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Detecting Long-Term Hydrological Patterns at Crater Lake, Oregon

Abstract

Tree-ring chronologies for mountain hemlock (*Tsuga mertensiana*) were used to reconstruct the water level of Crater Lake, a high-elevation lake in the southern Cascade Range of Oregon. Reconstructions indicate that lake level since the late 1980s has been lower than at any point in the last 300 years except the early 1930s to mid 1940s. Lake level was consistently higher during the Little Ice Age than during the late 20th century; during the late 17th century, lake level was up to 9 m higher than recent (1980s and 1990s) low levels, which is consistent with paleoclimatic reconstructions of regional precipitation and atmospheric pressure. Furthermore, instrumental data available for the 20th century suggest that there are strong teleconnections among atmospheric circulation (e.g., Pacific Decadal Oscillation), tree growth, and hydrology in southern Oregon. Crater Lake is sensitive to interannual, interdecadal and intercentenary variation in precipitation and atmospheric circulation, and can be expected to track both short-term and long-term variation in regional climatic patterns that may occur in the future.

Introduction

The time series of annual growth stored in tree rings is a repository of information on regional climate, as well as on local forest productivity. Dendrochronological techniques have proven particularly useful in reconstructing past hydrological variation by quantifying the relationship among interannual variation in climate, variation in hydrological parameters (e.g., streamflow) and radial tree growth (Meko et al., 1980, Cook and Jacoby 1983, Blasing and Duvick 1984, Meko and Stockton 1985, Landwehr and Matalas 1986, Brinkman 1987, 1989, 1992, Michaelsen et al. 1987, Robertson and Josza 1988, Stahle et al. 1988, Loaiciga et al. 1992, 1993, Stahle and Cleaveland 1993, Woodhouse 1993, Young 1994, Shen and Tabois 1995). These reconstructions quantify long-term trends and expected variation in hydrological systems associated with regional climate, and provide valuable input to policy decisions about water consumption and allocation (Stockton 1990).

Reconstructing the water level of lakes can be challenging, because most lakes comprise only a small fraction of the surface area in a watershed. Lakes frequently have unknown inputs from inflow streams, unknown losses to groundwater and outflow streams and complex evaporative relationships with the atmosphere. Crater Lake, a deep, high-elevation lake located in the southern Cascade Range of Oregon (Drake et al. 1990), is a notable exception to this generalization. The surface area of Crater Lake comprises 78.5% of its watershed surface area, and there are no streams flowing into or out of the lake. Because Crater Lake comprises such a large proportion of its watershed, water level is very responsive to interannual variation in precipitation (Redmond 1990, Nathenson 1992), giving the lake its reputation as "the world's largest rain gauge" (Larson 1990), despite the fact that there is some "leakage" due to seepage.

In this study, we used climatically-sensitive tree-ring chronologies and climatic and hydrological records from the 20th century to reconstruct annual precipitation and water level at Crater Lake. We quantified the rate of change in water levels since the late 1600s, which includes much of the Little Ice Age (ca. 1600-1850), a period with cooler climate in western North America (Fritts and Lough 1985, Graumlich and Brubaker 1986, Folland et al. 1990, Briffa et al. 1992). Knowledge about past water levels of lakes (prior to measurement records) is valuable for understanding hydrological variation at different temporal scales (Stine 1990, 1994) and can improve

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predictions of how hydrological systems in the Pacific Northwest may respond to various climatic conditions in the future.

Methods

Research was conducted in Crater Lake National Park in the southern Cascade Range of Oregon (Fig. 1). Crater Lake is a deep hyperoligotrophic lake that covers the floor of Mt. Mazama caldera which formed ca. 6,800 B.P. The average elevation of the lake is 1,882 m. Area of the water surface is 53.2 km^2, and the drainage basin is 67.8 km^2 (Redmond 1990, Nathenson 1992). As previously noted, the lake occupies 78.5% of its own drainage basin. Lake volume is 17.3 km^3, with maximum depth of 589 m (Collier et al. 1990). Steep walls form a high rim (elevation ca. 2,100 m) around the lake, inflowing waters originate within the caldera and there is no surface outlet. The only ways for water to leave the basin are through seepage and evaporation. Seepage is

