GEOPHYSICAL RESEARCH LETTERS, VOL. 26, NO. 10, PAGES 1445-1448, MAY 15, 1999

July temperature during the second millennium reconstructed from Idaho tree rings

Franco Biondi [1], D.L. Perkins [2], D.R. Cayan [3], and M.K. Hughes [4]

Abstract. An 858-year proxy record of July temperature for east-central Idaho shows multi-decadal periods of extreme cooling centered around AD 1300, 1340, 1460, and after AD 1600. These cold intervals are interrupted by prolonged warm spells in the early 1400s, late 1500s, and in the 1930s. The spatial signature of the paleoclimate record is centered on the north-central Rockies and central Great Plains, and expands over North America following a wave-like pattern. Neither instrumental nor proxy data in Idaho northeast valleys show unusual warming during the twentieth century. Climate episodes over the last three centuries are in broad agreement with the Greenland borehole temperature history. Low-frequency patterns are consistent with other northern hemisphere tree-ring records for the late Holocene, and provide a chronology of warm and cold intervals during the Little Ice Age.

Introduction

Temperature fluctuations found in the modern instrumental record can best be gauged by comparing them with the range of conditions that occurred in the distant past [*National Research Council*, 1995; *Barnett et al.*, 1996]. To date, the amount of regional variability incorporated into global averages has been difficult to quantify over long periods, such as the last millennium, because annually resolved proxy climate records of great length are still a tiny fraction of the instrumental data available for the 20th century. Among sources of paleoclimatic information, tree-ring chronologies have the advantage of being continuous, well replicated, exactly dated to the calendar year, and therefore easily comparable to instrumental records [*Cook and Kairiukstis*, 1990]. Temperature reconstructions from old trees found at high-latitude or high-elevation sites have uncovered climate fluctuations during the last few centuries [*Bradley and Jones*, 1995], but tree-ring records covering most of the second millennium A.D. are still too sparse for the application of spatial network analysis on such a long time interval. Here, we use newly developed tree-ring chronologies from east-central Idaho to investigate summer temperature variability between A.D. 1135 and 1992. These climate proxies suggest that the region is characterized by considerable low-frequency variability, highlight warm and cold intervals occurring throughout the Little Ice Age [*Grove*, 1988], and do not indicate any unusual warming during recent decades.

[1]Geosciences Research Division, Scripps Institution of Oceanography, University of California-San Diego.
[2] USDA Forest Service, Logan, Utah.
[3]Climate Research Division, Scripps Institution of Oceanography, University of California-San Diego.
[4]Laboratory of Tree-Ring Research, University of Arizona, Tucson.

Paper number 1999GL900272.
0094-8276/99/1999GL900272$05.00

Materials and Methods

The Interior Northwest of the United States is one of the areas where dendroclimatic reconstructions before A.D. 1600 are rare, despite the relative abundance of pristine forest stands with extremely old individuals [*Perkins and Swetnam*, 1996]. We analyzed tree-ring collections from semiarid mountains in the Sawtooth-Salmon River region (Fig. 1). Samples were taken nondestructively from whitebark pines (*Pinus albicaulis*) at or near treeline (about 3000 m on rocky terrain), and from Douglas-firs (*Pseudotsuga menziesii*) at the lower forest border (about 1700 m on a talus, steep slope with no visible soil). Tree-ring chronologies were produced after accounting for the geometrical constraint of annually adding a new wood layer over a growing bole. Ring-width measurements were fitted by a monotonically decreasing curve; the curve was either a modified negative exponential or a straight line with slope ≤ 0. Ratios between measurements and curve values were then averaged by year and by species to produce tree-ring chronologies. Sample size was 31 cores from 15 trees for Douglas-fir, and 23 cores from 11 trees for whitebark pine. The period between 1135 and 1992 is covered by both chronologies, which are particularly well suited to retrieve interdecadal-to-centennial climate fluctuations because they are based on long individual segments [*Cook et al.*, 1995]. Mean segment length is 454 years for Douglas-fir, and 327 years for whitebark pine. The whitebark pine chronology shows less high-frequency and more low-frequency variability than the Douglas-fir chronology, a typical difference between higher- and lower-forest border tree-ring records. Tree-ring chronologies were calibrated against instrumental climate records for Idaho central mountains and northeast valleys, two homogenous climatic divisions [*Karl et al.*, 1986; *Guttman and Quayle*, 1996] that include the sampled sites (Fig. 1).

