Reconstructing Historical Patterns of Fog Water Utilization and Coastal Climate Using Tree Ring Isotope Chronologies of Sequoia sempervirens: A Report for Save-the-Redwoods League

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Project Title:

Reconstructing historical patterns of fog water utilization and coastal climate using tree ring isotope chronologies of *Sequoia sempervirens*

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Project Summary

The presence of coastal summer fog has long been thought to be a crucial ingredient to the health and perpetuation of coast redwood ecosystems. The nature of fog utilization by redwoods, its variability, and its ecological importance, however, are poorly understood. Investigators have concluded that summer fog-drip in the redwood zone adds significant water to the ground surface and upper soil layers (Parsons 1960; Oberlander 1959; Azevedo and Morgan 1974). Further, is has been shown that fog water sources can be distinguished from winter rain supplies and that fog uptake by terrestrial plants can be traced by the analysis of stable isotope ratios of the hydrogen and oxygen atoms composing these different water sources (Dawson 1998; Ingraham and Matthews 1990, 1995). Coast redwoods (*Sequoia sempervirens* (D.Don) Endl.) obtain up to 45% of their water in summer via root-uptake from fog-drip when rain water supplies are at a minimum (largely absent), and fog dependence is apparently modulated by climatic factors that vary from year to year (Dawson 1998). An additional 6-8% can be taken-up directly by foliage (Burgess and Dawson 2004) showing its critical role the water relations of this tree. Work done by PI-Roden has shown that a relatively simple mechanistic model can be used to relate oxygen isotope ($\delta^{18}O$) ratios in tree-ring cellulose to those of source water taken up by the tree (Roden et al. 2000). Taken together, these advances suggested that redwood cellulose $\delta^{18}O$ should "record" past fog water uptake. Moreover, if trees used a greater proportion of fog in any given year and this influenced their water-use behavior, as we no know it can, then this should be recorded in the $\delta^{13}C$ of wood cellulose. Thus, stable isotope analyses would appear to provide us with a powerful method for re-constructing water uptake, water use and climatic variation all from annually-resolved cellulose in tree ring chronologies.

Our proposed research set-out to document redwood response to summer fog abundance and other climatic conditions using a suite of tree-ring techniques on growth rings spanning the past 50-100 years. We saw these objectives as the initial stage of a larger research program aimed at developing the use of environmental information from redwood tree-rings to reconstruct past climatic and ecological events in the coast redwood forest. From already established field sites where meteorological monitoring of the redwood environment was ongoing plus several new sites, our data was collected. This permitted the tree-ring research supported here to be linked to other ecosystem and ecophysiological research efforts that have been underway since 2000 and so that current climatic factors and their variation could be more easily linked with the tree ring width and isotope composition information gathered here. Our funding helped us successfully establish redwood-climate connections where abundant climate records existed and helped us leverage NSF-funding in late 2003 to extend our efforts to include a full paleo-climate reconstruction of climate, redwood water use and ecosystem hydrodynamics over the last 4 to 20 centuries. We believe that our findings have considerable conservation and management value as highlighted in Noss (2000) and have deepened our basic understanding of redwood ecology and the climate history of the coastal redwood forest zone.

Summary of Our Findings:

Funding provided by the Save-the-Redwoods League was dedicated to one year of academic support for Ph.D. student James Johnstone, who conducted research at the University of California, Berkeley, and to the costs of stable isotope analysis of redwood cellulose at the Center for Stable Isotope Biogeochemistry at Berkeley.

The funded work was conducted as an initial exploratory effort to document past variability of fog in northern California and to examine its potential influence on the growth and stable isotope characteristics of coast redwood tree rings. Three primary objectives were established and accomplished in the course of this project:

1. Collection of fog data and a calculation of a fog climatology to describe overall fog variability in northern California and assess possible linkages to large-scale atmosphere and ocean conditions over California and the Pacific Ocean.

2. Ring-width analysis of annual redwood growth and identification of potential relationships to climate variables.

3. Oxygen and carbon stable isotope analysis of redwood cellulose and determination of possible climatic influences.

Each goal was successfully accomplished, and results have led to more funded work, under the auspices of the National Science Foundation and the Berkeley Atmospheric Sciences Center. This redwood research agenda has developed in several ways to elaborate on the findings obtained here, and also to refine hypotheses tested in this initial stage of research.

