Proceedings of the Sixteenth Annual Pacific Climate Workshop

The Wrigley Institute for Environmental Studies
Two Harbors, Santa Catalina Island, California
May 24-27, 1999

Edited by
G. James West and Lauren Buffaloe

Technical Report 65
of the
Interagency Ecological Program for the
Sacramento-San Joaquin Delta

May 2000

PACLIM

Climate Variability of the Eastern North Pacific and Western North America

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Contents

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Acknowledgments

PACLIM workshops are produced by volunteers who always manage to put together a topically interesting and timely gathering of a wide range of researchers. The 1999 workshop was no exception.

For 1999, thanks go to the following people and institutions. **USGS**: Mike Dettinger, Program Chair, and Ray Wilson, Proceedings Editor. **Long Beach City College**: Janice Tomson, Meeting Organizer, and Melissa Andrews, Victoria Brooks, Jacqueline Cote, and Jessie Ramirez. **Scripps Institution of Oceanography**: Dan Cayan, Program Chair Emeritus. **California Conservation Corps**: Dustin Platter. **USC/WEIS**: Anthony "Tony" Michaels (special thanks to the Wrigley Institute for Environmental Studies and Tony Michaels for co-sponsoring and hosting the 1999 PACLIM on Santa Catalina Island). **USC**: Lowell Stott. **AGU**: Sandra Williams.

Sponsorship and funding for the workshops come from a wide variety of sources. This year's PACLIM Workshop was sponsored by Tony Michaels (Wrigley Institute for Environmental Sciences); Bill Kirby (USGS, Water Resources Division); Elliot Spiker (USGS, Geological Research Division); Roger Pulwarty (NOAA Office of Global Programs); Sandra Williams (American Geophysical Union) and Randy Brown (California Department of Water Resources).

For the second year running, Mike Dettinger chaired and organized the meeting and this year set up the web page. As she has done previously, Janice Tomson did a superb job of planning, organizing, and supervising the operation of the meeting—getting us there, getting us fed, watered, and roomed, and, with her Long Beach City College students, doing all the other numerous things that need to be done to make a successful meeting. The meeting moderators are also greatly acknowledged: Mike Dettinger, Kelly Redmond, Roger Pulwarty, Tony Michaels, Dan Cayan, Greg McCabe, Bob Webb, and Janice Tomson. Finally, we thank all our speakers and poster presenters (see Appendix A "Agenda" and Appendix B "Posters") for their contributions and enthusiasm.

For the 1998 Proceedings volume many thanks go to Ray Wilson and Lauren Buffaloe for their editing. For the production and printing of the proceedings, thanks go once again to Randy Brown of the California Department of Water Resources and Interagency Ecological Program for the Sacramento-San Joaquin Delta. The production of this volume was performed by my co-editor, Lauren Buffaloe, who I thank for her special expertise and knowledge. Kurt Angersbach and Katherine West assisted in editing several of the papers. Ann Watanabe, US Bureau of Reclamation, re-drafted several of the figures. Ray Wilson translated the MacIntosh files to a format we could use and answered numerous questions about producing the proceedings.

The precedents for the 1999 volume were established by the previous editors of the PACLIM Proceedings: Dave Peterson (1984–1988), with the able assistance of Lucenia Thomas; Julio Betancourt and Ana MacKay (1989–1990); Kelly Redmond and Vera Tharp (1991–1993); Caroline Isaacs and Vera Tharp (1994–1996); Ray Wilson and Vera Tharp (1997); and Ray Wilson and Lauren Buffaloe (1998).

G. James West

Special Recognition

As many PACLIM participants know, Dr. Randall Brown, Chief of the Environmental Services Office of the California Department of Water Resources (DWR), has quietly contributed to PACLIM since its beginning. Not only has DWR been a workshop sponsor, Randy's office has edited, composed, and published the workshop proceedings during the 1990s as part of the technical report series of the Interagency Ecological Program. Randy has been a motivating force for a wide range of scientific activities associated with the Sacramento-San Joaquin Delta for years and has provided much interest and focus to past PACLIM workshops.

So with with Randy's retirement from DWR this year, PACLIM participants and organizers gratefully recognize and thank Randy for his essential contributions to PACLIM and invite him to all future PACLIM workshops.

Statement of Purpose

In 1984, a workshop was held on "Climatic Variability of the Eastern North Pacific and Western North America." From it has emerged an annual series of workshops held at the Wrigley Institute for Environmental Studies at Two Harbors, Santa Catalina Island, California. These annual meetings, which involve 80–100 participants, have come to be known as the Pacific Climate (PACLIM) Workshops, reflecting broad interests in the climatologies associated with the Pacific Ocean and western Americas in both the northern and southern hemispheres. Participants have included atmospheric scientists, hydrologists, glaciologists, oceanographers, limnologists, and both marine and terrestrial biologists. A major goal of PACLIM is to provide a forum for exploring the insights and perspectives of each of these many disciplines and for understanding the critical linkages between them.

PACLIM arose from growing concern about climate variability and its societal and ecological impacts. Storm frequency, snowpack, droughts and floods, agricultural production, water supply, glacial advances, stream chemistry, sea surface temperature, salmon catch, lake ecosystems, and wildlife habitat are among the many aspects of climate and climatic impacts addressed by PACLIM Workshops. Workshops also address broad concerns about the impact of possible climate change over the next century. From observed changes in the historical records, the conclusion is evident that climate change would have large societal impacts through effects on global ecology, hydrology, geology, and oceanography.

Our ability to predict climate, climate variability, and climate change critically depends on an understanding of global processes. Human impacts are primarily terrestrial in nature, but the major forcing processes are atmospheric and oceanic in origin and transferred through geologic and biologic systems. Our understanding of the global climate system and its relationship to ecosystems in the Eastern Pacific area arises from regional study of its components in the Pacific Ocean and western Americas, where ocean-atmosphere coupling is strongly expressed. Empirical evidence suggests that large-scale climatic fluctuations force large-scale ecosystem response in the California current and in a very different system, the North Pacific central gyre. With such diverse meterologic phenomena as the El Niño–Southern Oscillation and shifts in the Aleutian Low and North Pacific High, the eastern Pacific has tremendous global influences and particularly strong effects on North America. In the western US, where rainfall is primarily a cool-season phenomenon, year-to-year changes in the activity and tracking of North Pacific winter storms have substantial influence on the hydrological balance. This region is rich in climatic records, both instrumental and proxy. Recent research efforts are beginning to focus on better paleoclimatic reconstructions that will put present-day climatic variability in context and allow better anticipation of future variations and changes.

The PACLIM Workshops address the problem of defining regional coupling of multifold elements, as organized by global phenomena. Because climate expresses itself throughout the natural system, our activity has been, from the beginning, multidisciplinary in scope. The specialized knowledge from different disciplines has brought together climatic records and process measurements to synthesize and understanding of the complete system. Our interdsciplinary group uses diverse time series, measured both directly and through proxy indicators, to study past climatic conditions and current processes in this region. Characterizing and linking the geosphere, biosphere, and hydrosphere in this region provides a scientific analogue and, hence, a basis for understanding similar linkages in other regions and for anticipating the response to future climate variations. Our emphasis in PACLIM is to study the interrelationships among diverse data. To understand these interactive phenomena, we incorporate studies that consider a broad range of topics both physical and biological, time scales from months to millennia, and space scales from single sites to the entire globe.

Summary

PACLIM 1999: ENSO Extremes Highlight Climate's Societal Connections

Andrea J. Ray and Kelly Redmond

Impacts of the recent El Niño and La Niña have highlighted the need and potential to use climate information in societal activities and decisions. Thus, "Climate and Society" was the theme of the 16th annual Pacific Climate (PACLIM) workshop. PACLIM is a forum for exploring perspectives and developing insights into the interactions between climate and a broad range of disciplines in the geographic area encompassed by the Pacific Ocean and western Americas. This year's meeting focussed on implications of seasonal climate forecasts and historical information about climate in natural resources management and in evaluation of past and planned policies.

One pathway to understanding the interaction of climate and society involves comparative geographic studies. The opening session took this approach, to compare and contrast the Colorado and the Columbia, two major river basins in western North America that are influenced by the equatorial Pacific. The basins respond nearly oppositely to ENSO forcing, and nearly oppositely to the two phases of ENSO, with somewhat more consistency for La Niña than El Niño. An introduction on the motivation and methodology was provided by Roger Pulwarty (NOAA Office of Global Programs) and Kelly Redmond (Desert Research Institute, Western Regional Climate Center). River flows in the Columbia and Colorado are largely driven by snowmelt; Martyn Clark (Univ. of Colorado) reviewed the relation of winter snowpack accumulation in the two basins to El Niño and La Niña. Ed Miles (U of Washington) discussed an ongoing regional assessment of climate and society in the Pacific Northwest, now in its fourth year, that focuses on how to integrate management of water to both promote health of fisheries and provide economic benefits such as hydropower. A historical and hydrologic overview of water resource management in the Colorado basin was provided by John Dracup (UCLA). Richard Stoffle (U of Arizona) presented examples of the significant role of cultural adaptations by American Indians in both basins that are both responses to and protection from climate fluctuations. He noted the power of culture to mediate the effects of climate variability by accumulating knowledge on coping mechanisms and embedding them into cultural practices and ceremony. A corollary to this is that there may be adverse impacts of replacing indigenous knowledge and conservation ethics with untried adaptive strategies from other cultures and places.

Roger Pulwarty also discussed adaptive management of reservoirs in the Colorado Basin for ecosystem and other needs; one issue is how to use information about wet seasons (such as the 1997–1998 ENSO) in the context of management objectives designed to mitigate drought. Drawing from studies of the basins, several factors to be considered in appraisals of climate impacts on water resources are: a) what climatic circumstances induce a critical situation for a resource, b) the difference between exposure to climate events and vulnerability, and c) flexibility of human systems to respond. Pulwarty discussed how institutions can incorporate responses which reduce vulnerability. A "lesson learned" from assessing the influence of climate in these cases is that it is unwise to ignore past and potential variability in natural systems (fisheries, water systems) especially where competing demands have evolved. Thus, decisions that generate rigidity in a system (such as inflexible allocation of water) are likely to generate more problems in the long run than are solved.

An extension of this lesson is that climatic variability should be considered in evaluating the effectiveness of policy or management actions. John Tracy (Desert Research Institute) described how climate variability has affected restoration efforts in the Lake Tahoe and Walker River basins in the Sierra Nevada, as well as the evaluation of success of those efforts. Degradation of the famous clarity of Lake Tahoe has led to many efforts to restore ecological integrity of the watershed. In the early 1990s, clarity stabilized and management actions were thought to be working -- but decreasing clarity in the middle 1990s brought calls for more attention to the problem. Climate records reveal that the early 1990s were a drought period, but the mid-1990s were relatively wet in the basin, associated with low and high sediment inflows respectively. Thus, clarity, the criteria for determining success of restoration efforts, is influenced not only by the management efforts, but also by climate variability. In the Walker River basin, low inflow years result in high salinity in a terminal desert lake which is home to declining Lahontan cutthroat trout and other species. Proposed restoration efforts include purchasing water rights for the lake; however, these efforts do not acknowledge that multiyear periods of average and lows occur, and will require more water to maintain the lake ecosystem. In both the Lake Tahoe and Walker river cases, ignoring multiyear variability both jeopardizes the success of the restoration efforts and can lead to a false perception of either success or failure of efforts.

Several other talks also emphasized that climate might affect natural resource management and evaluation of policies. Climate regime shifts (the theme of the 1991 PACLIM) are now thought to strongly affect fisheries recruitment in the Pacific Northwest (Nate Mantua, Univ. of Washington), and may confound the efforts of fish hatcheries in stock management. Mantua also reviewed the efforts to understand the Pacific Decadal Oscillation and the potential for predictability. Climate variability can also affect ecosystem analysis and land planning (Wally Woolfenden, US Forest Service), and the implications of the effect of year-to-year precipitation variability on salinity for planning the San Francisco Bay-Delta restoration (Noah Knowles, Scripps). Several talks discussed barriers to using climate information in natural resource management: the lack of understanding of forecasts, inappropriate information, and poor timing affect use of forecasts (Miles; Pulwarty and Redmond); legal constraints and barriers are often rigid systems limiting use of forecasts (Dracup); and the focus of attention is often on other environmental problems perceived to be more critical (Andrea Ray, NOAA Climate Diagnostics Center).