Results and Discussion

Based on dendroclimatic response functions [*Guiot*, 1991], the dominant climate signal in both tree-ring chronologies is July temperature. Mean July temperature is inversely correlated to Douglas-fir growth (r = -0.5 for 1904-1996), and directly correlated to whitebark pine growth (r = 0.3 for 1904-1992). Ecological differences between the two sites explain the opposite sign of the association. Douglas-fir

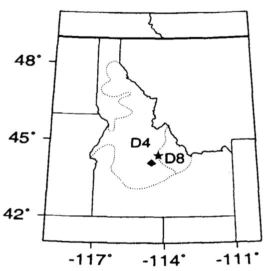

Figure 1. Location of tree-ring chronologies (★: Douglas-fir; ◆: whitebark pine) with respect to the boundaries of Idaho climate division 4 (central mountains; D4) and 8 (northeast valleys; D8).

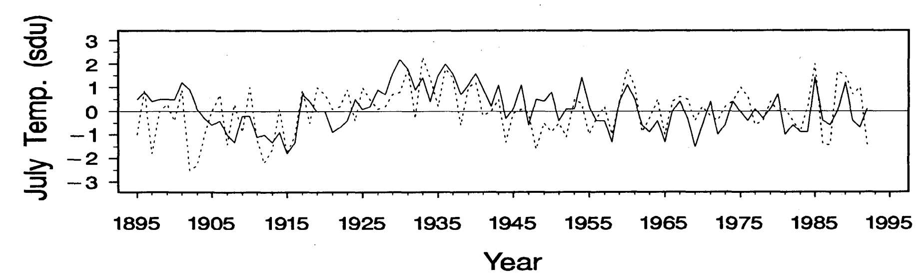

Figure 2. Instrumental (dashed line) and reconstructed July temperature for Idaho northeast valleys, 1895-1992. Divisional climate data are generally of excellent quality, but a complex series of adjustments was used to generate pre-1931 data in several western States, including Idaho [*NOAA*, 1983]. The initial years (1895-1903) were censored out for calibration-validation tests (Table 1). Correlation between the two series is 0.6 from 1904 to 1992. Both records point to a temperature rise culminating in the 1930s and returning to near-average conditions in recent decades.

growth at the lower forest border is favored by cooler summer temperatures because it is mostly limited by moisture stress during the growing season [*LaMarche*, 1974]. Whitebark pine growth on high elevation sites is favored by warmer summer temperatures because growth processes near timberline are more limited by cold air than by drought [*Fritts*, 1969]. Using as climate predictors two tree species from different environments with opposite response to the same climatic variable minimizes the risk of including stand-related and species-specific variability in the reconstruction. Furthermore, the two predictors are not significantly correlated to one another, hence there is no danger of collinearity in the model. Objective model selection criteria, such as Mallows' *Cp* [*Mallows*, 1973], repeatedly choose both predictors over either one in isolation. Statistical relationships obtained by using climate data from Idaho division 8 (northeast valleys) were consistent with those derived after averaging division 8 and 4 (central mountains), but associations were stronger for division 8 alone. Both tree-ring sites are located along the border between the two regions, but are much closer to the barycenter of division 8 than to that of division 4, which is considerably larger (Fig. 1). Presumably, meteorological variables over the northeast valleys better represent the climate regime experienced by the trees, and were then chosen as predictand.

The climate reconstruction was performed after a double calibration-validation test. First, the regression model was estimated using only the last decades (1949-1992), and model predictions were evaluated against the actual measurements for the early decades (1904-1947). Then, the periods used for calibration and validation were interchanged, and the model rechecked (Table 1). Statistical comparisons indicate enough skill in the model to warrant its use for climate backcasting [*Mann et al.*, 1998a], and the prediction captures the low-frequency features of the instrumental record (Fig. 2). The final regression parameters, estimated after pooling both periods together, are highly significant, both individually and as a whole, and the residuals are consistent with a white noise process [*Box and Jenkins*, 1976]. Based on standard partial regression coefficients [*Sokal and Rohlf*, 1981, pp. 621-622], the Douglas-fir contribution to the temperature reconstruction is about 60% greater in absolute value than the whitebark pine contribution. The average prediction error for a single observation [*Weisberg*, 1985, p. 230] is 0.97°C, lower than the 1.14°C standard deviation of the instrumental time series.