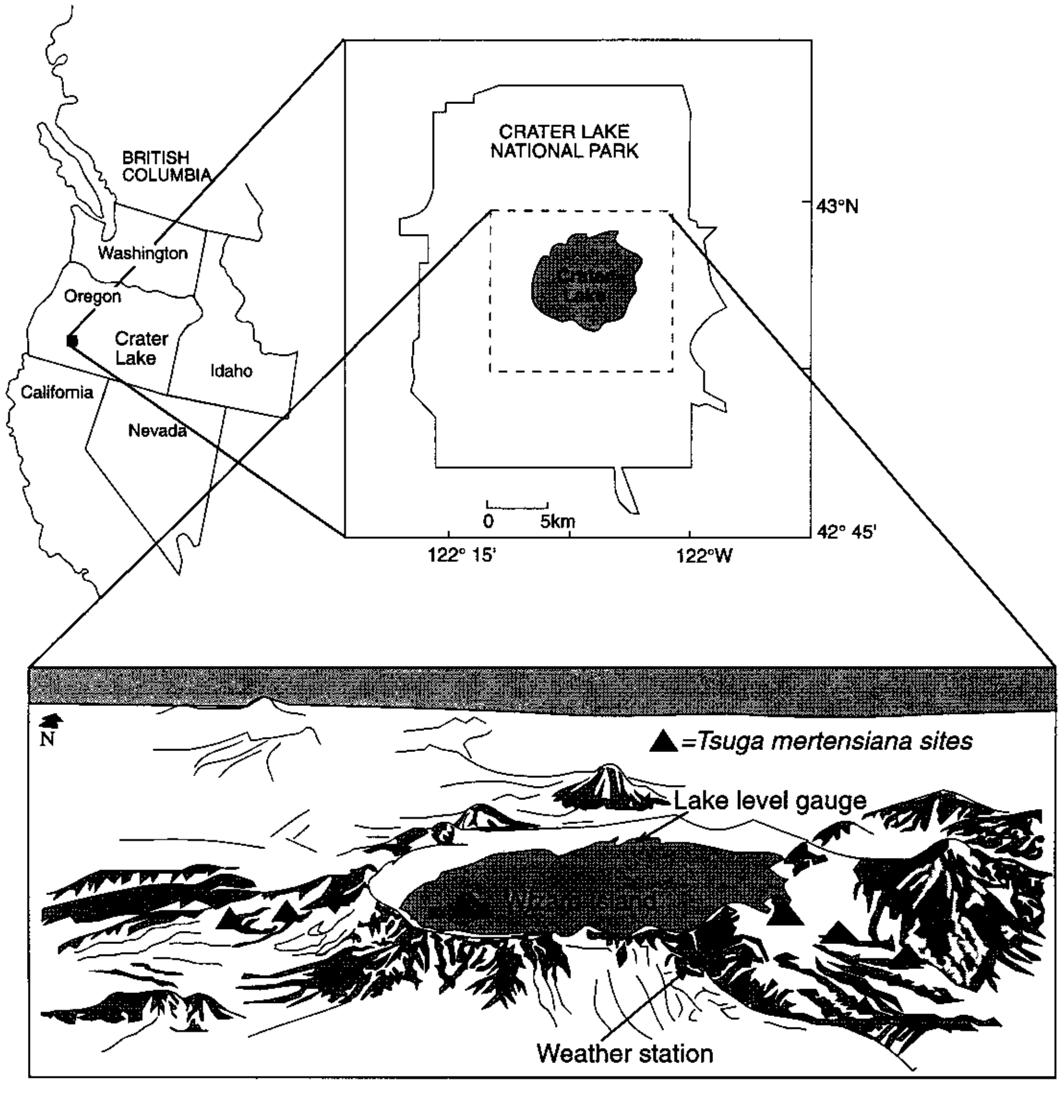

Figure 1. Location of Crater Lake in Crater Lake National Park, southern Cascade Range, Oregon. The weather station, lake-level gauging station and mountain hemlock (*Tsuga mertensiana*) sampling sites are indicated.

approximately 0.35 cm/day (128 cm/yr) and does not appear to vary with lake level, while evaporation is approximately 0.33 cm/day (120 cm/yr) (Redmond 1990, Nathenson 1992).