During an interlude that beautifully complemented the more traditional lecture style, photojournalist Michael Collier narrated a spectacular slide show consisting of aerial photos of the Colorado River from start to finish, taken from his new book, "Earth, Sky and Water."

A keynote talk by Michael Hammer (Centre Solutions), CEO of a financial services firm, emphasized the ways in which climate directly affects business activities. Businesses use equity capital to absorb unexpected shocks, and insurance allows them to "rent" capital. Thus, insurers might use climate information to assess the risks of events affecting businesses. Insurers are accustomed to using probabilistic information, thus he feels that information on the shifts in probability distributions of kinds of events (e.g., winter storms) will be usable even though perfect climate forecasts are not available. He urged climate scientists to learn about the needs of businesses and that could lead to cooperation in new areas. He cited the interactions between business and scientists in the Risk Prediction Initiative at the Bermuda Biological Station as an example. Tony Michaels (Wrigley Institute for environmental Sciences) recounted his experiences working with this Initiative, and reiterated the importance of scientists working directly with the users of information. Brian McGurty (Southern California Edison) discussed the implications of climate information for power contracts and generation operations given the new deregulation era. He also noted that the reservoir system is designed for late runoff, that is, the average annual cycle of early 20th century; if spring runoff timing changes, operations changes would be needed and perhaps more storage. Mike Dettinger (USGS, San Diego) presented evidence that there is significant decadal variability in the timing of peak runoff. For many streams he studied in the U.S., peak flows are occurring earlier in spring than earlier this century.

Interaction of climate and society is not a new phenomenon. A keynote address by Jeff Dean (U. of Arizona) highlighted Anasazi societies. Paleoenvironmental reconstructions indicate that high climate stress to Anasazi subsistence systems occurred many times. Culturally, they seem to have been adapted to the variability, so the impetus for abandonment of the Mesa Verde and other San Juan drainage settlements may have been better natural conditions elsewhere and social developments attracting migrants to other areas. In the more recent past, there is an association between the 1878 yellow fever epidemic and the El Niño of the same year (Greg McCabe, USGS). Sarah Otterstrom (UC Davis) described how farmers in different regions of Costa Rica have different anticipatory and preventative coping mechanisms for drought--which she documented during for ENSO-related 97-98 droughts--and thus differing vulnerability.

An annual feature of the meeting is a look back at the previous year's climate and current status. Recapping the rapid transition from El Niño to La Niña, Kelly Redmond described a classic La Niña pattern in 1998–1999 western winter precipitation: The southwest U.S. experienced one of its driest winters ever, and the Pacific northwest one of its wettest, with near record snowpack. By contrast, however, western winter temperature anomalies revealed a single sign (very positive) rather than the typical north-south dipole: usually the northern Rockies are colder than average and the southwest is warmer than average with La Niña, but this year showed warmth both north and south. A large number of windstorms also occurred during the winter. Maurice Roos (California Department of Water Resources) noted that the peak season Sierra Nevada snowpack percentages showed as much north to south variation as has ever been observed (wet north and central, dry south).

Analysis of time series records of natural phenomena are another common PACLIM theme. This year, Tony Westerling (UCSD) presented evidence for an increase in the frequency of extreme storm surges from large winter storms in the northeast Pacific with implications of future extreme sea levels for San Francisco. Shaleen Jain (Utah State) discussed how variations in precipitation and temperature associated with climate mode might affect annual maximum floods in Utah. David Jay and Pradeep Naik (Oregon Graduate Institute) discussed how ENSO variability influences sediment transport variability in west coast rivers. Lake sediment cores at Mono Lake reveal lake level variability during the last millennium (Lowell Stott, USC). Marine sediments in San Diego Penasquitos Lagoon are the source of proxy data on changes in climate on adjacent land and changes in sedimentation rate after human settlement (Ken Cole, (USGS). Marine sediments also reveal decadal variability in marine productivity in the Santa Monica Basin since 1500 (Will Berelson, USC). Cary Mock (U. of South Carolina) described how avalanche types vary with ENSO in different mountain regions of the west, and this information might be useful in avalanche forecasting and mitigation.

PACLIM 1999 was sponsored by the Wrigley Institute for Environmental Sciences, the USGS (Water Resources, Geological Research), California Dept of Water Resources, and NOAA Office of Global Programs. An agenda with presentation titles, authors, and meeting information is available at Web site meteora.ucsd.edu/paclim. A proceedings volume is published annually by the California Department of Water Resources and will be available in early 2000. This summary was prepared for *EOS, Transactions*, and the American Geophysical Union.

Introduction

G. James West

The Sixteenth Annual PACLIM Workshop was held at the Wrigley Institute of Environmental Studies campus at Two Harbors, on Santa Catalina Island, California. The island location of the workshop has proved to be ideal for conferences on climate of the eastern Pacific, and we experienced a most ideal Pacific climate during the workshop. Attended by about 70 registered participants (see Appendix C, Attendees), the workshop included 40 talks and 21 poster presentations. The talks consisted of a one-day theme session, "Climate and Society," with featured (30- to 45-minute) talks (see Appendix A, Agenda). Throughout the remainder of the meeting, shorter (20-minute) presentations were made. On the first evening, Michael Hammer, CEO of Centre Solutions, provided an enlightened presentation on climate's effect on business, an area that is developing a significant interest in climate studies. In addition, Mike Collier shared wonderful aerial views of the Colorado River from its start in the Colorado Rockies to its demise before it reaches the Gulf of California. Tuesday evening's keynote speaker, Jeff Dean, presented his well-researched perspective on the environment and prehistoric cultures of the Colorado Plateau. Wednesday evening, Nat Mantua gave a clear, coherent discussion of the Pacific decadal climate oscillation and the potential for its predictability. Poster presentations were displayed throughout the entire meeting and time was set aside for their presentation (see Appendix B, Poster Presentations).

All presenters were invited to expand their abstracts into a manuscript for inclusion in the Proceedings volume, and nearly all presentations are included in manuscript or abstract form. In this Proceedings volume, 16 papers are presented full-length and one as an extended abstract. The abstracts submitted to the meeting are printed in a separate section in this volume.

PACLIM, A Personal View

From my viewpoint, PACLIM workshops have been a matrix of ideas and data allowing for the exploration of climate phenomenon from many different perspectives. This year's PACLIM workshop was no exception: the examination of the linkage between climate variability and society, with a geographic focus primarily on the eastern Pacific and western America. As always, a multi-disciplinary approach characterized the workshop by bringing together specialists from diverse fields including the social, physical, and biological sciences. Time scales ranged from contemporary weather to paleoclimate. The interactions were addressed at varying levels through studies of the public sector, private sector, and prehistoric societal responses. The rich mix of topics ranged from a review of the previous year's climate to the examination of artificial neural networks to produce winter precipitation forecasts to the reconstruction of past climates and their application in the management of water resources. The social and biological affects of ENSO were highlighted by several presenters. As with previous workshops, participants ranged through a wide spectrum of specialization: pure academic research to resource managers and decision makers to entrepreneurs. PACLIM workshops provide a meaningful interface between disciplines that is seldom achieved in other forums.

The connection between climate and human behavior varies greatly, depending on diverse cultural and biological factors. While there is often not a direct link, since the interaction is filtered by culture, there is no doubt that climate variation either causes or allows humans to make decisions that may lead either to social change or stability. Technology has allowed humans to overcome some of the constraints of climate, but decisions are still made that lead to situations in which climate can have a direct affect on human behavior. Exploration of both the direct and indirect linkages is important since it will allow for a greater understanding of how decisions are made and what their outcomes might be. The more we understand the relationship between climate variation and human behavior the greater are the chances that our decisions will lead to desired outcomes.

A Review of Water Year 1999: A Classic La Niña Pattern

Maurice Roos

Water year 1998–1999 seemed to embody a classic La Niña pattern. By contrast, the previous water year was one of the strongest El Niño years this century with relatively warm eastern tropical Pacific sea surface temperatures. The eastern Pacific cooled rapidly during the summer of 1998. By fall, a large pool of cooler-than-normal water was evident east of the date line. The expected outlook was a dry American Southwest and a wet Pacific Northwest. In fact, this basic winter precipitation pattern did occur with dryness extending westward into the southern half of California. The season in the Northwest, including British Columbia, was wet with many days of rain and record snowpack at some stations.

Northern California is between the two extremes; historically this winter season could have been as wet as 1974 or dry as 1976. We have also noticed that some of our worst floods, notably December 1955 and December 1964, occurred in La Niña years. The odds of a large, rain-on-snow flood seemed to be a little higher then because of more meridianal winter weather patterns. This year the north Pacific storm track was vigorous, and wetness extended almost to central California, especially in the mountains. The exception was a month-long dry spell centered around New Year's Day. The dry period included a temperature extreme with a severe freeze the week before Christmas. During the winter, many storms seemed to run out of energy between Stockton and Fresno leaving the southern Sierra rather dry.

Figure 1, taken from the DWR May 1 edition of Bulletin 120, *Water Conditions in California*, shows seasonal precipitation patterns by hydrologic area. The northern areas, particularly the North Coast, were wetter while the south was dry with a statewide figure near average. After May 1, the northern California was fairly dry; by September, precipitation percentages dropped about 5%, except in the southeastern deserts, which turned out to have some heavy summer showers. Figure 2 shows an update of seasonal precipitation for the water year.

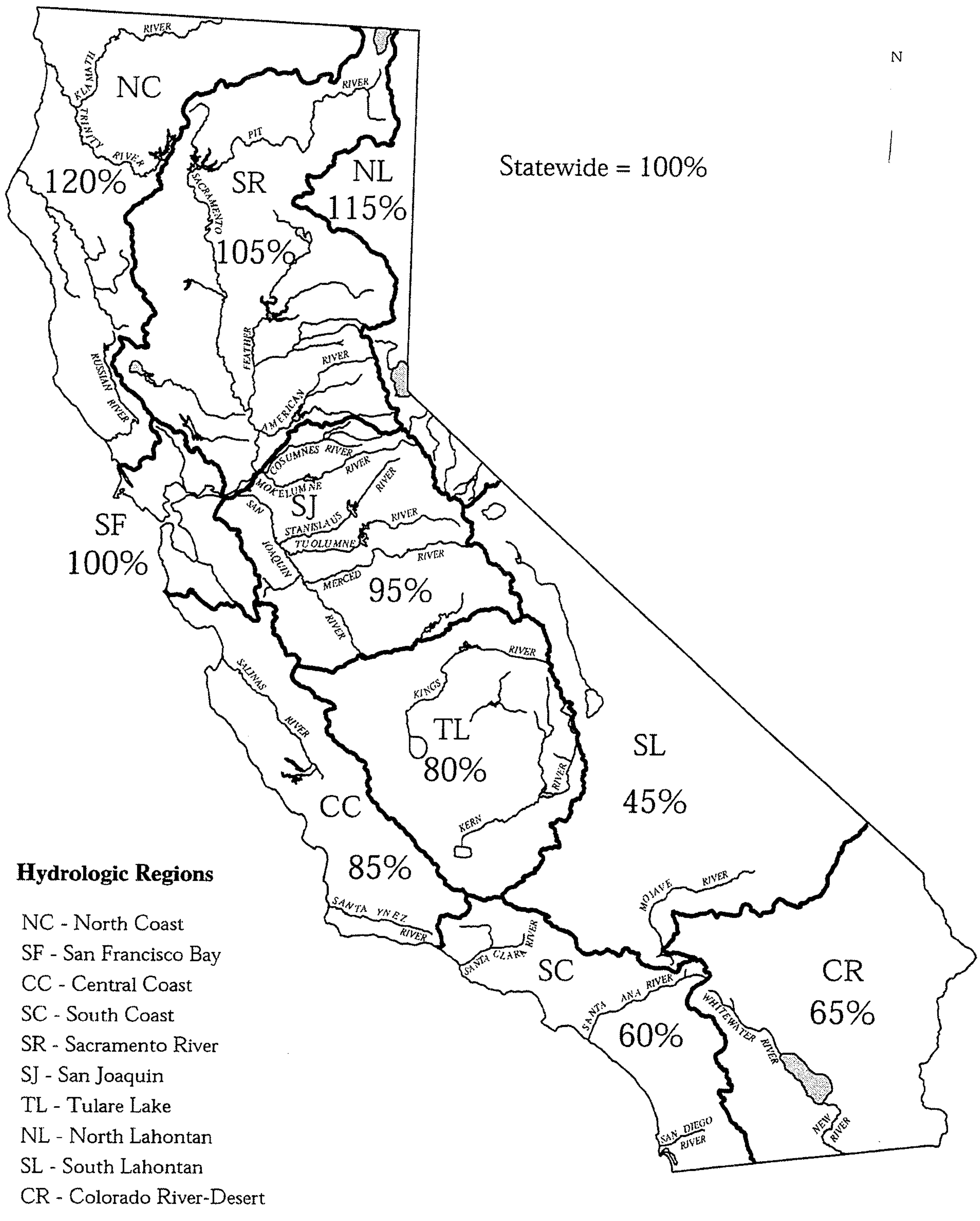

Figure 1 Seasonal precipitation in percent of average to date from October 1, 1998 through April 30, 1999