To investigate the large-scale spatial coverage of the climate reconstruction, we correlated the reconstructed temperatures with July data from the U.S. divisional network during 1895-1992. Time series were smoothed with a 5-year low-pass filter to emphasize low-frequency components of the temperature fluctuation. The correlation map (Fig. 3) reveals a strong connection with the Northern Rockies and the north-central Great Plains, and it indicates a link with most of the conterminous United States, following a sinusoidal pattern with rather large positive correlations in the southeastern states. The broad spatial relevance of the tree-ring reconstruction during the last century at multi-annual scales justifies the analysis of the entire proxy record in terms of supra-regional climate changes.

The 858-year proxy temperature record shows both high- and low-frequency departures from the long-term mean (Fig. 4). The low-frequency pattern was estimated using a cubic smoothing spline [*Cook and Peters*, 1981] that preserves most of the decadal-scale variance, 50% of the variance at a period of 50 years, and almost no variance at periods longer than 100 years. Extreme cooling continuing for several decades begins halfway through the thirteenth century, and culminates around AD 1300. A major cold interval, ca. 1200-1350, has also been identified from tree-ring records for the Columbia Icefield in Alberta, Canada [*Luckman et al.*, 1997]. In that and in our reconstruction, temperatures returned to normal by the end of the fourteenth century, and were followed by alternatively warm and cold excursions up to the present time. The lack of a continuously cold interval spanning

Table 1. Calibration (CAL) and Validation (VAL) Statistics[a] for the Tree-ring Reconstruction of July Temperature over East-central Idaho.

	CAL	VAL	CAL	VAL
Time period	1949-'92	1904-'47	1904-'47	1949-'92
Variance explained (R^2_a)	0.18	0.35	0.43	0.13
Cross-product t-test	2.83	4.35	4.12	3.68
Linear correlation test	0.44	0.60	0.66	0.39
Reduction of error test	0.20	0.36	0.44	0.12

[a] Two 44-year periods were alternatively used for calibration and validation. All tests are statistically significant. The lower explained variance in recent decades should not indicate a change in the response function model, which was extensively tested using multiple time intervals [*Biondi*, 1999].

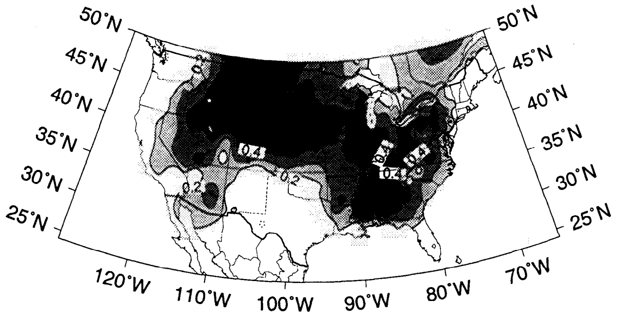

Figure 3. Spatial correlation of the reconstructed July temperature (☆) with the rest of the conterminous United States during 1895-1992. Correlations were computed after smoothing time series with a 5-year low-pass filter. The wavy spatial signature is centered on the north-central Rocky Mountains and the central Great Plains.

several centuries has often been observed in temperature-sensitive tree-ring records [*Bradley and Jones*, 1993; *Luckman et al.*, 1997]. Summer temperature in Fennoscandia was above average in the 1400s, suggesting that even European climate experienced a considerable amount of spatial variability over the last thousand years [*Briffa et al.*, 1992a]. Our reconstruction shows that high temperatures in the early 1400s were followed by a cold episode that peaked around 1460 and ended by the turn of the fifteenth century (Fig. 4). Pronounced growth reductions in the mid 1300s and second half of the 1400s, separated by a period of greater than normal values, have also been found in a network of six high-elevation, temperature-sensitive, tree-ring sites in the Great Basin and Sierra Nevada [*M.K. Hughes and G. Funkhouser*, unpublished data]. The average of those sites, plotted in Fig. 5, is based on many ring-width series, each one being 500 years or longer, without individual growth surges or suppressions, and from 'strip-bark', five-needle, upper forest border pines of great age. Such record is not a reliable temperature proxy for the last 150 years, as it shows an increasing trend starting in about 1850 that has been attributed to atmospheric CO_2 fertilization [*Graybill and Idso*, 1993].