Monthly total precipitation and mean air temperature data for Crater Lake (measured at Crater Lake National Park headquarters, elevation 1,973 m) are available since 1931. Mean annual precipitation at Park headquarters is 171 cm, of which 80-90% falls as snow during the winter (October through April); mean annual snowfall (in solid form) is 1,314 cm (Redmond 1990). Mean annual temperature (1961-1990) is 3.1°C, with a mean annual minimum of -2.9°C and mean annual maximum of 8.9°C. Lake level has been measured since 1908; since 1961, data have been recorded at a permanent gauge located on the west side of the lake, although measurements prior to this time are also considered to be accurate (Redmond 1990).

Tree-ring chronologies were developed for mountain hemlock (*Tsuga mertensiana*) at each of 7 sites in Crater Lake National Park. Mountain hemlock is the dominant tree species throughout much of the region adjacent to the rim of the lake. Shasta red fir (*Abies magnifica* var. *shastensis*) is codominant at some sites, especially at lower elevations. Sites were located along an elevational gradient on the western side (3 sites) and eastern side (3 sites) of the lake, and on Wizard Island (1 site) within the lake basin (Fig. 1). Tree age at 1 m height was up to 439 years (Table 1). Twenty trees from each site were cored with increment borers at 1 m above the ground; only larger (and presumably older) trees without visible injury to the crown and bole were sampled. Two cores were extracted per tree, of which one core was analyzed. Tree cores were sanded and crossdated (Fritts 1976), and ring widths were measured to the nearest 0.01 mm in the laboratory.

Tree-ring chronologies were calculated (through standardization) with the program ARSTAN (Holmes 1984) using a stiff cubic smoothing spline with a 50% frequency response cutoff of 200 years (Cook and Peters 1981, Holmes 1983) applied to the ring-width series of each tree. The ring width for each year in the series was divided by the spline value to give a time series of index values. An autoregressive model was fit to each index, and the residual series for all trees in a stand were averaged to give a site chronology. More flexible smoothing splines (50% frequency response cutoff of 25, 50 and 100 years) were tested to determine the potential impact of standardization on reconstructions of precipitation and lake level. These other curve-fits had minimal effect on the chronologies or ultimate reconstructions, so we retained the stiffer spline which would tend to retain low-frequency variance in the calculated chronologies.

Correlation analysis was used to determine the relationship between annual tree growth and monthly and annual precipitation (based on hydrological years, October through September). The period of concurrent tree-growth and climatic data used in the analysis was 1931 through 1991.

Principal component analysis (PCA) was conducted on the 7 site chronologies as well as the chronologies lagged forward 1 year (total of 14 variables in the PCA). PCA is commonly used to define the common variance among chronologies

TABLE 1. Summary of characteristics of sampled mountain hemlock (*Tsuga mertensiana*) in Crater Lake National Park. Trees on the western and eastern rim of the lake (20 trees per site) were sampled across an elevational gradient (high, mid, low); only one site was sampled on Wizard Island.

Site	Elevation (m)	Mean diameter (cm, ±1SD)	Earliest year in chronology: Mean (yr, ±1SD)	Earliest year in chronology: Range (calendar yr)	Chronology statistics: Mean sensitivity	Chronology statistics: Auto-correlation	Chronology statistics: Common variance (%)
West - high	2200	82.6 (14.1)	1715 (57)	1607-1787	0.201	-0.061	52.0
West - mid	2060	70.8 (10.8)	1745 (36)	1687-1809	0.230	0.052	50.7
West - low	1940	66.7 (14.1)	1757 (68)	1597-1856	0.173	0.193	44.0
East - high	2290	89.5 (20.2)	1766 (64)	1641-1889	0.196	0.076	49.4
East - mid	2060	73.6 (9.6)	1796 (49)	1640-1887	0.193	0.208	56.8
East - low	1900	61.6 (12.7)	1736 (60)	1576-1833	0.144	0.215	41.8
Wizard Island	2000	58.6 (11.5)	1726 (83)	1553-1856	0.189	0.157	41.6