Fog Climatology:

Fog records of hourly resolution were obtained and compiled, consisting primarily of cloud ceiling height measurements at five northern California airport locations over the period 1949-2001 (Arcata, San Francisco, Oakland, Alameda, and Mountain View). The most complete fog dataset exists for Arcata Airport, whose location is also most representative of the redwood environment. We also collected airport measurements of wind, temperature, humidity, and several other variables in addition to buoy data from the northern California coast to augment the land-based data with sea surface conditions. We have assembled a large dataset on environmental conditions in the redwood zone and the coastal ocean which will be of further use for both climatic and ecological research in the region.

We determined that fog frequency varies substantially at interannual and interdecadal time scales. Of primary importance was the finding that fog variability in northern California is highly related to the dominant mode of extratropical Pacific variability, termed the Pacific Decadal Oscillation. A major component of this mode involves abrupt shifts in sea surface temperatures (SST) along the Pacific coast of North

America, which exert a direct influence on northern California fog. The most notable manifestation of the PDO-fog connection was a persistent reduction in fog frequency of approximately 12% following the 1977 PDO shift (Fig. 1). This reduction in fog coincided with an SST increase along the Pacific coast of North America, and cooling throughout the remainder of the north Pacific. We conclude that fog in northern California is a strong indicator of regional to hemispheric-scale ocean conditions in the northeast Pacific.

The correlation between SST and fog extends over wide areas of the north Pacific (Fig. 2), while sea-level pressure (SLP) correlations with fog are largely restricted to the coastal region (Fig. 4). Positive SLP correlations with fog are seen off the coast of the Oregon and Washington, while weaker negative correlations occur in a band which crosses central California from the Pacific coast to the Great Basin. At daily time scales the atmospheric pattern is largely similar. High pressure offshore has several influences: it compresses the marine layer, bringing the cloud layer into contact with the land surface near the coast, it reduces the coastal ocean temperature by strengthening northerly winds which enhance upwelling, and also contributes to the ocean-land pressure gradient which draws marine fog onshore. Fog occurrence at daily and annual time scales is but one piece of a coupled ocean-atmosphere system along the California coast. In summary, at interannual time scales fog is associated with high pressure in the northeast Pacific, and relatively low SST along the Pacific Coast of North America, from Alaska to southern California.

Another key finding was the determination that northern California fog represents a regional, rather than local, climate signal. Similar interannual patterns of fog were found at all five locations despite large differences in latitude and local topography. This discovery was supported by evidence of a fog-related signal in summer temperature fields across California.

Mean summer temperatures in California closely follow the upward-trending record of global mean temperature (Fig. 5). A principal components analysis of a set of 25 long-term California temperature stations indicates that this pattern dominates summer temperatures across the state, explaining 54% of the overall variance. A secondary pattern reveals a tendency for coastal temperatures to vary inversely with those in the interior of California. This pattern explains 17% of overall temperature variability, and is strongly connected to fog frequency (Fig. 6, Table 1). This relationship has allowed us to create a century-long temperature-based proxy record of fog frequency, which has the added benefit of representing an inherently large-scale signal. This proxy record suggests that fog has declined substantially (perhaps 50%) over the 20th century and that an earlier abrupt decline in fog frequency occurred around 1940. Maximum correlations between global mean and California summer temperatures occur with a lag of 2 years (California trailing), while the California temperature gradient tends to trail the global mean temperature by 5 years. A plausible explanation for these observations is that deeper upwelled waters in the California current warm more slowly than surface waters, so that the impact on the coastal temperature gradient (and fog) is delayed. We infer that global temperature increases have negatively impacted fog frequency, through a combination of land and coastal ocean warming.

One limitation to our fog data analysis was a lack of thorough spatial coverage across the redwood region. Over the past year, the National Climatic Data Center has increased the availability of stations substantially in California and beyond. Further work will utilize these records to better detail local fog patterns, and to extend fog analysis to the entire Pacific Coast of the Americas.

Table 1. Correlations with Arcata fog frequency:

Arcata fog correlations:	
CA summer temperature	-0.20
CA summer Coast-Inland temp. gradient	**0.61***
PDO	**-0.48***
Global mean temp.	-0.26

*95% significance

Figure 1. Long-term variability of fog at Arcata Airport. Fog declined approximately 12% following the PDO reversal of 1977. T-test indicates 95% significance of a 1977 regime shift.