July air temperatures remained generally warm throughout the 1500s, but plummeted to extreme lows right after 1600 (Fig. 4). According to a circumpolar network of temperature-sensitive tree-ring chronologies, the most severe Northern Hemisphere cold snap of the past 600 years occurred in 1601, following the year 1600 eruption of Huaynaputina in southern Peru [*Briffa et al.*, 1998]. Our reconstruction might reflect the global influence of the Huaynaputina eruption [*de Silva and Zielinski*, 1998], but its delayed timing suggests a connection with the cold and wet conditions that characterized the years around 1605 in the American Southwest and other parts of the globe [*Schimmelmann et al.*, 1998]. For instance, the exceptional occurrence of a perennial lake in the Mojave Desert around 390±90 yr. B.P. [*Enzel et al.*, 1992] could have been generated not only by increased winter precipitation, but also by reduced evaporation losses during the summer. Temperatures returned to normal by the mid-1600s, and during the 1700s they fluctuated on shorter time scales, showing an overall tendency to remain slightly above the long-term mean (Fig. 4). In the early 1800s the amplitude of multi-decadal patterns increased again: the first half of the nineteenth century was cooler, and the second half warmer, than normal. This agrees with other published summer temperature reconstructions for North America, which was usually colder in the early 1800s than later in that century [*Bradley and Jones*, 1995; Fig. 5).

Anomalously high tree-ring values have been found during the twentieth century at several locations [*LaMarche et al.*, 1984; *Cook et al.*, 1991; *Briffa et al.*, 1995; *Jacoby et al.* 1996]. In the region we considered, neither instrumental nor proxy temperature records show an increasing trend during the twentieth century (Fig. 2). Warm summers were most common in the 1930s, the 'dust-bowl' years, but near-normal conditions have prevailed in recent decades. Based on instrumental data, July is not unique: of all monthly variables for Idaho northeast valleys, none shows a significant linear trend from 1895 to 1992. From a statistical perspective, the absence of a positive trend during the 1900s reduces the risk of bias when calibrating the instrumental and proxy records to one another [*Box and Jenkins*, 1976]. From a climatological perspective, global warming or cooling usually incorporates a large degree of spatial and seasonal variability [*IPCC*, 1996; *Mann et al.*, 1998b]. The same patterns we found were obtained for summer mean temperature up to 1982 over the whole Western United States using a network of 23 maximum-latewood tree-ring chronologies [*Briffa et al.*, 1992b; Fig. 5]. On one hand, near-normal summer conditions in western North America during recent decades highlight the need to consider regional variability alongside global averages. On the other hand, the major, multi-decadal warm and cold intervals in our temperature reconstruction from 1600 to the present share major features with those identified from Greenland Ice Sheet boreholes [*Dahl-Jensen et al.*, 1998; Fig. 5], suggesting that large-scale connections modulated by hemispheric circulation should have remained

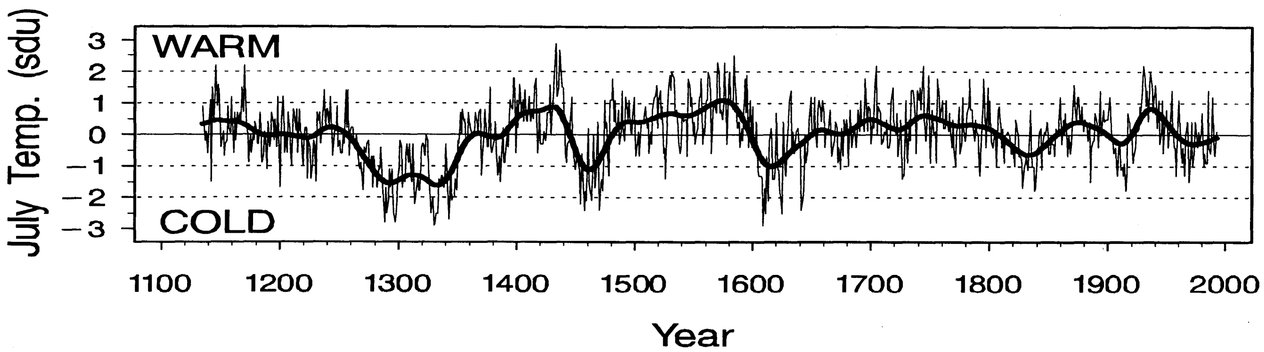

Figure 4. Interannual and interdecadal (thick line) variability of July temperature during the second millennium, A.D. 1135-1992. Cold and warm intervals of decadal to centennial duration alternate in the temperature chronology.