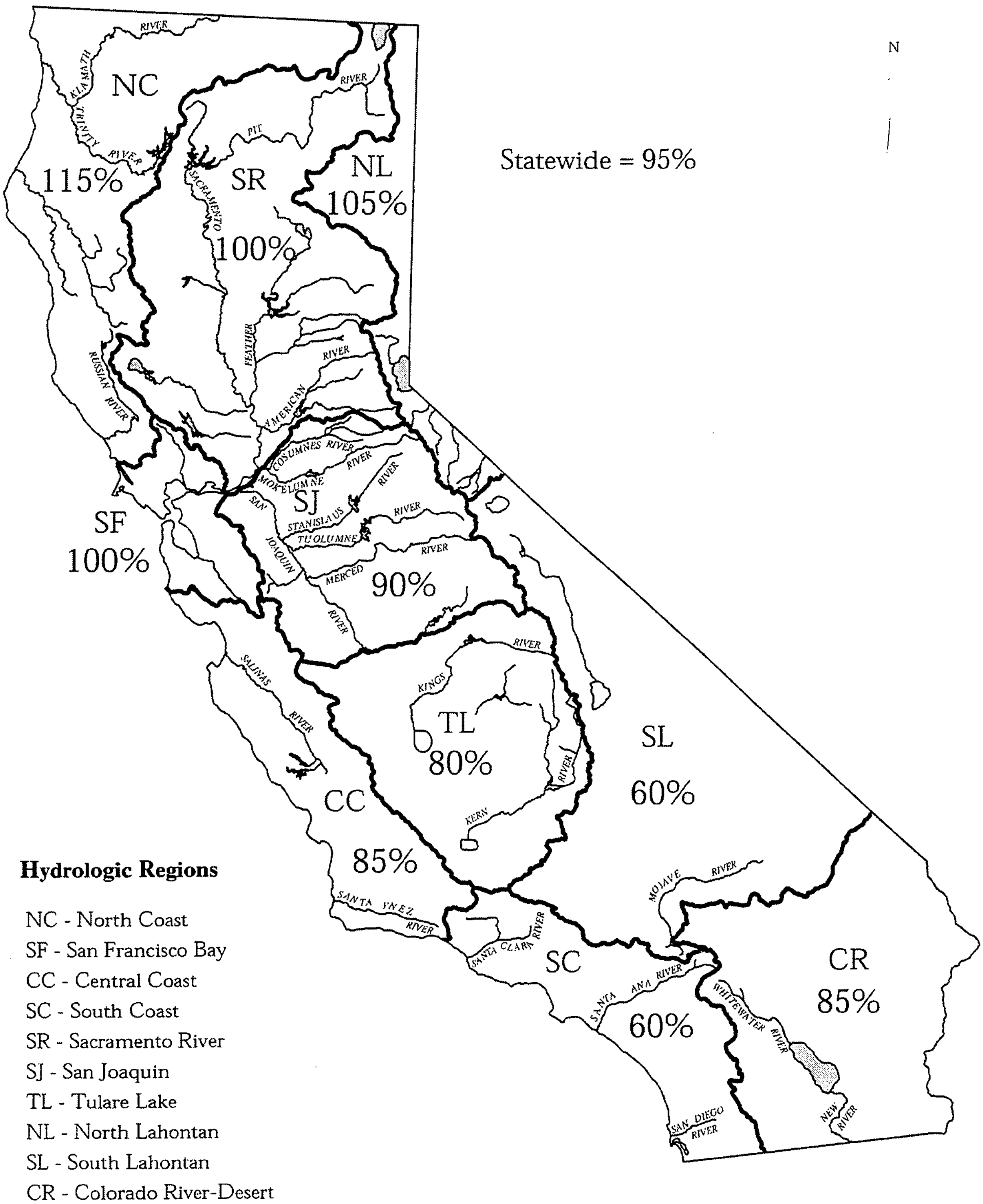

Figure 2 Seasonal precipitation in percent of average to date from October 1, 1998 through September 30, 1999

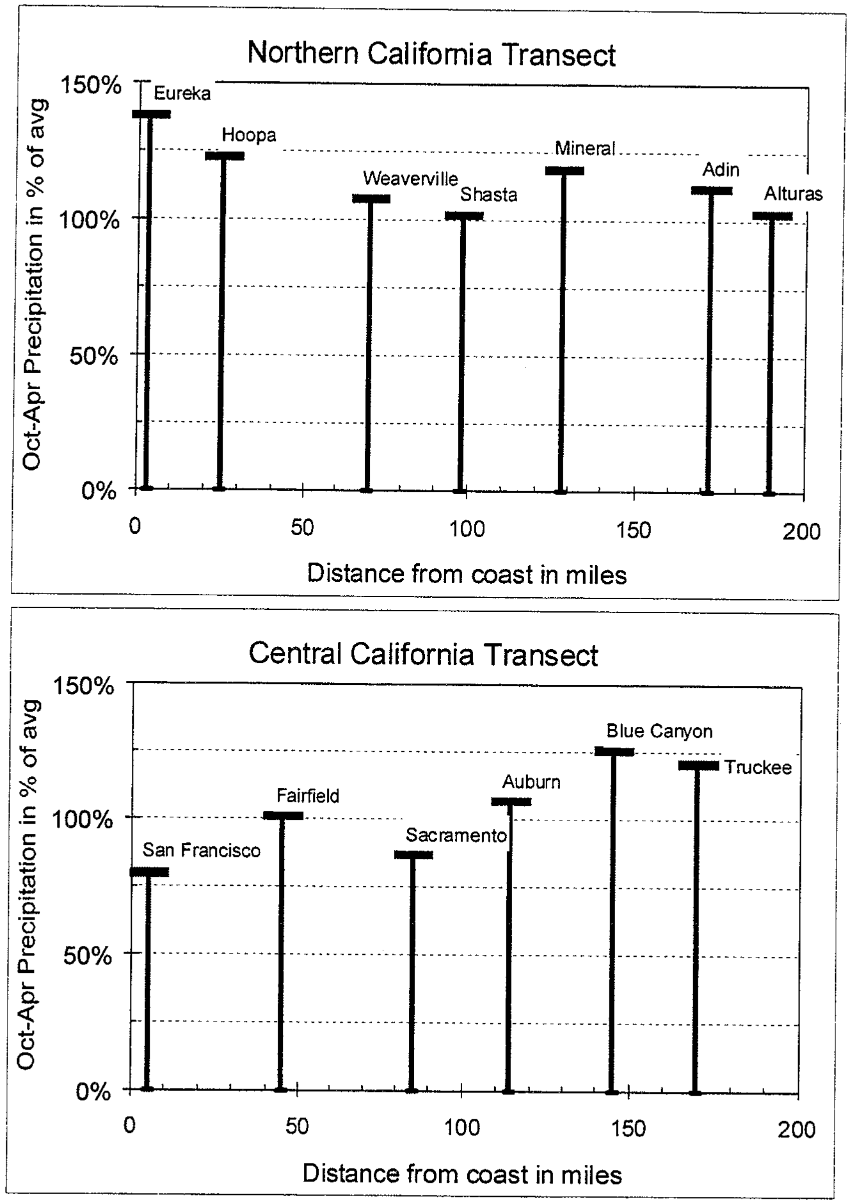

Figure 3 1999 Precipitation profiles

Figure 3 shows two transects of seasonal precipitation from October through April. One transect is across the north from Eureka through Shasta Dam over to Alturas. Percentage amounts decrease inland, but rise somewhat over the Sierra, as exemplified by the Mineral station near Lassen Park. The second transect is roughly along Interstate 80; it shows lowland locations with lighter amounts and a pronounced orographic gain in the mountains, especially at Blue Canyon. Although Fairfield is at a low elevation, it is influenced by its proximity to the axis of the Coast Range. The vigor of the storm systems is evident in the mountain area orographic effects. Eureka, on the other hand, is closer to the heavier activity in the Northwest and shows some of that regional effect.

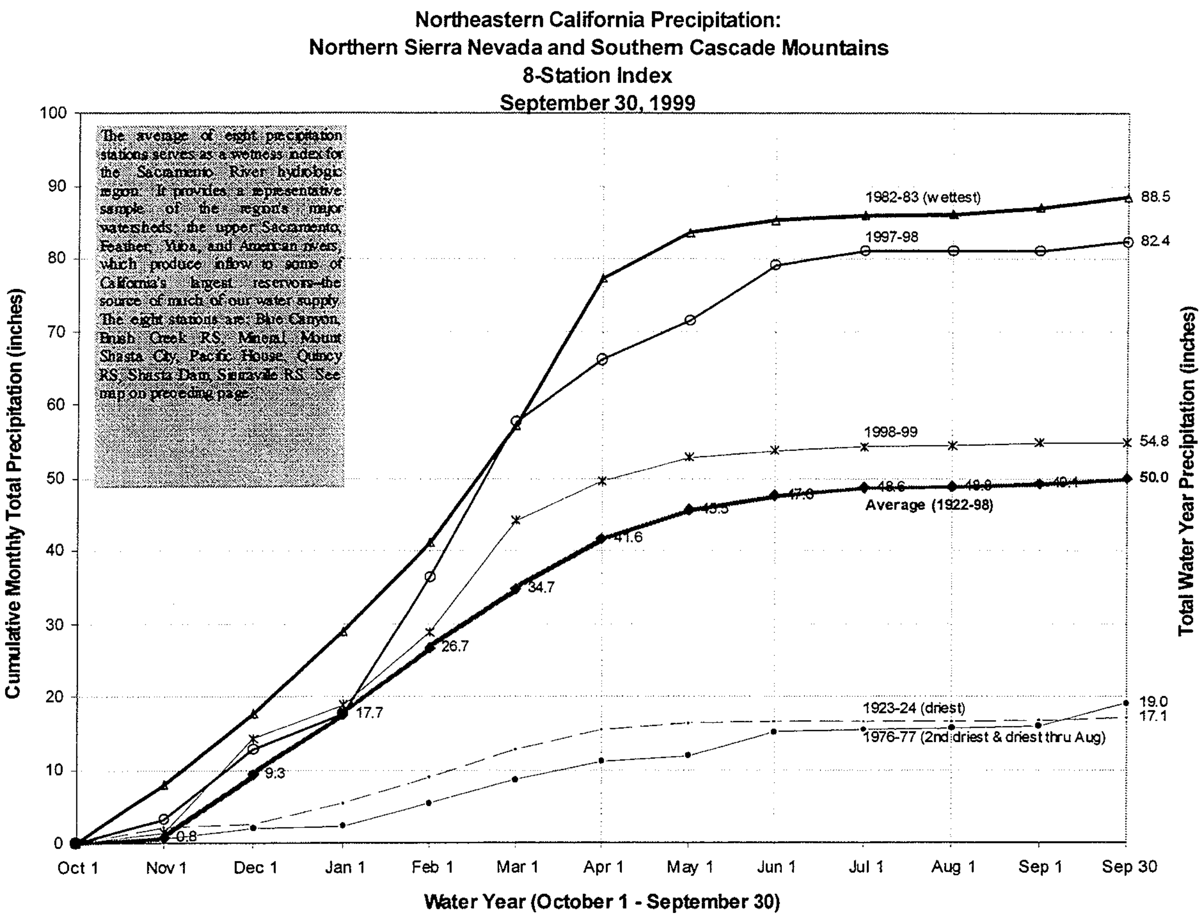

Figure 4 Northern Sierra precipitation accumulation, 8-station index, August 31, 1999

For the northern Sierra, the season is closing out at about 110% of average. Figure 4 shows the accumulated amounts this season compared to average and to selected other years. The wet months were November and February. Without a wet February, the season would have been near average.