(Graumlich 1993), reduce the number of variables used in regression and reduce multicollinearity between variables (Graumlich 1987, Loaiciga et al. 1993, Peterson et al. 1993). PCA was conducted for the entire time series of tree growth, and 6 principal components (PCs) since 1931 (when climatic data are available) were included in a stepwise regression procedure to predict annual precipitation change. The PCs were not rotated. Coefficients of determination (r^2) were calculated for the regression model. Observations were left out of the regression model one at a time (one-fold cross-validation) (Graumlich 1987, Michaelsen et al. 1987, Michaelsen 1988, Loaiciga et al. 1993) to determine predictive power, and reconstructions were developed back to 1687, the point at which tree-growth data are available for a total of 25 trees and all 7 sampling sites are represented in the data set. Although this is subjective, the variance properties of the reconstructions did not seem to be affected much by sample size moving forward in the time series from this point. Residuals from the regression were examined for departure from a normal distribution with the Shapiro-Wilk statistic, and autocorrelation structure was tested with the Durbin-Watson statistic.

An identical procedure was used to develop a regression model with 4 PCs relating tree-ring chronologies (growth indices) to annual changes in lake level since 1908 (when lake-level data are available). Absolute lake levels over time were calculated from the reconstructed changes in lake level.

Results and Discussion

Annual tree growth is negatively correlated with precipitation during winter prior to the current growing season (Fig. 2), indicating that growth of *T. mertensiana* is enhanced by a longer snow-free period and reduced by deep snowpacks that

