (−7°C)). This result is consistent with the plot of maximum temperature (Figure 2B) and the response function results, where temperature was found to be directly associated with good growth. This relationship was found throughout the χ^2 and response function results, but does not appear in the simple correlation results (Figure 1). Some evidence for frost damage has been noted in the younger trees, but this appeared to be associated with an unusual freeze just after the growing season began. At present, we have not observed anatomical evidence of freeze damage in the prior year affecting the current year's growth.

CONCLUSIONS

The iterative chi-square results using daily meteorological variables, in addition to being mostly consistent with the main features of the correlation and response function results, provide additional information including non-linear responses and threshold values in response for *Pinus ponderosa* trees growing in the middle of their range in southern Arizona. Clearly, the variability of precipitation over much of the two-year period prior to tree measurement is a major factor determining tree-ring width—a larger number of precipitation days contributes to a wider than normal tree-ring width. The major significant precipitation associations occur during the monsoon season of the previous and current years that runs roughly from June through August and the winter season precipitation period that runs from about November through March.

A deficit of high maximum temperatures throughout most of the two-year period prior to, and including the current year's growth, is associated with a wider than normal ring width. The response is most inversely related to high maximum temperatures during April through July of the current year. The greatest adverse effect occurs about mid-June within this period, when temperatures tend to be the highest of the year, just prior to the onset of July monsoon rains. A noted exception to the above relationships occurs during late September to October prior to growth when precipitation is inversely related to growth. This relationship is also found in the response function results but not in the correlation analysis. This result provides independent evidence that the response function is not just a simple reflection of the correlations between monthly climatic conditions and ring width, but that the rotation using principal components reveals different meaningful and significant relationships between climatic factors and ring growth. The response function and the chi-square analyses both indicate that warm, dry Octobers favor the next year's ring growth.

The χ^2 approach clearly identifies nonlinear relationships not revealed by the correlation and response function results. One such relationship probably involves wintertime net photosynthesis that, if scant, is likely to be associated with a narrow ring. However, greater amounts of net photosynthesis will not necessarily lead to a wide ring. Warm moist conditions at the time growth begins in late April or May can lead to an earlier and perhaps more vigorous initiation of growth and a wider ring can result. Warm weather conditions during March and April can be detrimental as it can lead to early growth initiation that is susceptible to late spring freeze or respiration may become enhanced and less net photosynthesis is a result. A narrow ring results primarily if winter precipitation is deficient. A deficiency in summer precipitation alone is not likely to cause a narrow ring. The χ^2 analysis provided the best evidence for such high-resolution information because daily rather than monthly meteorological information was used in the analysis.

A larger number of days with high minimum temperatures during the winter and spring are associated with narrow ring years. High minimum temperatures in the previous October favor good growth suggesting that warm, dry, and sunny conditions in October may favor late season photosynthesis and food reserves that promote subsequent growth. Temperatures are less limiting by November and the relationship with precipitation reverses and becomes favorable, probably through enhanced soil moisture storage, wintertime photosynthesis, and high subsequent growth. The strongest association identified occurred during March of the growth year when maximum temperatures of 59°F (15°C) and above and minimum temperatures of 26°F (−3°C) and above appear to be most adverse for subsequent tree-ring growth.

Low minimum temperatures associated with narrow rings could be an indication of plant freeze damage. The results indicate that, should there be an adverse impact of freezing temperatures on tree growth, likely times would be during the February to mid-March period of the previous year and/or during October of the previous year. The cardinal minimum temperatures during these two periods are $\leq$22°F (−6°C) and $\leq$20°F (−7°C), respectively. Such low temperatures at these times of the previous year might be a significant factor in reducing the potential for the tree-ring growth of Arizona pine in the Santa Catalina Mountains.

We believe this chi-square analysis, which uses daily rather than monthly climatic data, should be added to our array of dendroclimatic analysis programs. The results are reasonably consistent with the correlation and response function analysis but identify additional details about the weather/tree growth relationship, as well as shorter periods of time when specific meteorological conditions are likely to impact on tree growth. Nonlinear as well as linear relationships are identified and additional information is provided on limiting conditions and critical threshold levels, above or below which they begin to influence growth.

ACKNOWLEDGMENTS

We are grateful to Henri Grissino-Mayer for his patience, support and extensive and editorial help. The Laboratory of Tree-Ring Research, University of Arizona provided support for the development of the software used in this analysis. The most up-to-date version of this program (CHISQ) is included in the Dendrochronology Program Library. It may be obtained free of charge from http://www.ltrr.arizona.edu/pub/dpl/. Documentation for the program is contained in a compressed file DOCUMENT.ZIP provided with the program.

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Received 9 May 2002; accepted 20 August 2003.