The 1999 season turned out to be a pretty good snowpack year with 110% of average statewide water content on April 1. In 1998, the April 1 snowpack was 160%, about half again more than this year. The heaviest snowpack in this decade occurred in 1995 at 175%. In 1997, the year of the big flood, the April 1 snowpack was 75% of average.

The May 1 forecasts of April through July snowmelt runoff this spring were about 110% statewide. Amounts were well above average in the north and in the central Sierra south through the Tuolumne River basin (which had a cloud-seeding project), then started to peter out. The Tulare Lake hydrologic region forecast was the lowest at 65% of average as a result of the poor snowpack there (60% on April 1). Figure 5 shows the May 1 forecasts from DWR Bulletin 120. Notice the steep percentage gradient from the Tuolumne south to the Kaweah River basin.

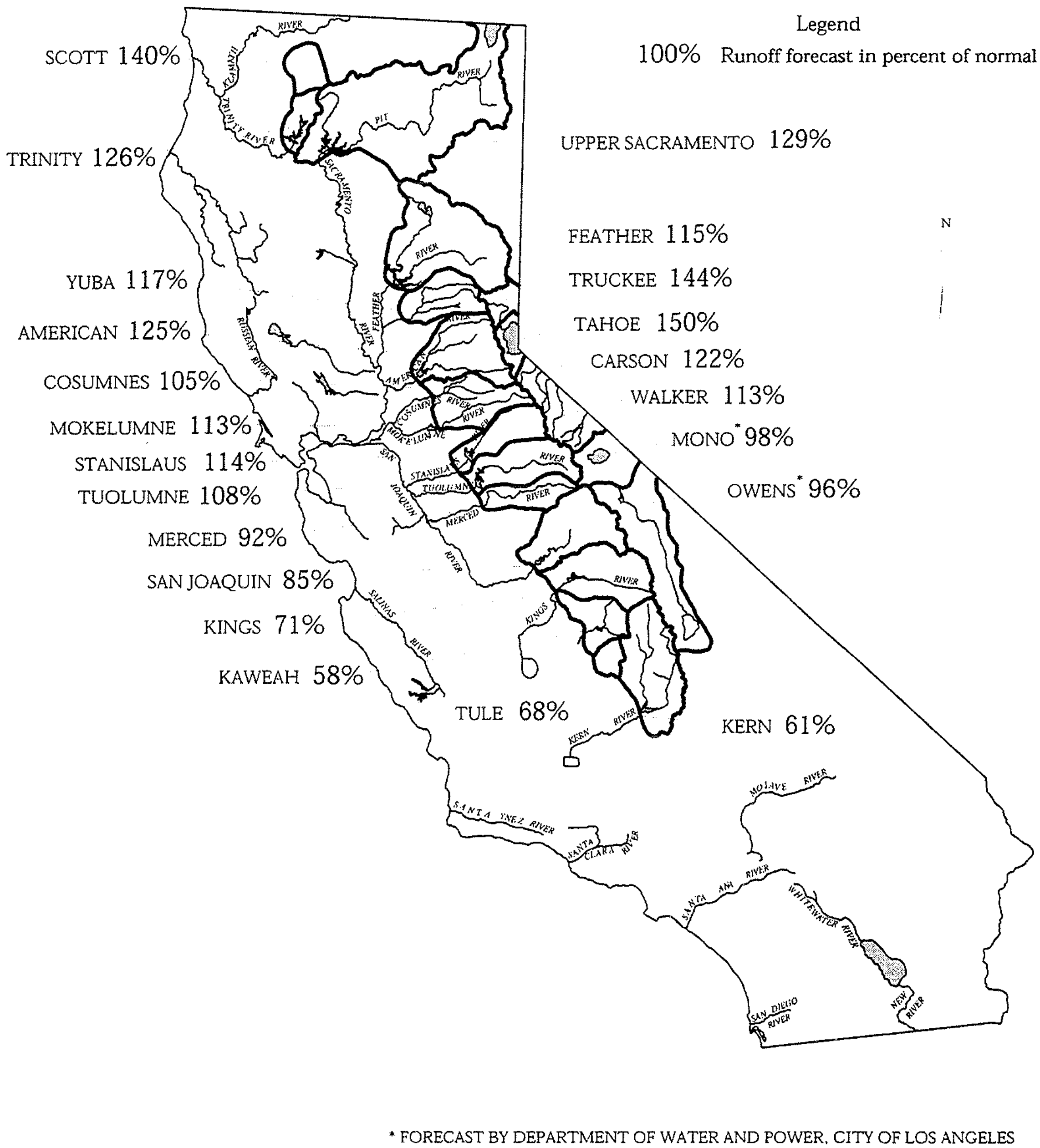

Figure 5 Forecast of April through July unimpaired snowmelt runoff, May 1, 1999

This is one of the steepest drops in history, showing how rapidly many storms tapered off from north to south in the San Joaquin River region. At the far south end of the San Joaquin Valley, normally dry Bakersfield, with an average of around six inches per year, was above normal in seasonal precipitation, an exception caused by a cold upper level low in January, which produced record rain and snow.

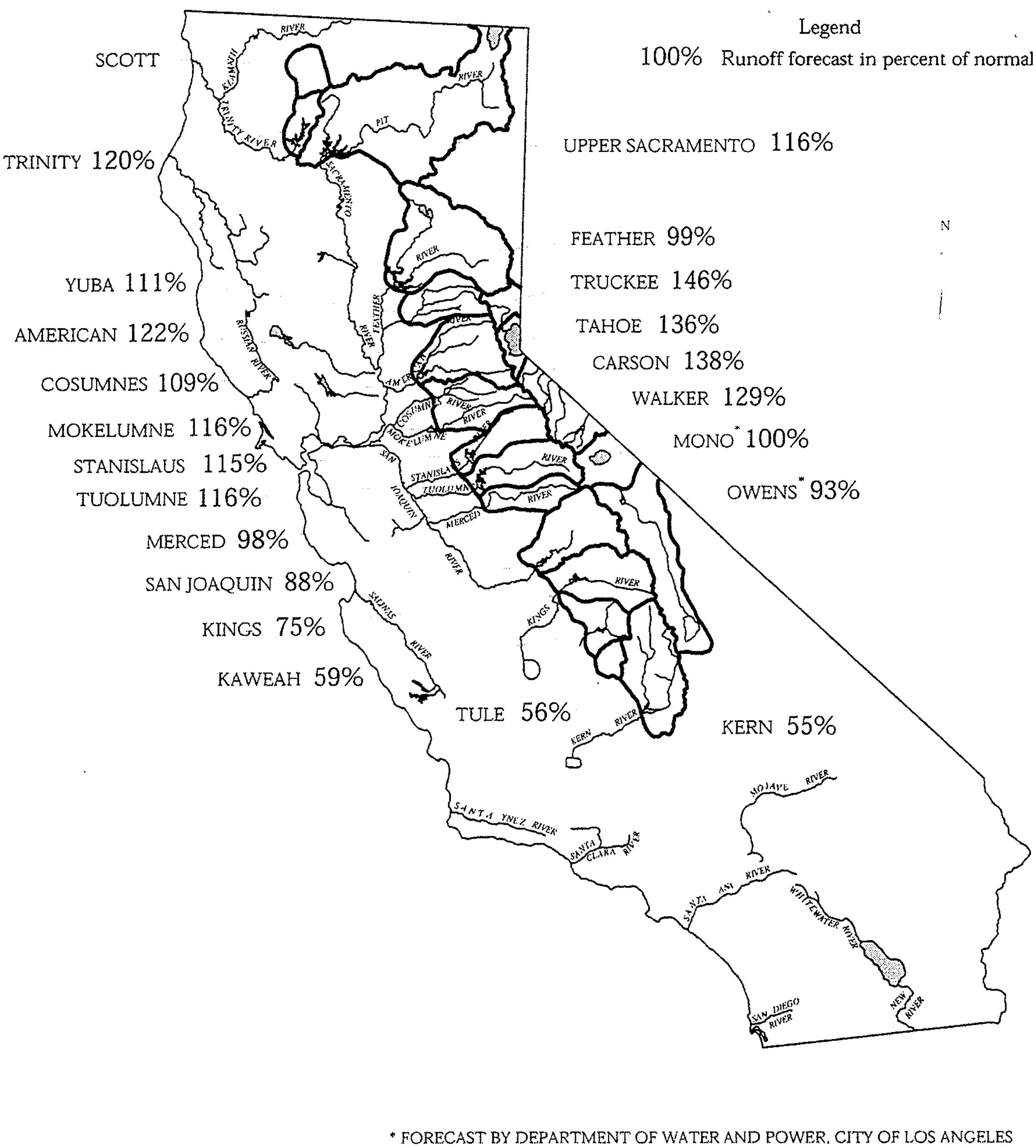

Figure 6 Estimated 1999 unimpaired snowmelt runoff

Figure 6 is an update with preliminary estimates of the actual April through July snowmelt runoff. The drop-off gradient is even steeper than forecasted on May 1.