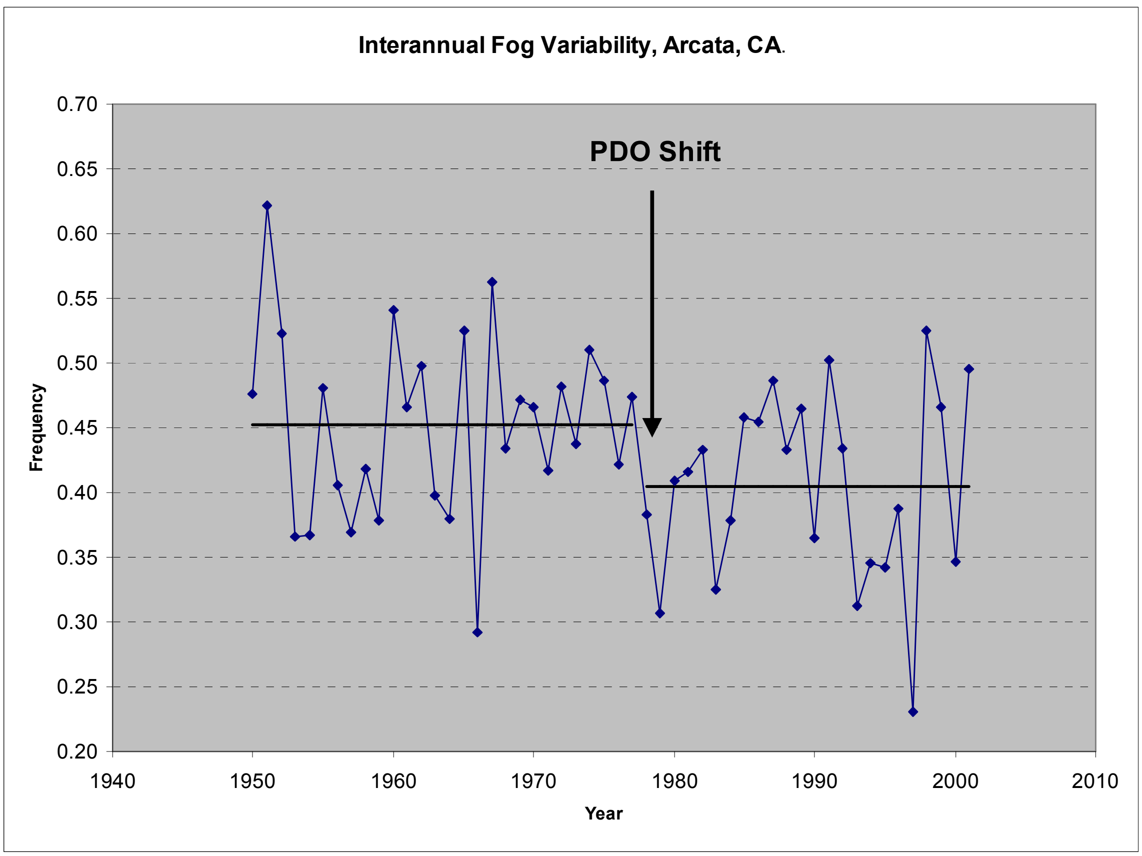
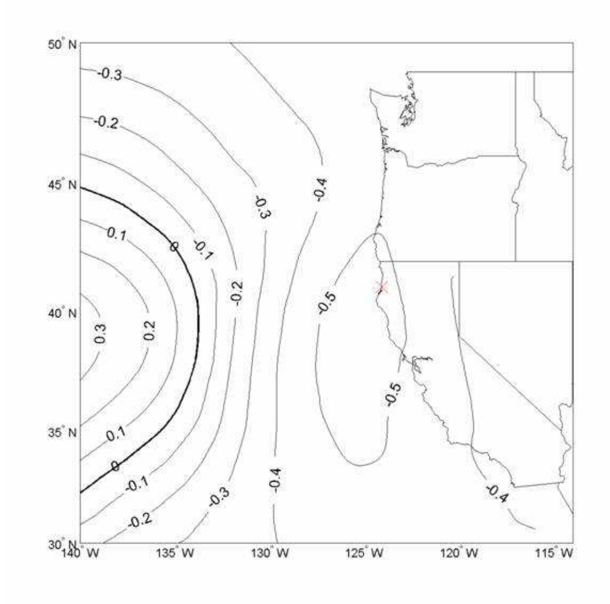


Figure 2. SST correlations with Arcata fog frequency.
Correlations exceeding +/- 0.27 are significant at 95%.
2a. Coastal region