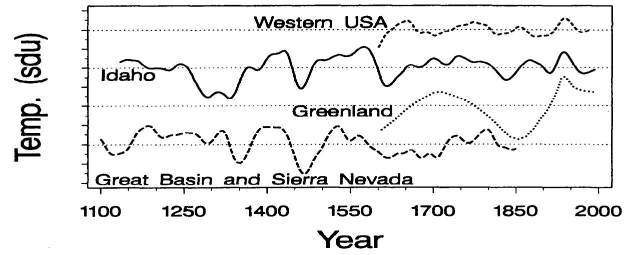

Figure 5. Low-frequency patterns of July temperature for Idaho northeast valleys match those obtained for western USA summer temperature [*Briffa et al.*, 1992b], and for Greenland temperature histories [*Dahl-Jensen et al.*, 1998], especially during the twentieth century. Prior to 1600, multi-decadal warm and cold episodes resemble those identified in 'strip-bark' tree-ring records from the Great Basin and Sierra Nevada (see text for details). Data were converted to standard deviation units, and tree-ring records were smoothed with a 50-year cubic spline.

unchanged for the past few centuries. Overall, our study supports the idea that the second millennium AD has been characterized by both warm and cold episodes, whose extent, seasonality, and intensity exhibited a considerable amount of geographical variability.

Acknowledgments. We thank the USDA Forest Service and the USDOI Bureau of Land Management for permission to obtain tree-ring samples. Research funding was provided in part by NSF Earth System History Program. D.L. Perkins was supported by the USDA Forest Service Rocky Mountain Research Station. Gary Funkhouser helped with assembling the 'strip-bark' tree-ring chronology. The comments of W.H. Berger, J.S. Gee, E.R. Cook, and two anonymous referees are gratefully acknowledged.

References

Barnett, T. P., Santer, B. D., Jones, P. D., Bradley, R. S. and Briffa, K. R., Estimates of low frequency natural variability in near-surface air temperature, *Holocene*, *6*, 255-263, 1996.

Biondi, F., Are climate-tree growth relationships changing in north-central Idaho?, *Tree-Ring Bull.*, *in press*, 1999.

Box, G. E. P. and Jenkins, G.M., *Time Series Analysis: Forecasting and Control*, revised ed., Holden-Day, Oakland, CA, 1976.

Bradley, R. S. and Jones, P. D. (Eds), *Climate Since A.D. 1500*, revised ed., Routledge, London, 1995.

Bradley, R.S. and Jones, P.D., 'Little Ice Age' summer temperature variations: their nature and relevance to recent global warming trends, *Holocene*, *3*, 367-376, 1993.

Briffa, K. R., Jones, P.D., Bartholin, T.S., Eckstein, D., Schweingruber, F.H., Karlén, W., Zetterberg, P. and Eronen, M., Fennoscandian summers from AD 500: Temperature changes on short and long timescales, *Climate Dynamics*, *7*, 111-119, 1992a.

Briffa, K.R., Jones, P.D. and Schweingruber, F.H., Tree-ring density reconstructions of summer temperature patterns across Western North America since 1600, *J. Climate*, *5*, 735-754, 1992b.

Briffa, K. R., Jones, P. D., Schweingruber, F. H., Shiyatov, S. G. and Cook, E. R., Unusual twentieth-century summer warmth in a 1,000-year temperature record from Siberia, *Nature*, *376*, 156-159, 1995.

Briffa, K.R., Jones, P.D., Schweingruber, F.H. and Osborn, T.J., Influence of volcanic eruptions on Northern Hemisphere summer temperature over the past 600 years, *Nature*, *393*, 450-454, 1998.

Cook, E. R., Bird, T., Peterson, M., Barbetti, M., Buckley, B., D'Arrigo, R., Francey, R. and Tans, P., Climatic change in Tasmania inferred from a 1089-year tree-ring chronology of huon pine, *Science*, *253*, 1266-1268, 1991.

Cook, E. R. and Kairiukstis, L. A. (Eds), *Methods of Dendrochronology*, Kluwer, Dordrecht, 1990.

Cook, E. R., Briffa, K. R., Meko, D.M., Graybill, D.A.and Funkhouser, G., The 'segment length curse' in long tree-ring chronology development for palaeoclimatic studies, *Holocene*, *5*, 229-237, 1995.

Cook, E. R. and Peters, K., The smoothing spline: a new approach to standardizing forest interior tree-ring width series for dendroclimatic studies, *Tree-Ring Bull.*, *41*, 45-53, 1981.