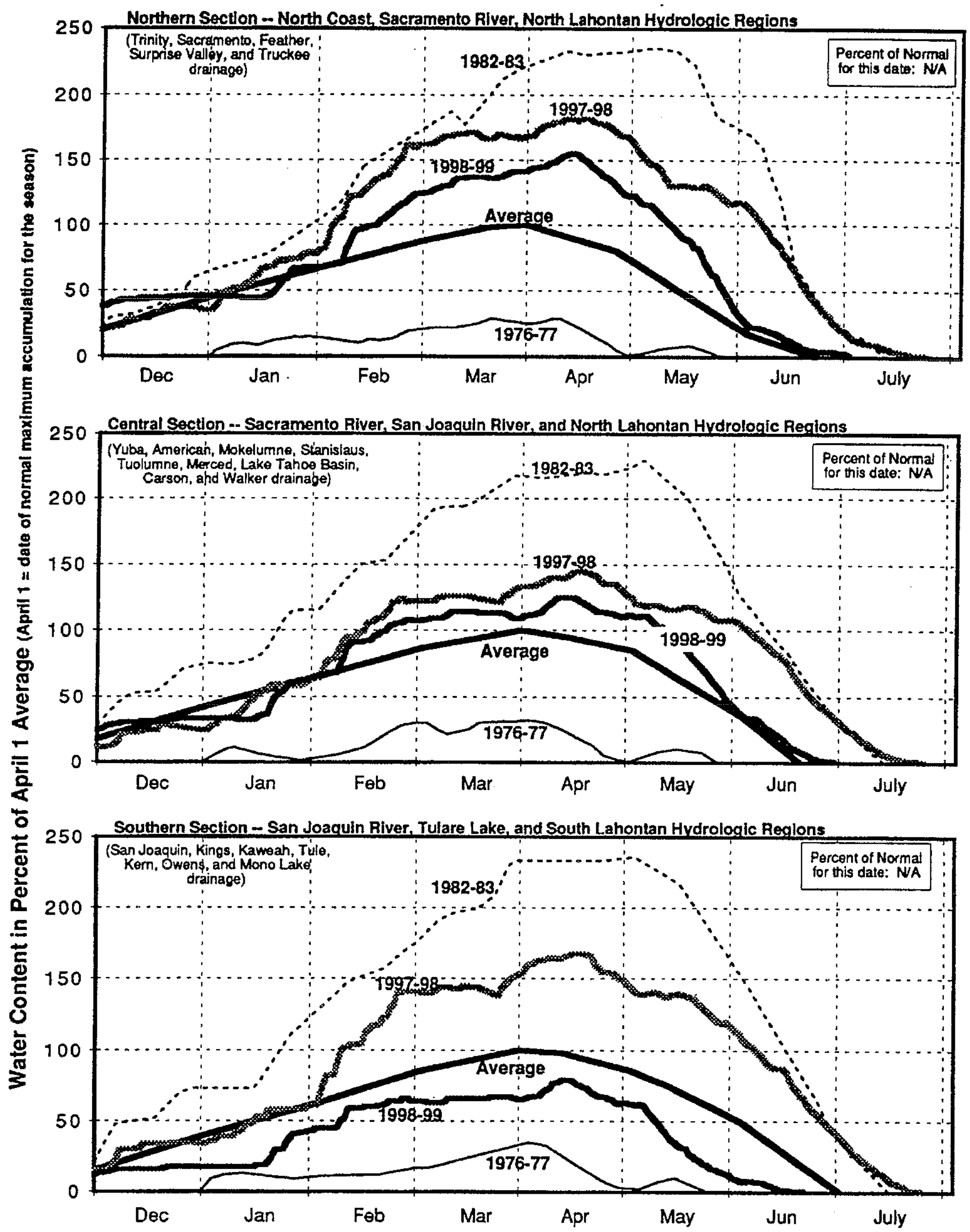

Figure 7 Telemetered California snow water content for water year 1999

Figure 7, a three-panel chart of the northern, central, and southern Sierra, shows how the snowpack accumulated this year. The mid-winter dry spell is evident in the flat period from early December to the middle of January, when the storms resumed. The large boost in February is what moved the snowpack well above average in the northern and central Sierra. Only in the southern Sierra did the snowpack show a persistent lag all season. Also, the peak accumulation was about two weeks late this year. Usually melting starts about April 1, in fact, earlier in several recent years. This year snowmelt was delayed; however, solar radiation and a dry and sunny May caused the snowpack to melt to near normal levels by June 1.

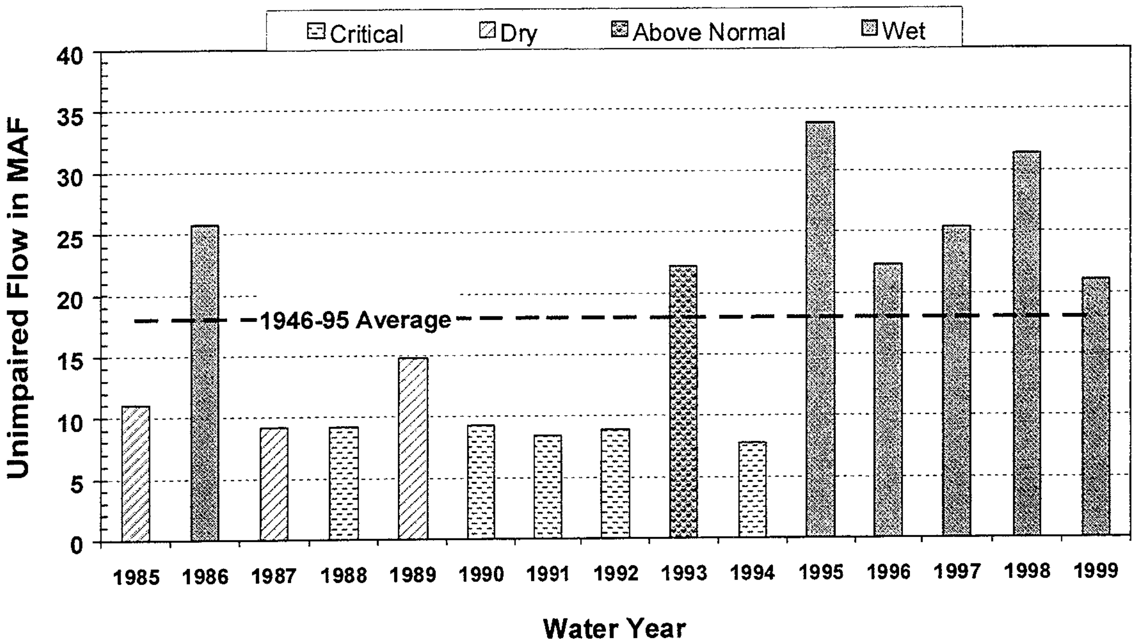

Figure 8 Sacramento River runoff. Sum of Sacramento Rive above Bend Bridge, Feather River at Oroville, Yuba River at Smartville, and American River at Folsom.

The peak rates of snowmelt generally occurred during the last week of May; peak rates were not excessive, being tempered by periodic intervals of cooler weather without any sustained hot weather. Total April through July snowmelt was about 105% statewide, slightly reduced from the May 1 forecast by the significantly less than average precipitation in the north during May. May and June showers were heaviest in the middle to southern Sierra zone from about Lake Tahoe to east of Fresno, which increased runoff amounts somewhat over the May forecast on those rivers.

For the four rivers of the Sacramento River system, the expected runoff for 1999 is about 21 million acre-feet, slightly over 115% of average (Figure 8). This marks the fifth consecutive wet year. That long a run has not occurred before in this century and probably not since some early rainfall records in northern California began in 1850. The longest previous wet runs lasted four years in succession, which occurred twice since 1900—during 1940 to 1943 and 1904 to 1907.

A tree ring reconstruction study of Sacramento River runoff was made in 1986 by the University of Arizona Laboratory of Tree-Ring Research. They estimated the annual runoff back to year 1560. That 420-year reconstruction revealed three other runs of five years or longer: 1601 to 1606 (6 years), 1801 to 1806 (6 years) and 1808 to 1812 (5 years). One could wonder about a 200-year cycle in the records. Just a decade ago we were in the throes of a six-year drought.

San Joaquin River runoff was not as heavy. The four rivers of this system are expected to produce 5.9 million acre-feet, which is just over average. The runoff year there is classified as “above normal” ending a string of four wet years.

Reservoir storage has been excellent all season with good carryover from a wet 1998. Amounts during the winter were limited by flood control requirements, with considerable excess water released at most major foothill reservoirs. Statewide storage on June 1 was approximately 115% of average, 85% of capacity. About the same as last year at the time. But this year statewide storage peaked about June 1, whereas in 1998 it continued to climb for another month because of heavy snowmelt runoff. By the end of August of this year, statewide storage was still about 115% of average, and had dropped to 71% of capacity. Storage in 1998, however, was about 135% of average at the same time. Major foothill reservoirs in the north came close to filling this year. Southern Sierra foothill reservoirs, while above average, did not fill, except for Millerton (Friant) which filled in mid-May and again in the first week of June until mid-month. Water supplies were average or better in most areas. One exception is deficiencies of up to 30% in Central Valley Project service areas on the west side of the San Joaquin Valley. Central Valley Project Friant deliveries on the east side of the valley are also below average at 100% of Class I and 20% of Class II supplies, compared to an average which includes around 50% of Class II water.

The water year was benign insofar as flood problems go—different than the past four years. The rains of November and the first week of December produced modest amounts of weir overflow into Sutter and Yolo Bypass, with more overflow in February. The peak overflow into Yolo Bypass at Fremont Weir was about two feet in mid-February, much below its design level of 7.3 feet. The lower Sacramento River at Sacramento (I Street gage) just barely exceeded its flood warning stage of 25 feet for less than a day. To sum up, there were some periods of high water on Central Valley and coastal rivers this year but no large floods. For a change, water year 1998–1999 was benign. The only unusually high stages occurred on November 21 on the Smith River of northwestern California, which had the highest water level since 1990. The peak stage at the gage near Crescent City was 31.1 feet, 2.1 feet over flood stage, and higher than the 1997 floods. Often the climate of the Smith River basin is more similar to Oregon; its weather and runoff patterns tend to be different from those of the major portion of northern California.

Table 1 shows comparisons of hydrologic parameters for 1999 and the previous five years.

Table 1 Comparisons of hydrologic parameters for 1994 through 1999

	Percent of Average (unless noted)					
	1999	*1998*	*1997*	*1996*	*1995*	*1994*
Statewide						
Precipitation	95	175	125	115	165	65
April 1 Snowpack	110	160	75	95	175	50
Runoff	110	175	145	125	180	40
Reservoir Storage, September 30	118	136	104	120	130	73
Reservoir Storage, million acre-feet	25.6	29.6	22.7	26.0	28.1	15.9
Regional						
Northern Sierra Precipitation	110	165	138	123	171	64
8 Station Index, inches	54.8	82.4	68.7	61.3	85.4	31.8
Sacramento River	117	174	141	123	191	43
Unimpaired Runoff, million acre-feet	21.1	31.5	25.4	22.3	34.4	7.8
San Joaquin River	104	183	167	127	217	45
Unimpaired Runoff, million acre-feet	5.9	10.4	9.5	7.2	12.4	2.5

It now appears that La Niña, the cooler, eastern tropical, Pacific sea surface condition, will continue into the next winter. The National Weather Service long range forecasts are similar to those of a year ago, predicting above normal precipitation in the northern end of California and in the Pacific Northwest and drier than average conditions in the southern end of California, as well as in Arizona and New Mexico. In other words, the forecasts are for a generalized repeat of the last season. But no two years are identical, and the details often accumulate to yield significantly different water supplies.

Climate Variability in the Southwest: An Integrated Assessment

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Gregory D. Packin, and Malcolm K. Hughes

Expanded Abstract

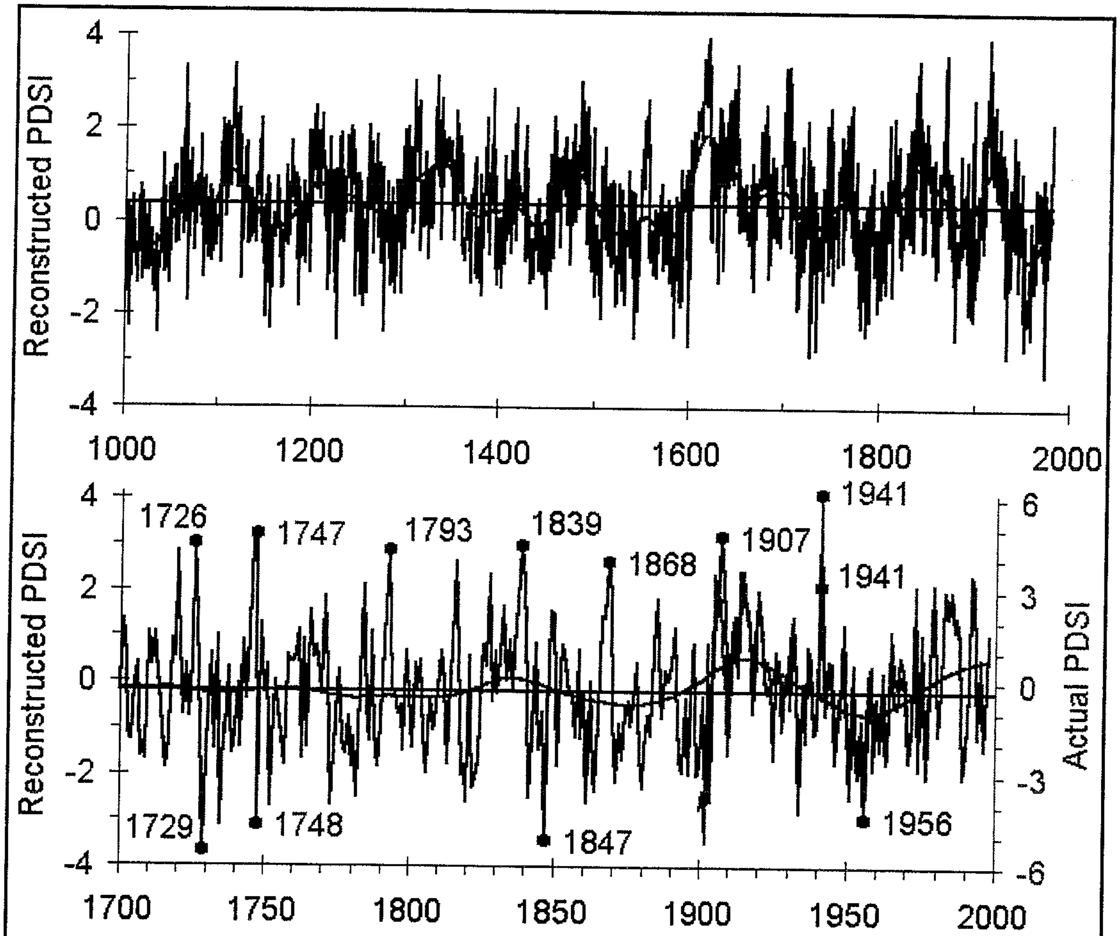
As part of a multidisciplinary study of climate and its societal impact, instrumental meteorological records and "natural archive" paleoclimate records are reviewed and synthesized into a white paper and web-supported database. The purpose of the white paper is to summarize understanding of climate variability in this region on seasonal to multi-decadal and longer time scales in a form accessible to the science-literate non-climatologist. This study builds upon existing climate variability research and will ultimately be integrated with other regional assessment information for the Southwest Climate Assessment Project. The companion database, which forms part of the ongoing research activity on Southwest Climate Assessment, is currently under development. The database provides references and links to research literature and other readings, as well as to instrumental and reconstructed climate data and metadata (http://www.ispe.arizona.edu/swclimate/index.html).