2b. North Pacific region

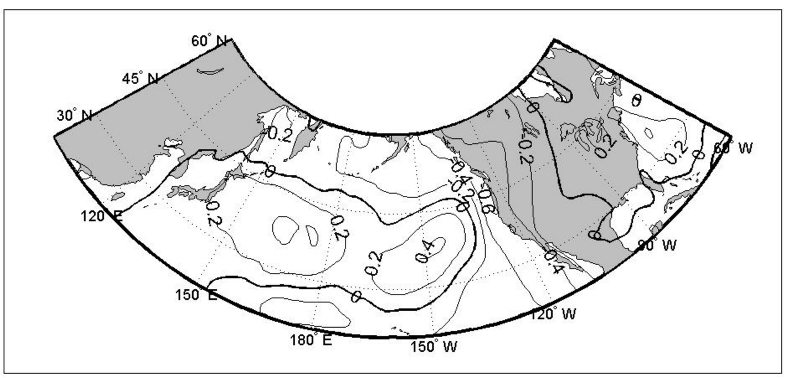


Figure 3. The Pacific Decadal Oscillation. Colors indicate SST anomalies, vectors indicate wind stress anomalies. SST patterns associated with fog are closely related to those of the PDO. Note similarity to SST pattern in Fig. 2b. (source: <u>http://jisao.washington.edu/pdo/</u>)

<u>PDO + (1977-present)</u> **<u>PDO - (1945-1976)</u>**

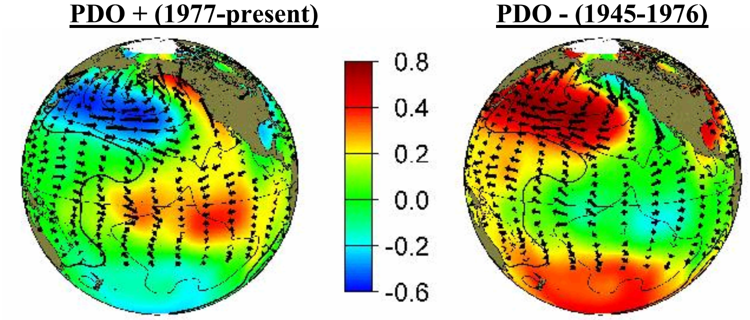


Figure 4. SLP correlations with Arcata fog frequency. Correlations exceeding +/- 0.27 are significant at 95%.

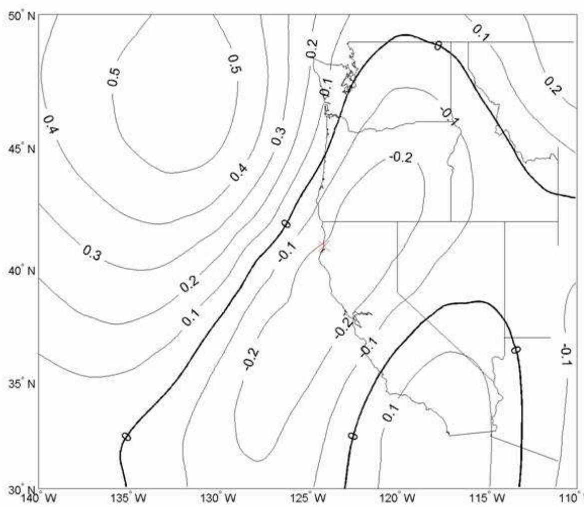


Figure 5. Mean summer temperature in California is strongly connected to mean annual global temperature (Correlation = 0.63).