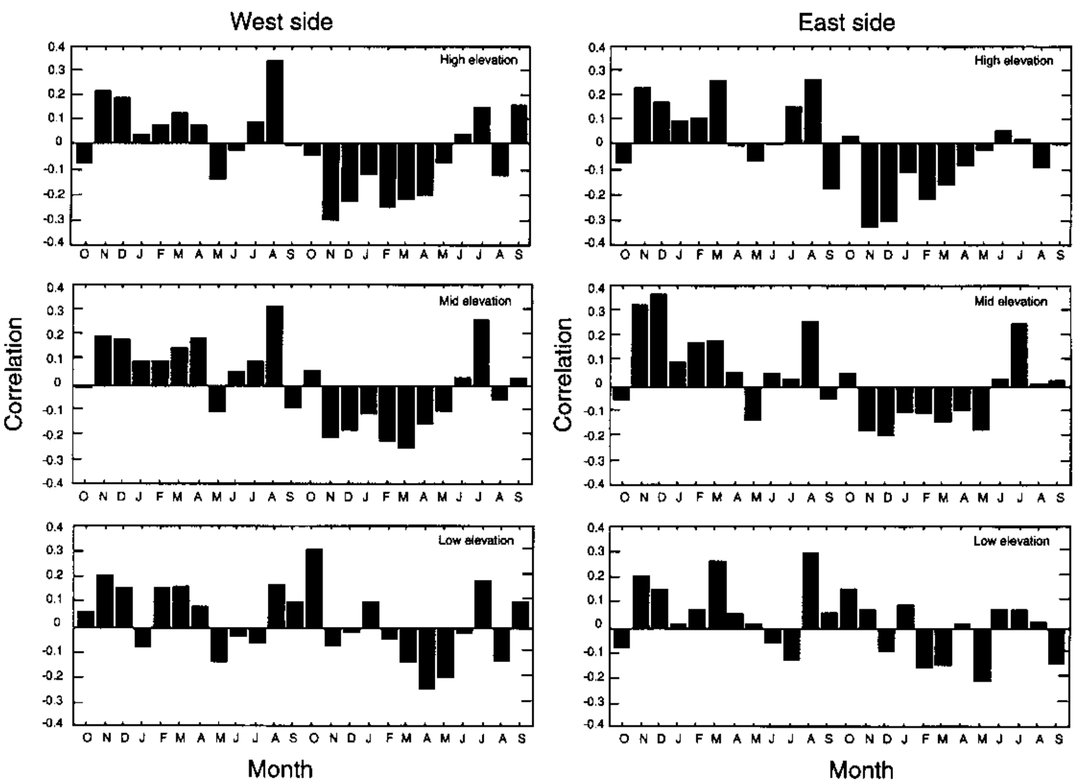

Figure 2. Correlations of annual tree-growth index with precipitation for the current (year *t*) and previous (year *t-1*) hydrological year (October through September, 1931-1991) are shown for 6 mountain hemlock (*Tsuga mertensiana*) sites in Crater Lake National Park. Although it is possible to calculate significance levels for the correlations, alpha levels could be inflated by potential between-month intercorrelation of the growth-climate relationship. Correlations for Wizard Island trees (not shown) are similar to those for the west-side, low-elevation site.

extend into the summer. This climate-growth relationship is similar to that found for *T. mertensiana* at other sites (Graumlich 1987, Peterson and Peterson in review) and for other subalpine conifer species in the Pacific Northwest (Peterson and Peterson 1994, Ettl and Peterson 1995a,b, Peterson 1998, Smith and Lraoque 1998) and the Rocky Mountains (Colenutt and Luckman 1991, Villalba et al. 1994; although growth of these species has an equal or greater positive correlation with summer temperature). Correlations for winter precipitation are greater for higher elevation sites located near the rim of the Crater Lake caldera (Fig. 2). These sites generally begin to accumulate snowpack in late October, have a peak snowpack of >300 cm in April, and reach complete snowmelt by early July (Redmond 1990). Growth is enhanced by winter precipitation during the previous year (positive correlation) (Fig. 2) because of the effect of high snowfall on long-term soil moisture storage (Peterson and Peterson 1994, Ettl and Peterson 1995b). August precipitation during the previous year also has a positive correlation with growth.

In addition, growth is positively correlated with current-year spring and early summer temperatures, indicating that growth is enhanced by warm temperatures favorable for photosynthesis and early snowmelt (Peterson and Peterson in review). Growth may be reduced by high temperatures during the previous summer (negative correlation) because of the impacts of low soil moisture on carbohydrate storage (Ettl and Peterson 1995b).

The first 6 PCs derived from PCA, which account for 88% of the variance in the data (of which the first two PCs account for 75%), were retained in the stepwise regression procedure for predicting annual precipitation. Regression of precipitation on these PCs results in a significant model (r^2=0.46, $p<0.001$). The correlation between the reconstructed value of the deleted observation and actual precipitation is 0.60 ($p<0.001$). Residuals from the regression show no significant autocorrelation (first-order autocorrelation=0.03, Durbin-Watson statistic=2.06) or departure from a normal distribution.

Using the same analytical approach, regression of lake-level change on PCs 1, 3, 5, and 6 results in a significant model (r^2=0.40, $p<0.001$). Cross-validation indicates that the correlation between the reconstructed value of the deleted observation and the actual change in lake level is 0.57 ($p<0.001$). Residuals from the regression contain some serial correlation (first-order autocorrelation=0.14, Durbin-Watson statistic=1.70), and the distribution of residuals departs from normal in the shortness of the tails (low kurtosis, $p<0.05$).

Because precipitation is so strongly correlated with lake-level change at Crater Lake, (Redmond 1990), our analyses focus on the quantitative relationship of tree growth, precipitation (most of which falls as snow) and lake level. Measured annual precipitation (since 1931) and reconstructed precipitation at Crater Lake (from 1687 to 1930, based on the model derived through PCA) are shown in Fig. 3. The precipitation model based on tree growth represents interannual variation reasonably well, although several of the higher values are underestimated. Reconstructions often underestimate extreme values because tree-ring chronologies are based on a spatially variable aggregate of trees used to develop a time series of mean, rather than extreme, values (Fritts 1976, Fritts and Guiot 1990). High precipitation is indicated for the early and mid 1700s, the mid 1800s and the early 1900s. These general trends corroborate previous reconstructions of precipitation for the Pacific Northwest (Brubaker 1980, Graumlich 1987, Fritts 1991).