Low annual precipitation, clear skies, and year-round warm weather over much of the Southwest are due in large part to a quasi-permanent subtropical high-pressure ridge over the region. However, the Southwest is located between the mid-latitude and subtropical atmospheric circulation regimes, and this positioning relative to shifts in these regimes is the fundamental reason for the region's climatic variability. Additionally, climate variation within the region results from overall physiography and topographic relief, along with proximity to the moist air mass sources of the Gulf of Mexico, the Gulf of California and the eastern Pacific waters. El Niño has a well-developed teleconnection with the Southwest, typically resulting in cooler, wetter winters. The North American monsoon, which, in the United States, is most noticeable in Arizona and New Mexico, is the major summer season event that distinguishes the Southwest's climate from the rest of the US.

This paper examines the instrumental period (i.e., the 20th century) in the context of longer-term patterns from the natural archive paleoclimate record. Instrumental meteorological records extend back about 100 to 120 years in the Southwest, while the tree-ring archive extends the climate record to up to 1000 years or more. Tree-ring data collection sites are widespread throughout the Southwest. Tree rings are annually resolved and integrate well the influences of both temperature and precipitation. A commonly used climate variable in paleo-precipitation studies, including tree-ring analysis, is Palmer Drought Severity Index (PDSI), a single variable derived from variation in precipitation and temperature. The combined paleo-modern climate record for the Southwest shows at least three occurrences of a multi-decadal pattern of variation of alternating below to above average PDSI (Figure 1).

Should this pattern persist, then perhaps the American Southwest will next enter an extended period of declining to below average PDSI. The most obvious feature of the temperature record is its current increase to an extent unprecedented in the last four hundred years (Figure 2). Because this warming trend is outside the varia-

tion of the natural archives, it is possible that anthropogenic impacts are playing a role in climate change in the Southwest.



Occurrences ~80-Year-Period Variation In Southwest PDSI.

Occurrence	Below Average	Above Average	Length (yrs)
antepenultimate	1770-1825	1825-1840	70
penultimate	1840-1905	1905-1925	85
ultimate	1925-1980	1980-present	>75

Figure 1 Southwest PDSI. Tree-ring reconstructed PDSI (blue) since AD 1000 (top) and since 1700 (middle) with actual PDSI (green). During the period of overlap (1900 to 1978), the two series correlate strongly but have different ranges (note the different y-axis scales). The reconstructed series show an approximately 80-year variation, one that has been increasing in amplitude with time since the late 18th century. The dates of the most recent periods of this multi-decadal variation are given in the table.

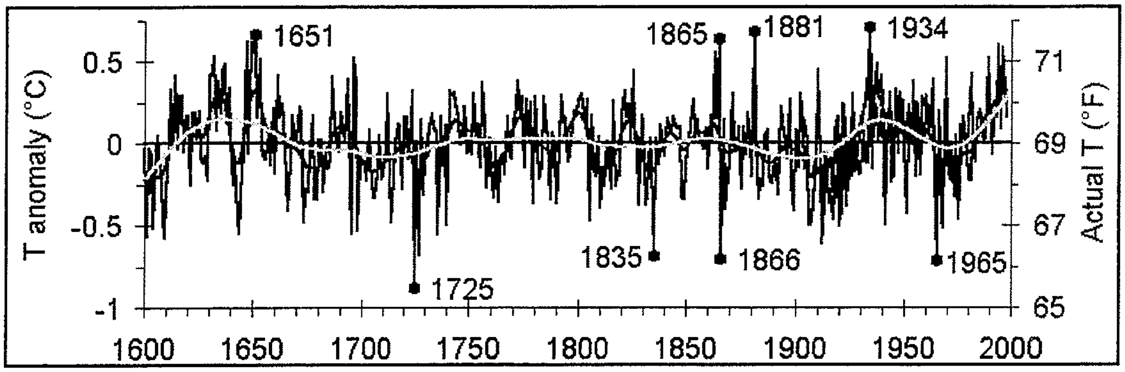


Figure 2 Southwest Temperature. Tree-ring reconstructed temperature (blue) and actual temperature (green). During the period of overlap (1900 to 1980), the two series correlate strongly. Red line shows 20-year variation, and yellow line shows 80-year variation.

Environment and the Anasazi Abandonment of the Four Corners Area

Jeffrey S. Dean

Abstract

During the last 4,000 years, the southern Colorado Plateau was occupied by societies, collectively called Anasazi, that practiced an agricultural lifeway focused on maize, squash, and beans. Because much of this vast and varied region is marginal for farming, scholars believe environmental variability to have been a major causal factor in Anasazi population movements and sociocultural change. A case in point is the long-standing idea that the "Great Drought" of 1276–1299 was the principal cause of the Anasazi abandonment of the San Juan drainage at the end of the 13th century. Recent paleoenvironmental research—involving alluvial chronostratigraphy, packrat midden analysis, palynology, and dendroclimatology—provides integrated reconstructions of past environmental variability that, in combination with archaeological data on human behavior and demography, indicate the degree to which Anasazi subsistence systems may have been affected by environmental variation and change. The evidence indicates that the relationship is not simple and that complex combinations of factors determine the outcome of any particular episode. The 13th century abandonment, for example, was due both to environmental deterioration in the Four Corners area and attractive environmental conditions and sociocultural developments elsewhere.

Introduction

According to the media, the Anasazi were a mysterious group of people who occupied the Four Corners area of the Southwest and who "vanished" around the end of the 13th century AD. In fact, the Anasazi are not mysterious and they did not vanish. The Anasazi are the antecedents of, among others, the modern Pueblo Indians who still thrive in the northern Southwest. Furthermore, they didn't vanish, they simply moved out of the Four Corners into the areas now occupied by modern Puebloans.

The mystery is why the Anasazi vacated the entire San Juan River drainage so abruptly at the end of the 1200s. Numerous explanations of this exodus have been offered, many of which invoke environmental change as a major causal mechanism. Others discount environment and emphasize social causes such as conflict, warfare, and socioreligious developments. Only careful examination of the complex interrelationships among Anasazi history, culture, and demography on the one hand and environmental stability, variability, and change on the other can resolve this issue. Adequate archaeological understanding of the former and accurate paleoenvironmental reconstructions of the latter are vital to illuminating these relationships. Fortunately, the Southwest is blessed with both plus detailed ethnographic data on the modern inhabitants of the region.

The Southern Colorado Plateau

The Colorado Plateau is one of the world's great uplands, ranging from 3,000 feet (900 m) to nearly 13,000 feet (4,000 m) in elevation. Geologically, the Plateau consists primarily of flat lying, tilted, folded, and faulted sedimentary rocks locally altered by igneous intrusions (Navajo Mountain, Sleeping Ute Mountain, Carrizo Mountain), volcanos (San Francisco Peaks, Mount Taylor, Jemez Mountains), lava flows (El Malpais), and pyroclastic deposits (Pajarito Plateau). Pleistocene and Holocene surficial deposits occur as alluvium along the drainages of the region and as colluvium on upland surfaces. Cycles of erosion and deposition have altered the agricultural potential of these Quaternary formations. Conforming to the geology, the topography of the southern Colorado Plateau is generally flat, curved where rocks have been folded into anticlines, monoclines, and synclines, or stepped where erosion has exposed rock formations of differing hardness. A few mountain masses—such as the San Francisco Peaks, Navajo Mountain, and the Abajo, La Plata, San Juan, and Chuska mountains—rise above the landscape. Most uplands, however, take the form of relatively flat-lying plateaus, mesas, or buttes. The Plateau is dissected by numerous canyons ranging from innumerable spectacular gorges, such as Canyon de Chelly and Zion Canyon, to the Grand Canyon.

The Plateau is characterized by a cool steppe climate with cold winters and warm summers. Climate exhibits a strong elevational gradient with precipitation increasing and temperature decreasing with increasing elevation. Precipitation has a bimodal seasonal distribution with winter and summer peaks separated by a dry autumn and an extremely dry spring. Winter precipitation is generated by frontal storms that pass across the region and commonly falls as snow. Summer rainfall derives from convectional storms associated with the Southwestern monsoon. This bimodal distribution is crucial to aboriginal agriculture on the southern Colorado Plateau. Winter precipitation provides the soil moisture necessary to germinate crops and carry them through the spring into the monsoon season whose rains are vital to crop survival and maturation. The weather is not always benevolent, however. Insufficient precipitation in winter or summer causes serious crop reductions or total failure. Too much rain drowns crops and/or washes out fields. Late spring or early fall freezes can totally destroy crops or severely reduce yield, and violent hailstorms can devastate crops.

In keeping with the elevational variation in precipitation and temperature, the vegetation of the Colorado Plateau is sharply zoned by elevation. Originally, lower areas supported extensive grasslands that, since the advent of domestic animals, have been mostly replaced by grazing tolerant shrubs such as snakeweed, saltbush, greasewood, and Russian thistle. Deep soils at higher elevations support dense sagebrush or blackbrush communities. Somewhat higher, a broad swath of pinyon-juniper woodland dominates much of the Plateau. Higher elevations support ponderosa pine forests that grade upward into subalpine habitats dominated by Douglas firs, true firs, spruces, and aspens. A few high mountains and plateaus support sparse stands of limber and bristlecone pines, and the tops of the highest ranges have alpine plant communities. Streamside environments in all zones originally supported riparian vegetation dominated by cottonwoods and willows that currently are being replaced by saltcedar and Russian olive. A unique aspect of Plateau vegetation is the inverted zonation that develops in some canyons where Douglas fir trees grow below the pinyon-juniper woodlands that cover the surrounding mesa tops.

The great environmental diversity of the southern Colorado Plateau provided the Anasazi with a variety of subsistence opportunities and limitations that shaped the regional variants of the Anasazi pattern. Geology, topography, climate, and vegetation combine to create four major habitats that offered a wide range of resources. The mountains provided wild plant foods, large game, and construction timbers. Other uplands provided wild plant and animal resources, timber and firewood, and climate and soil conditions amenable to dry farming. Broad valleys provided plant and animal resources, large areas of alluvial land along drainages, and climatic and hydrologic conditions conducive to dry, groundwater, and irrigation farming. The wet environments of many canyons provided varied wild plant resources, timber for construction and fuel, alluvial farmland, and hydrologic conditions favorable for farming. These habitats are defined on the basis of local topography rather than absolute elevation. For example, the upland mesas of the Rainbow Plateau are lower (c. 1,600 m) than the lowland canyons and valleys of the Marsh Pass area (c. 1,950 m).