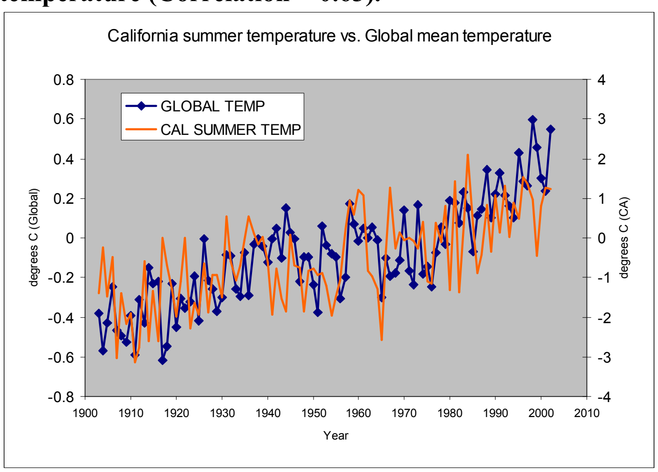
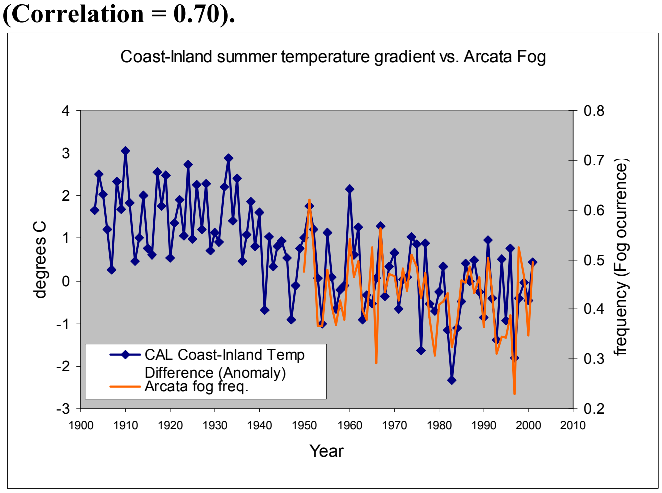


Figure 6. Fog frequency is highly correlated with the coast-inland temperature gradient in California (Correlation = 0.70).



Ring-width analysis:

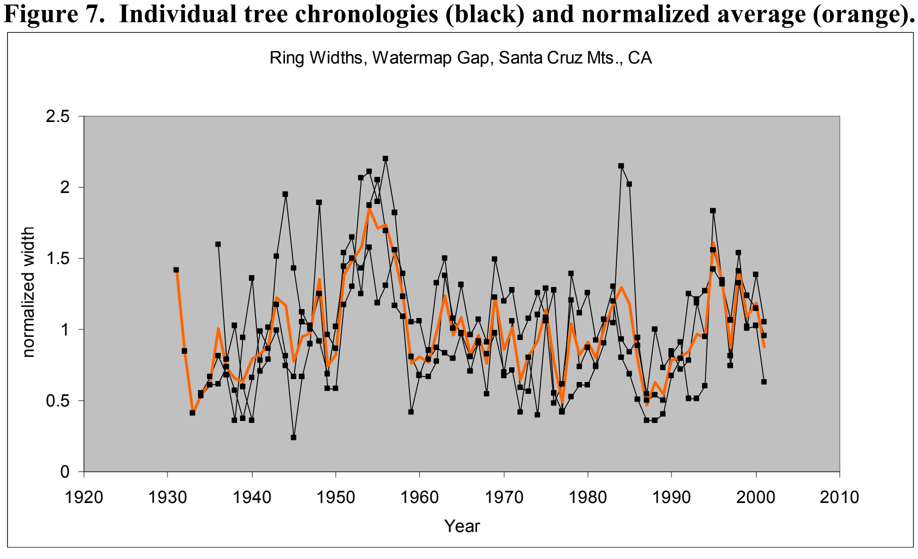
Ring-width analysis was conducted on three cross-sections obtained from previously felled trees at Waterman Gap, a foggy ridgetop location in the Santa Cruz Mountains. These trees permitted a ring-width reconstruction for the years 1931-2001. The use of cross sections was preferred for this initial study in order to assess and avoid potential problems of ring compaction and aid in cross-dating where the dominant climate influences were unknown.

Measurements were obtained by digital photography of the cross-sections along four radii per section. Ring-widths were measured along each radius, and a chronology was computed for each tree. Individual growth curves were removed from each tree chronology and the detrended tree ring time series for the site was then calculated.

Strongest correlations with ring-widths were found with precipitation from the previous winter (positive), and with the temperature-based fog index (negative). The positive effects of winter precipitation on growth were an expected finding. The inverse relationship between ring widths and coastal temperature was less expected, and indicates that cool coastal conditions and fog can inhibit annual growth. This could occur due to several factors including reduced solar radiation, low temperatures limiting metabolic activity, or high humidity which can limit transpiration. This finding also suggests that the importance of fog to redwood growth may be limited to drought years in which water supplies are limited. We found generally that multi-year high-growth periods occurred during unusually wet intervals (early 1980s, mid-late 1990s). The high-growth period during the early 1950s corresponds to a succession of high-fog years from 1950-52, but may reflect nonclimatic influences.