Measured lake level (since 1908) and reconstructed lake level at Crater Lake are shown in Fig. 4. Reconstructed lake level represents the general pattern of interannual variation in measurements reasonably well, although the magnitude of high and low extremes is underestimated. Mean reconstructed lake level during the measurement period (1908-1991: -92.2 cm) is less than that of the pre-measurement period (1687-1907: 175.7 cm). Mean reconstructed lake level during the 20th century (-84.8 cm) is much lower than that prior to 1850 (226.3 cm). Lake level starting in the late 1980s has been lower than at any time during the past 300 years except in the early 1930s to mid 1940s. Periods of greatest lake-level increases track periods of generally higher reconstructed precipitation (Brubaker 1980, Fritts 1991, Graumlich 1993) (Fig. 3).

Reconstructed lake level is generally much higher during the Little Ice Age than during the 20th century (Fig. 4). The highest reconstructed levels during the late 17th century are 9 m greater

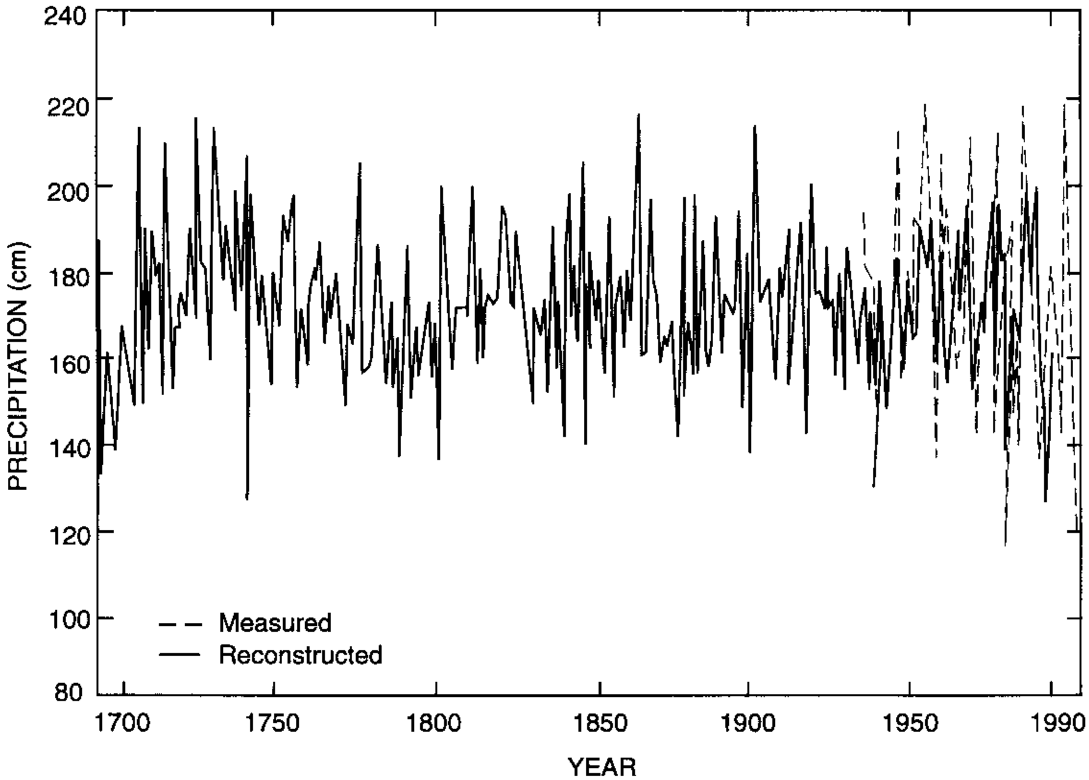

Figure 3. Measured (dashed line) and reconstructed (solid line) precipitation for the Crater Lake weather station, based on hydrological year (October through September). The reconstruction was extended to 1687, the point at which tree-growth data are available for a total of 25 trees and all 7 sampling sites are represented in the data set.