Dahl-Jensen, D., Mosegaard, K., Gundestrup, N., Clow, G.D., Johnsen, S.J., Hansen, A.W. and Balling, N., Past temperatures directly from the Greenland Ice Sheet, *Science*, *282*, 268-271, 1998.

de Silva, S.L. and Zielinski, G.A., Global influence of the AD1600 eruption of Huaynaputina, Peru, *Nature*, *393*, 455-458, 1998.

Enzel, Y., Brown, W.J., Anderson, R.Y., McFadden, L.D. and Wells, S.G., Short-duration Holocene lakes in the Mojave River drainage basin, Southern California, *Quat. Res.*, *38*, 60-73, 1992.

Fritts, H.C., Bristlecone pine in the White Mountains of California: Growth and ring-width characteristics, Papers of the Laboratory of Tree-Ring Research No. 4, University of Arizona Press, Tucson, 1969.

Graybill, D.A. and Idso, S.B., Detecting the aerial fertilization effect of atmospheric CO_2 enrichment in tree-ring chronologies. *Global Biogeochemical Cycles*, *7*, 81-95, 1993.

Grove, J.M., *The Little Ice Age*, Methuen, London, 1988.

Guiot, J., The bootstrapped response function, *Tree-Ring Bull.*, *51*, 39-41, 1991.

Guttman, N.B. and Quayle, R.G., A historical perspective of US climate divisions, *Bull. Amer. Meteor.Soc.*,*77*, 293-303, 1996.

IPCC, *Climate Change 1995: The Science of Climate Change*, Cambridge University Press, Cambridge, 1996.

Jacoby, G. C., D'Arrigo, R. D. and Davaajamts, T., Mongolian tree rings and 20th-century warming, *Science*, *273*, 771-773, 1996.

Karl, T. R., Williams, C. N. Jr., Young, P. J. and Wendland, W. M., A model to estimate the time of observation bias associated with monthly mean maximum, minimum, and mean temperatures for the United States. *J. Clim. Appl. Meteorol.*, *25*, 145-160, 1986.

NOAA, Statewide Average Climatic History, Historical Climatology Series 6-1. National Climatic Data Center, Asheville, NC, 1983.

LaMarche, V. C. Jr., Graybill, D. A., Fritts, H. C. and Rose, M. R., Increasing atmospheric carbon dioxide: Tree ring evidence for growth enhancement in natural vegetation. *Science*, *225*, 1019-1021, 1984.

LaMarche, V.C. Jr., Paleoclimatic inferences from long tree-ring records. *Science*, *183*, 1043-1048, 1974.

Luckman, B.H., Briffa, K.R., Jones, P.D. and Schweingruber, F.H., Tree-ring based reconstruction of summer temperatures at the Columbia Icefield, Alberta, Canada, AD 1073-1983, *Holocene*, *7*, 375-389, 1997.

Mallows, C.L., Some comments on C_p, *Technometrics*, *15*, 661-675, 1973.

Mann, M.E., Bradley, R.S., Hughes, M.K. and Jones, P.D., Global temperature patterns, *Science*, *280*, 2029-2030, 1998a.

Mann, M.E., Bradley, R.S. and Hughes, M.K., Global-scale temperature patterns and climate forcing over the past six centuries, *Nature*, 392, 779-787, 1998b.

National Research Council, *Natural Climate Variability on Decade-to-Century Time Scales*, National Academy Press, Washington, D.C., 1995.

Perkins, D.L., and Swetnam, T.W., A dendroecological assessment of whitebark pine in the Sawtooth-Salmon River region, Idaho, *Can. J. For. Res.*, *26*, 2123-2133, 1996.

Schimmelmann, A., Zhao, M., Harvey, C.C. and Lange, C.B., A large California flood and correlative global climatic events 400 years ago, *Quat. Res.*, *49*, 51-61, 1998.

Sokal, R.R. and Rohlf, F.J., *Biometry*, second ed., Freeman, New York, 1981.

Weisberg, S., *Applied Linear Regression*, second ed., Wiley, New York, 1985.

F. Biondi, UCSD-SIO-GRD, Mailcode 0215, La Jolla, CA 92093-0215. (e-mail: fbiondi@ucsd.edu)

D.R. Cayan, UCSD-SIO-CRD, Mailcode 0224, La Jolla, CA 92093-0224.

M.K. Hughes, Laboratory of Tree-Ring Research, University of Arizona, Tucson, AZ 85721.

D.L. Perkins, USDA Forest Service, 860 North 1200 East, Logan, UT 84321.

(Received February 8, 1999; revised March 26, 1999;
accepted March 29, 1999.)