Both climatic correlations, while significant, were too low to construct a meaningful predictive model. In order to improve on these findings, additional funding has been obtained to collect cores at the northern and southern extremes of the redwood range, and to increase replication, both of which should aid in the isolation of climatic signals in ring width series.

Figure 7. Individual tree chronologies (black) and normalized average (orange).



Stable Isotope Analysis:

Isotopic analysis was conducted on two trees from our research site in Sonoma County. Measurements were taken at subannual resolution in order to isolate different isotopic signatures which we expected from winter rain and summer fog influences. Under SRL funding we obtained full records of early and late portions of each annual ring, and for recent years we also analyzed intermediate 'middle wood' on an experimental basis.

For the oxygen analysis, our initial hypotheses stem from the observation that summer fog moisture has a higher $\delta^{18}O$ value (~0) than that from winter rain (~ -10). To a first-order approximation the oxygen isotope values of the tree-ring cellulose were expected to parallel those of the volume-weighted values of the two water sources. Carbon isotope fractionation by biochemical processes in trees is largely controlled by stomatal behavior in response to moisture stress, of which ambient humidity is a large component.

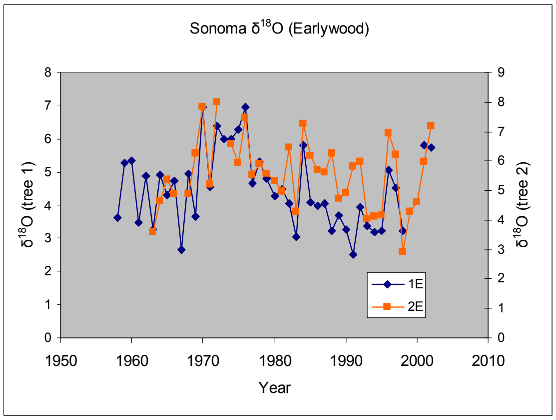
Subannual sampling allowed us to demonstrate that the fog signal is contained in the mid-to late-year *changes* in $\delta^{18}O$ and in mid-year values of $\delta^{13}C$ of cellulose in the manner hypothesized. Abundant summer fog tends to produce a spike in $\delta^{18}O$ during the growing season due to a high- $\delta^{18}O$ (fog) water source. We also see a similar reduction in $\delta^{13}C$ in association with fog abundance, presumably in response to reduced moisture stress in the soil and/or atmosphere. The use of middle wood sampling was vital to these conclusions.

Absolute values of $\delta^{18}O$ did not show significant interannual correlation with fog or any other identified climate variable. This may have resulted from noisy meteorological processes which control winter rain $\delta^{18}O$, or other hydrological or biochemical factors which obscure any climatic relationship. Further high-resolution isotope analyses are underway which may elucidate these processes.

We are currently expanding the $\delta^{13}C$ and middle wood datasets using NSF funding. We are strongly encouraged by the significance of the isotope-climate correlations in the sense hypothesized. We believe that stable isotope techniques do indeed provide a basis for paleo-fog reconstructions.

Figure 8. Oxygen isotope data, Sonoma.

a. Early wood



b. Late wood

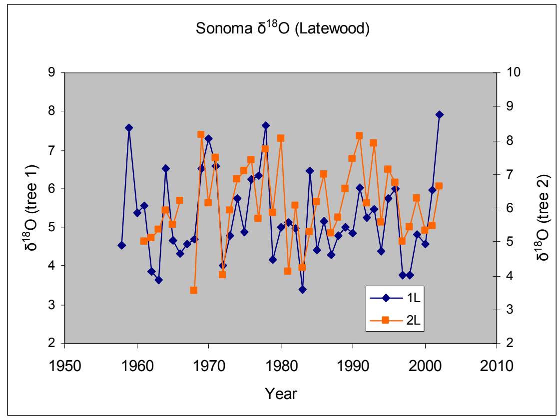


Figure 9. Carbon isotope data, Sonoma.