than the lowest measured levels of the 20th century. The magnitude of this lake-level change is supported by the fact that only younger trees (primarily *T. mertensiana* and *A. magnifica* <150 years old) are found along the lower wall of the caldera and shoreline of Wizard Island, compared to much older trees at higher elevations. The lowest lake levels (measured and reconstructed) occur during the early 1930s to mid 1940s, following a period of low precipitation in western North America (Graumlich 1993), including the Pacific Northwest (Graumlich 1987), with additional low levels starting in the late 1980s. The highest lake levels (reconstructed) occur in the mid 1700s, with evidence for additional high levels in the late 1600s. Even the lower peak in lake level in the mid 1800s is higher than any measured in the 20th century. If the model underpredicts extreme values as suggested by data for the 20th century, then the higher actual lake-level changes during the Little Ice Age may have been even higher than indicated by reconstructed values (Fig. 4); lower actual lake-level changes may have been lower than reconstructed as well.

Because the reconstructed parameter is lake-level *change* rather than *absolute* lake level (the sum of interannual changes, as shown in Fig. 4), it is difficult to directly link reconstructed precipitation (Fig. 3) and absolute lake level visually in the figures of reconstructed values. Another factor that obscures directionality of trends is that both standardization (a regression procedure) and regression modeling of the growth-index values produce time series with lower magnitude of variance than in the original data. Therefore, a small but persistent anomaly in precipitation—which would affect lake-level change—could be obscure in the reconstruction. Even if precipitation were relatively constant over time, but temperature was lower, as it surely was during the Little Ice Age, then lake level could have been higher prior to the 20th century as a