Paleoenvironment of the Southern Colorado Plateau

Because environmental conditions vary through time as well as space, present conditions are not necessarily good indicators of past conditions. As a result, variability in numerous environmental factors must be reconstructed using all the paleoenvironmental techniques and evidence available: geology, alluvial geomorphology, packrat midden analysis, palynology, paleobiology (botany and zoology), and dendroclimatology. Important variables that must be reconstructed include fluctuating groundwater levels in floodplain alluvium, the deposition and erosion of floodplain sediments, changes in plant community composition and distributions, variations in arboreal and nonarboreal pollen production, and climate.

Figure 1 illustrates fluctuations in several environmental variables likely to have been important to Anasazi survival on the Colorado Plateau (Dean 1996a, Figure 3; Dean and Funkhouser 1995, Figure 10). The aggradation-degradation curve (Figure 1A) and the hydrologic curve (Figure 1B) are based on chronostratigraphic analyses of floodplain sediments (Karlstrom 1988) and represent, respectively, the deposition and erosion of floodplain sediments and the rise and fall of alluvial groundwater levels. Together, these two elements are vital for floodplain agriculture, especially in areas where rainfall is insufficient or too variable to produce consistent crop yields. Aggradation and rising water tables replace rainfall as a controlling factor and foster consistent crop yields from one year to the next.

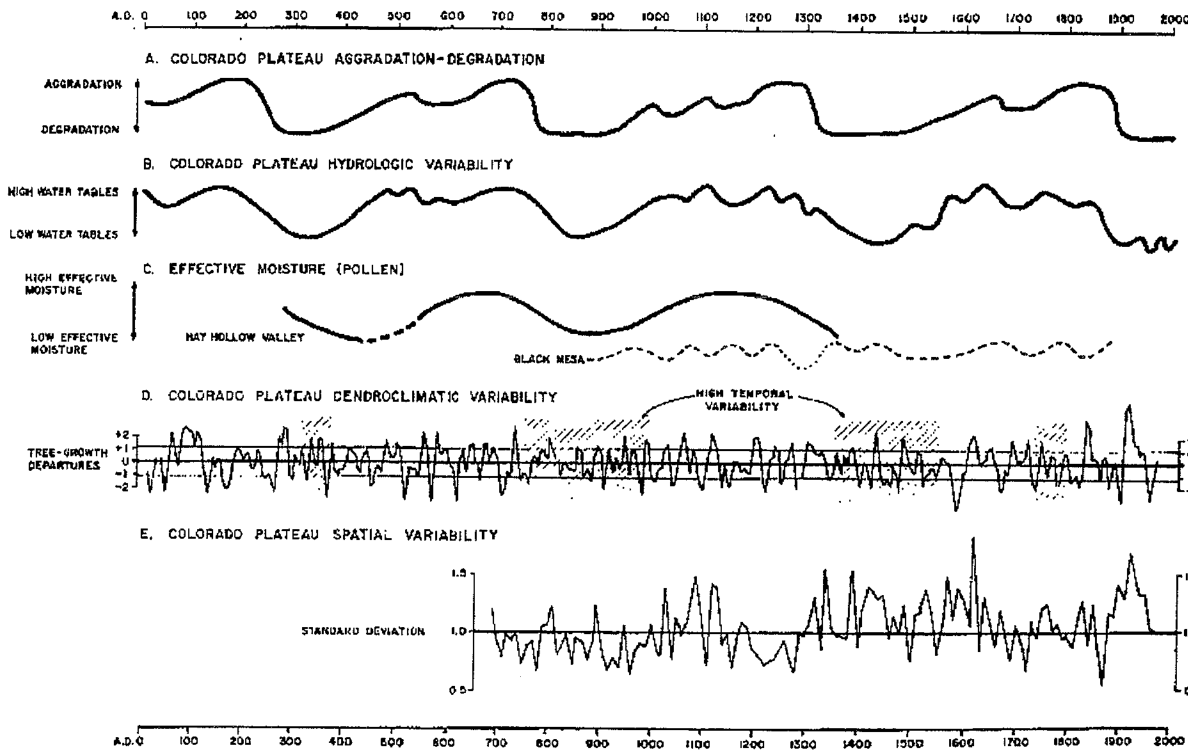


Figure 1 Paleoenvironmental variability on the southern Colorado Plateau, AD 1–1990

Falling groundwater levels and channel incision (degradation) disjoin the water table from the farmland atop the terraces and make precipitation, which is much less reliable, the primary controlling factor in the agricultural equation. The pollen based effective moisture reconstruction (Figure 1C) represents the amount of water available to plants and parallels the hydrologic curve (Hevly 1988).

Climatic variability is indicated by the dendrochronological graphs in Figure 1D and 1E. Figure 1D plots positive and negative departures of tree growth from the long-term chronology mean in standard deviation units for decades overlapped five years. Shading indicates periods of high temporal variability when the transitions from maximum to minimum values were rapid, usually encompassing no more than a decade. The intervening periods were characterized by low temporal variability when the transitions from maxima to minima were more gradual. Agricultural problems caused by high temporal variability can be offset by producing food surpluses in good years to compensate for the poor years that can be expected to follow shortly. Storage is a less viable response to low temporal variability because, when the trend is upward, annual production usually suffices, and, when the trend is downward, surpluses may be difficult or impossible achieve.

Figure 1E shows spatial variability in dendroclimate. High values indicate periods when conditions varied widely across the region, with high rainfall in some areas and low rainfall in others. Low values identify periods when uniform conditions, bad or good, prevailed everywhere. High spatial variability creates interareal food production differentials and favors exchange or conflict depending on whether populations suffering from poor conditions resort to trade or raiding to acquire food from people living in favorable areas. Low spatial variability inhibits exchange or conflict because all groups are more or less equally affected, and production differentials are minimal. When things are bad everywhere, no one develops surpluses that can be exchanged or expropriated; when things are good, everyone has plenty and needs no input from other groups.

The effects of environmental stability, variability, and change on human populations are mediated by two nonenvironmental factors (Dean 1988): the number of people involved and their sociocultural ability to deal with the environment. Environmental stress has a greater impact when high population inhibits mobility as a response to environmental fluctuations. When all suitable localities in an area are occupied, people cannot readily move from adversely affected to less affected places. Similarly, the Anasazi's relatively simple Neolithic technology limited their ability to intensify agricultural production.

Combining environmental, demographic, and sociocultural factors allows us to assess the magnitude of the environmental changes associated with the abandonment of the Four Corners area relative to other episodes of high environmental stress. For the period AD 1 to 1500, only one other interval rivals the severity of the environmental degradation of the late 13th century. Between AD 1130 and 1180, a secondary decline in fluvial conditions, a prolonged drought, low temporal climatic variability, declining spatial climatic variability, and relatively high populations combined to adversely affect Anasazi subsistence systems. Even more severe effects occurred at the end of the 13th century: a primary downturn in fluvial conditions (falling water tables and severe arroyo cutting), an intense drought (the "Great Drought" of 1276–1299), low temporal and spatial variability in climate, and a breakdown in the long-term seasonal patterning of precipitation (Dean 1996a; Figure 9) all began around 1250 at a time of even higher population levels.

Anasazi Archaeology

Anasazi is a technical term applied to the distinctive archaeological materials and patterns produced by the farming populations of the southern Colorado Plateau between approximately 2000 BC and AD 1600 when Spanish colonists arrived and the Anasazi entered history as the various Puebloan groups. In addition to agriculture, this pattern includes characteristic traditions of ceramic production and decoration, a domestic architectural tradition that developed from pithouses to masonry and/or adobe pueblos, and a ceremonial architecture that involved kivas, great kivas, plazas, towers, and other features. Anasazi archaeological remains are found from the Pecos River on the east (with periodic expansions into the Great Plains) to southern Nevada on the west and from the Colorado River on the north to the Mogollon Rim on the south (with occasional incursions into the Sonoran Desert as far south as Tucson). As might be expected from this vast geographic range, considerable spatial and temporal variability characterizes material that falls within the general Anasazi pattern, which encompasses everything from the comparatively simple Virgin branch of southern Nevada to the complex, hierarchical regional interaction systems of the San Juan Basin and from early small pithouse hamlets to large complex towns of later periods.

The Anasazi archaeological pattern appeared on the southern Colorado Plateau around 2000 BC when the adoption of maize created a mixed hunting, gathering, horticulture economy. Around 500 BC, farming became the dominant element of Anasazi subsistence. Over the next 21 centuries, Anasazi societies and culture became increasingly more complex, although setbacks in certain times and places and infusions from other cultures modified the basic Anasazi pattern of development. This pattern persisted in the various Puebloan societies that Spanish colonists encountered after 1540. Today, elements of the pattern endure with considerable vigor in the modern Puebloan groups of the Southwest, from the Hopis and Zunis in the west to the Rio Grande Pueblos in the east.

The general Anasazi developmental sequence proceeded from small farming hamlets of scattered pithouses and storage structures in the late BC period to large Puebloan villages, towns, and communities that appeared after AD 800. Different areas exhibited markedly different rates of change and development with the western Anasazi lagging a century or more behind their eastern counterparts in terms of sociocultural complexity. For the sake of brevity, this variability is epitomized here by the three major geographical variants of the Anasazi tradition: Chaco, Mesa Verde, and Kayenta.

The Chaco expression was the most precocious and complex of the three. By the middle 800s, the residents of Chaco Canyon began to diverge from other Anasazi populations. Instead of pithouse villages, they constructed multistoried masonry pueblos that, over time, grew extremely large (over 800 rooms) and complex. Chacoan "towns" included blocks of domestic rooms fronted by large, walled plazas that commonly were divided into two segments. Ceremonial architecture included small, circular, subterranean kivas in the roomblocks, and large, circular great kivas in the plazas. The Chaco Canyon core also was characterized by a variety of unusual artifacts (turquoise and shell ornaments, turquoise and jet inlaid baskets and bone tools, unique ceramic vessel shapes, carved wooden items) and exotic imports such as macaws. By the early 11th century, the Chacoans had created a regional system in which the Chaco Canyon core was linked by a network of roads to numerous outlying communities scattered across the San Juan Basin and beyond into southwestern Colorado, southeastern Utah, and northeastern Arizona. A wide variety of material items—chert for stone tools, turquoise, construction timbers, ceramic vessels, and probably food—was funneled into the canyon from the outlying areas. The Chacoan regional system began to fade in late 1100s, and, by 1200, the core had collapsed leaving two attenuated derivatives to carry on, one in the north (Mesa Verde) and one in the south (Cibola-Zuni).

Mesa Verde Anasazi, which occurs in southwestern Colorado and southeastern Utah, was not as complex as the Chacoan version. Large Mesa Verde sites tended to be less highly structured than the Chacoan great houses, but both areas exhibited aggregated settlement configurations. In addition, the Mesa Verde area is famous for its cliff dwellings, a site type rare in the Chacoan domain due to the paucity of suitable rock shelters. Ceremonial architecture is less flamboyant than that of Chaco Canyon and includes kivas, great kivas, towers, and plazas. Mesa Verde sites tend to lack the quantities of exotic artifacts found in Chaco Canyon sites. In the 11th century, many Mesa Verdean communities were incorporated into the Chacoan system and were linked to Chaco Canyon (or to outlying centers such as the Aztec Ruin) by roads. After the Chacoan attenuation in the middle 1100s, the Mesa Verde area developed its own regional system characterized by clusters of large central sites surrounded by satellite communities. Mesa Verde population began to decline by 1250, and the area was abandoned in the late 1200s.