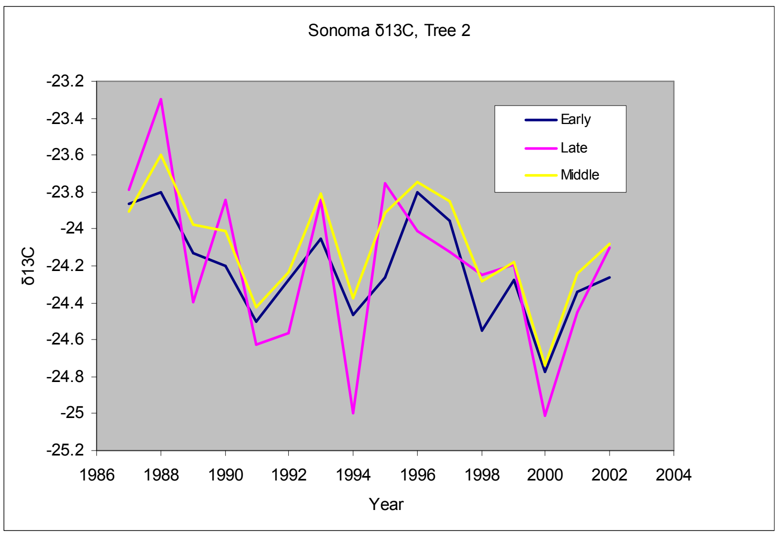
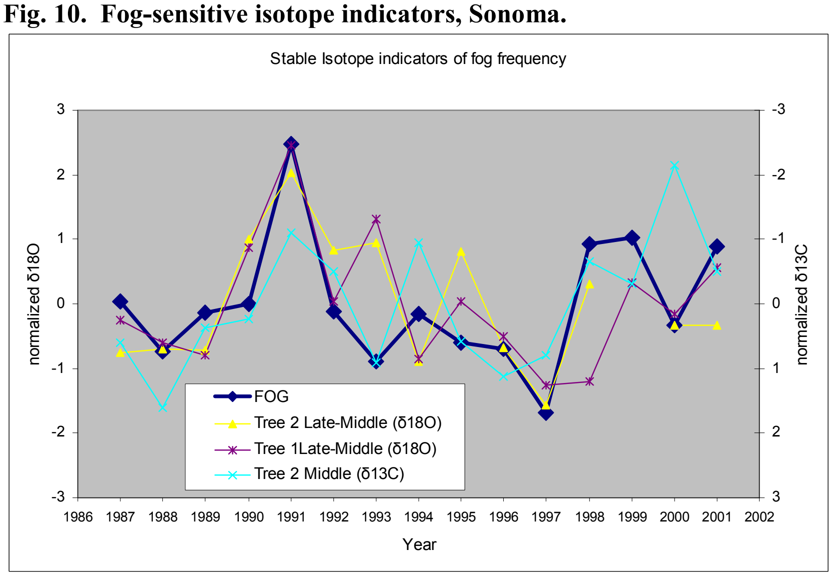


Fig. 10. Fog-sensitive isotope indicators, Sonoma.



Conclusions:

We have determined that summer fog is a reliable indicator of regional climate in the northeast Pacific, and displays strong correlation to the PDO, the dominant mode of north Pacific climate variability. Fog declined 12% following the 1977 PDO shift. Temperature-based proxy indicators of fog indicate sensitivity to the summer coast-inland temperature gradient in California, and also to the 20th century global temperature trend. Both factors have contributed to in inferred reduction in fog over the past century.

Ring-widths show significant, albeit weak, correlations to climate such that prior winter precipitation enhances growth, and a strong coast-inland temperature gradient tends to inhibit annual growth.

We find that fog inputs are detectable by both carbon and oxygen stable isotope analysis of coast redwood, and that high-resolution sampling is necessary to isolate this signal, at least for oxygen.

Ongoing NSF-supported research is building upon these initial findings in several ways:

1. High resolution (10 samples/year) analysis of stable isotope variability within rings (funded by NSF) has been conducted.

2. Focused ring-width analysis emphasizing northern and southern extremes of the redwood range will begin this spring in order to isolate limiting climatic variables and increase replication. (Fellowship funded by the Berkeley Atmospheric Sciences Center).

3. Expansion of fog records, both temporally and spatially, using newly-published data sets.

4. Analysis of the spatial variation of stable isotope signatures in redwood cellulose across a watershed.

SRL funding has been invaluable in providing the labor and resources to implement a new and exciting multidisciplinary redwood research agenda. The findings obtained from this pilot study have produced new science in a number of areas, and the potential for extension in a variety of directions. We are encouraged about the prospects for eventually constructing long paleoclimate records from coast redwood, and that these records will reflect climatic conditions across a wide region. We are grateful to the Save-the-Redwoods League for their support, and we will keep you apprised of publications stemming from this research.