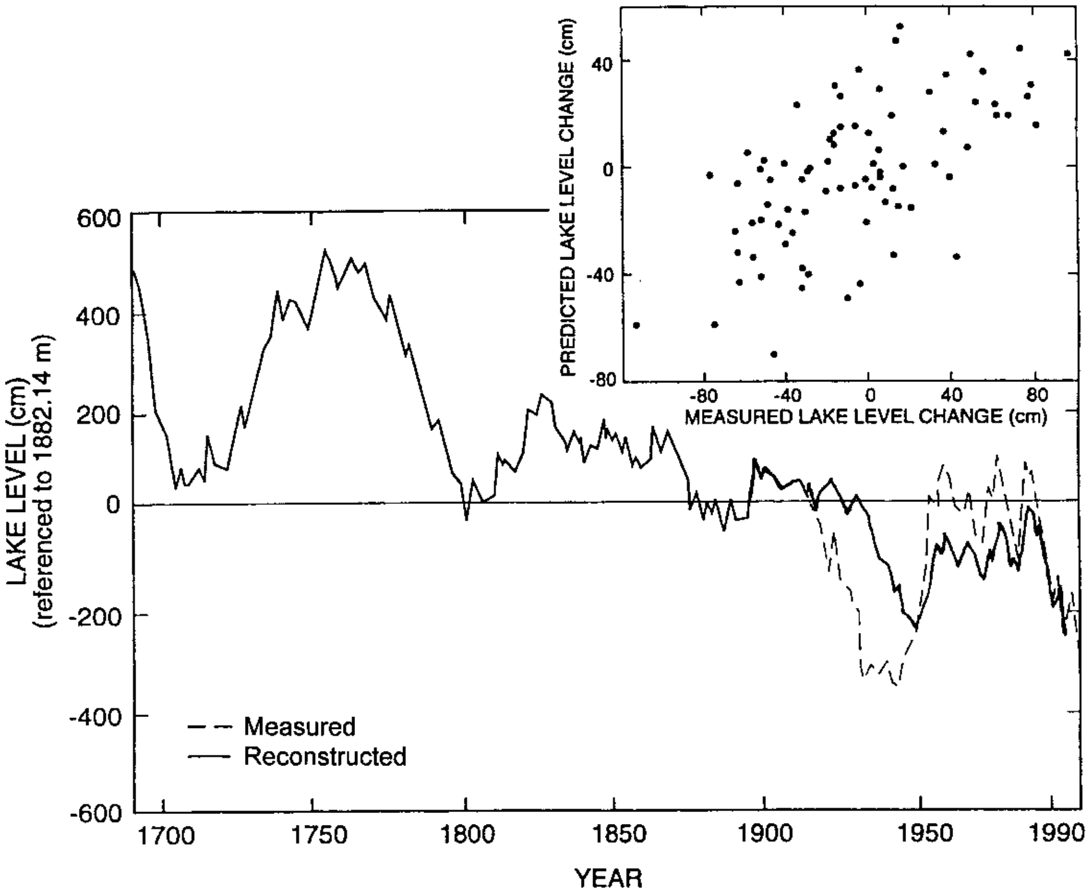

Figure 4. Measured (dashed line) and reconstructed (solid line) lake level for Crater Lake. Lake-level variations are adjusted to 30 September. Water stage is referenced to an elevation of 1,882.14 m above mean sea level and shown as a departure from this elevation (Redmond 1990). The reconstruction was extended to 1687, the point at which tree-growth data are available for a total of 25 trees and all 7 sampling sites are represented in the data set. The scatterplot shows the relationship between predicted and measured (since 1908) lake-level change (r^2=0.57).

result of lower evaporative rates. Lower temperatures could also have promoted ice formation on the lake, a very rare occurrence in the 20th century, thereby reducing winter evaporation.

Variation in atmospheric circulation can result in multidecadal anomalies of sufficient magnitude to produce significant changes in the water level of lakes and other bodies of water, as has been shown for California's Sierra Nevada (Stine 1990, 1994). The mid-latitude storm track of the northern hemisphere, which has a strong impact on general precipitation patterns in far western North America (Graumlich 1993, Stine 1994), may have tracked consistently over southern Oregon during the Little Ice Age. These conditions are supported by previous climatic reconstructions which indicate the prevalence of low pressure and high precipitation in this region during the latter half of the 17th century and much of the 18th century (Fritts 1991).

During the 20th century, periods of lower lake level coincide with the positive (dry, warm) phase of the Pacific Decadal Oscillation (PDO) (Mantua et al. 1997), and periods of higher lake level coincide with the negative (wet, cool) phase of the PDO (Fig. 4). In addition, mountain hemlock chronologies from treeline at Crater Lake—and throughout most of the Pacific Northwest—are generally in phase with the PDO Index (PDOI) (Peterson and Peterson in review), and trees attain more growth during periods with less snowpack (Smith and Laroque 1998). Conversely, low-elevation chronologies (especially in southern Oregon), for which high summer temperature can limit growth, are generally out of phase with the PDOI (Peterson and Peterson in review). These phenomena suggest that there are strong teleconnections among atmospheric circulation patterns, tree growth, and hydrology in southern Oregon. Because Crater Lake is so responsive to variation in precipitation, the PDO may have a significant influence on interdecadal variation in lake levels.

The climatically-sensitive hydrological system of Crater Lake, coupled with the dendrochronological record, is capable of tracking variation in regional precipitation. Even small changes in annual precipitation, including a few extreme years, can have a substantial cumulative impact on lake level. For example, the 9 m difference in lake level cited above can be accounted for by a deviation of only 3 cm/yr in precipitation (<2% of mean annual precipitation during the measurement period). Most assessments of the impact of climatic variability during the next century have focused on how potential *temperature* increases would affect natural resources (e.g., Watson et al. 1996). However, even small changes in *precipitation* can have major effects on hydrological systems (Arnell et al. 1996).

Lake-level variation and rates of lake-level change are straightforward hydrological effects of precipitation trends, and will reflect natural or human-induced variability in climate that may occur during the next century. Large, deep lakes are sensitive indicators of variation in precipitation if the lakes comprise a sufficiently large proportion of a watershed. Given the correlation between lake-level change and tree growth determined in this study, it may also be possible to use lake-level change as a means of estimating interannual and interdecadal tree growth. This would be a simple, economical approach for estimating temporal variability in forest productivity, which is an important indicator of ecosystem health. Crater Lake and other large lakes that dominate watershed surface area may be valuable for monitoring future changes in hydrology and productivity that result from variability in climatic patterns in the Pacific Northwest.

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