The third Anasazi example, the Kayenta of northern Arizona and southern Utah, was the simplest of the three (Dean 1996b). Until 1250, sites were small and widely dispersed, few sites achieving as many as 50 rooms. The Kayentans lacked the ceremonial variety of the other two expressions, kivas and plazas being the only ceremonial structures associated with these sites. Kayenta sites lack the artifactual richness of Mesa Verde and Chaco, but are somewhat compensated for by distinctive and refined ceramic design styles. The Kayentans were not incorporated into the Chacoan system, which lapped up against Kayenta groups on the north and east. Kayenta social complexity peaked after 1250 when settlement systems characterized by large central pueblos surrounded by satellite communities developed, some 250 years after this pattern appeared in the Chacoan area. Kayenta population peaked in the 1280s and dropped rapidly thereafter until the area was abandoned by 1300.

The Mesa Verde and Kayenta Anasazi populations that abandoned the Four Corners area late in the 13th century moved east and south into areas now occupied by modern Pueblo groups. Mesa Verdeans appear to have moved primarily eastward into the Rio Grande Valley in New Mexico (Lekson and Cameron 1995), while Kayenta groups moved into the modern Hopi area in Arizona, with some continuing south of the Mogollon Rim into the Safford and San Pedro Valleys and Tonto Basin of southern Arizona.

Conclusions

Several aspects of large scale Anasazi population movements and cultural change appear to be related to environmental variations and changes of the AD 1–1500 period. Each major Anasazi division—Chaco, Mesa Verde, and Kayenta—achieved its maximum geographic expansion, cultural differentiation, and distinctiveness under especially favorable environmental conditions between AD 925 and 1130. During this interval, the Chacoan regional system of outlying communities connected to the Chaco Canyon core by road and signalling networks developed, the distinctive Mesa Verde architectural and ceramic patterns coalesced, and Kayenta populations expanded to their maximum geographic extent.

Similarly, all three expressions underwent significant changes during the environmental downturn of AD 1130–1180. The Chacoan system began to wane, probably because of the combined effects of overexpansion, high population densities, secondary fluvial system degradation, the long drought, and low spatial variability in climate. In Chaco Canyon, the middle 12th century drought was especially severe during the summers, the season when local agriculture, based largely on rainfall and collecting upland runoff (Vivian 1990), was particularly vulnerable to climatic perturbations (Dean 1992). In addition, low spatial variability in climate reduced production differentials between the system's core and outlying communities so that the latter had no surpluses to deliver to the former. Thus, environmental stress helped topple a regional system that was poised on the brink of collapse.

During this interval, the Chacoan system relinquished its hold on the Mesa Verde Anasazi who reorganized into a somewhat less grandiose regional system of their own (Varien 1999). New central communities, which lacked many of the diagnostic attributes of Chacoan outliers, became the foci of large settlement clusters scattered across the landscape. These changes reflected adjustments to both a sociopolitical landscape reconfigured by the "collapse" of the Chacoan system and the midcentury drought, which was particularly troublesome for an economy based primarily on dry farming (Van West 1994).

Kayenta farmers were seriously affected by the drought and by the interruption of floodplain deposition and alluvial groundwater accretion. The population that had dispersed throughout the region during favorable times began to contract. The peripheries of the Kayenta range and higher areas within the heartland were abandoned as people concentrated in areas where agriculture could be successfully pursued under conditions of arroyo cutting and increased aridity. This period also was characterized by experiments in settlement that culminated around 1250 in a pattern featuring clusters of settlements with each cluster focused on a central pueblo (Dean 1996b; Dean and others 1978).

It surely is no coincidence that the severest environmental stress on the Colorado Plateau between AD 1 and 1500, that of the 1250 to 1450 interval, coincided with great demographic and sociocultural changes. Following 1250, the Anasazi experienced major population dislocations and internal rearrangements. The San Juan drainage was abandoned as the population moved east and south away from the Four Corners. At the same time, major Anasazi population influxes occurred in the Rio Grande Valley, Hopi Mesas, Middle Little Colorado River Valley, Mogollon Highlands (Haury 1958; Reid 1989), Tonto Basin (Stark and others 1995), and the Safford and San Pedro valleys of southern Arizona.

In many areas, agriculture was intensified, involving increased irrigation and more productive dry farming techniques such as mulch and akchin farming. Important settlement transformations involved greater site diversification, extremely large towns, hierarchical settlement systems, and the rise of new occupation centers. Interareal interaction, as measured by the spread of ceramic styles and trade networks, increased. New socioreligious ideas and organizational principles were elaborated. Among these were the spread of the Katsina Cult across the Plateau (Adams 1991), the spread of the Southwestern Cult south of the Mogollon Rim (Crown 1994), and the rise of the Casas Grandes system in northern Chihuahua (Di Peso 1974).

Widespread sociocultural stability was not reestablished until the reassertion of the long-term Southwestern seasonal climate regime and the resumption of aggradation and rising alluvial water tables along the drainages after 1450. These developments were followed closely by the arrival of Spanish colonists in the late 16th century and the imposition of a colonial dominion that wrought yet another major transformation in the native populations of the Southwest.

While it would be foolish to attribute the population and cultural changes of the middle 12th and late 13th centuries solely to environmental causes, it would be equally unwise to ignore these potent sources of cultural and demographic upset as important factors in the sociocultural transformations of these periods. Living near the northern limit of large-scale maize agriculture, the Anasazi were susceptible to even small perturbations in the environmental factors that limited crop production. Because wide ranges of variation in the amplitudes and temporal and spatial attributes of a number of environmental factors were involved, we need detailed paleoenvironmental reconstructions to adequately understand the nature and degree of environmental impact on Anasazi cultural change, adaptation, and evolution. Once we have identified outcomes due to responses to environmental stability, variation, and change, we will be better able to focus on the less easily isolated historical, sociocultural, and demographic forces that shaped Anasazi prehistory.

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A Possible Connection Between the 1878 Yellow Fever Epidemic in the Southern United States and the 1877-1878 El Niño Episode

Henry F. Diaz and Gregory J. McCabe

Abstract

One of the most severe outbreaks of yellow fever, a viral disease transmitted by the *Aedes aegypti* mosquito, affected the southern United States (US) in the summer of 1878. The economic and human toll was enormous, and the city of Memphis, Tennessee, was most affected. We suggest that as a consequence of one of the strongest El Niño episodes on record (the 1877–1878 El Niño), exceptional climate anomalies occurred in the US (as well as in many other parts of the world), which may have been partly responsible for the widespread nature and severity of the 1878 yellow fever outbreak.

In this study we document some of the extreme climate anomalies that were recorded in 1877 and 1878 in parts of the eastern United States, highlighting the evolution of these anomalies, as they might have contributed to the epidemic. Other years with major outbreaks of yellow fever in the 18th and 19th centuries also occurred during the course of El Niño episodes, which appears not to have been noted before in the literature.

Introduction

Yellow fever (YF), an acute viral disease, is transmitted when an infected human is bitten by a female *Aedes aegypti* mosquito and, after an incubation period, varying from 4 days to 2 weeks depending on the temperature, the mosquito bites another human, thereby passing the virus from one person to another.

The vector, the female *Aedes aegypti*, is an urban insect that breeds in small bodies of water. The life cycle and activity of *Aedes aegypti* is climatically sensitive. For example, the temperature limits for functional activity (in other words, breeding and feeding) are from approximately 20 °C to 39 °C (Carter 1931; Smith and Gibson 1986). In addition, temperatures below 0 °C and above 41 °C are fatal to the adult (Christophers 1960).

One of the more severe YF epidemics to affect the southern US in the 19th century occurred in 1878. The 1878 epidemic resulted in the loss of 16,000 lives, and it has been estimated that the total loss to the country resulting from this epidemic was at least $1 million (Reed and Carroll 1911). Memphis, Tennessee, was one of the most affected areas: about 17,600 cases were recorded resulting in 5,150 deaths (Carroll 1911). The present study considers the effect that the exceptionally warm El Niño episode of 1877–1878 had on the climate of the central and southern US (see Kiladis and Diaz 1986), which produced unprecedented temperature and precipitation anomalies from mid-1877 to late 1878 (see also Bloom 1993, p 26–27) and may have contributed toward enhancing the mosquito population during 1878.

The Yellow Fever Epidemic of 1878

The spring of 1878 was warm, and weather diaries kept by observers contain remarks referring to the early blossoming of trees in the spring. Precipitation during the spring (April through June), a period important for the hatching of eggs and the maturing of individual insects, was about 150% of normal, and temperatures averaged about 1.5 °C above the mean. The summer months also were warm. In July and August, however, rainfall was somewhat below normal (about 90% of the mean), but temperatures remained in the optimum range, averaging about 0.5 °C above average in Memphis and throughout much of the South.

As the *Aedes aegypti* breeds in water, the availability of water in breeding areas is critical. While the total amount of rainfall is important, the number of rainy days also is crucial. A season may have a high rainfall total, but all of the precipitation may have fallen in a few intense storms. Storms separated by long dry periods may not provide the constant water supply needed for proper breeding areas for the mosquito. Thus, the number of rainy days during a breeding season is important because it indicates the degree to which a constant supply of moisture is available to provide proper breeding grounds. Figure 1A illustrates the number of rainy days during March through August in Memphis for 1873 through 1880 (the climate record for Memphis begins in 1871). Figure 1A shows that 1878 was a period of above normal raininess. Although other years exhibit an equivalent number of wet days, 1878 clearly exhibits a relatively high value for the period. The previous year, 1877, also was associated with a high number of rainy days (and high precipitation totals); this is important because wetter-than-average climate conditions during 1877 would have contributed to a greater than normal number of mosquito eggs, which would lead to the development of a strong population base during 1878.

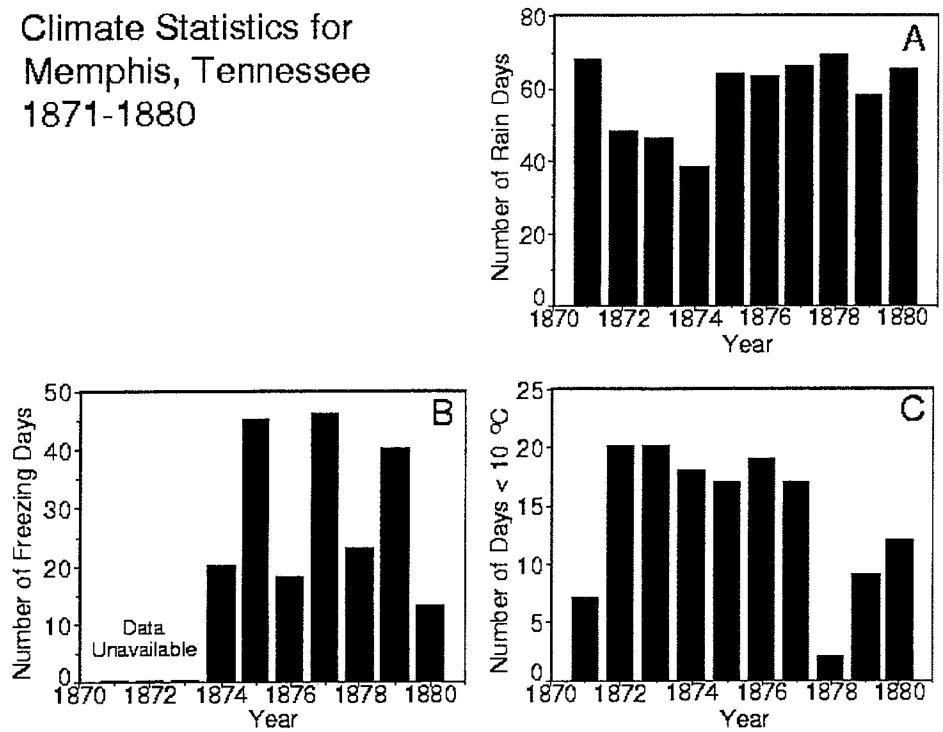

Figure 1 Climate statistics for Memphis, Tennessee, in the years spanning the 1878 outbreak of yellow fever: (A) total number of rain days from March through August for 1871 through 1880; (B) total number of days with minimum temperatures below 0 °C from November through February for 1873 through 1880; (C) Total number of days with a mean temperature below 10 °C from March through November for 1871 through 1880.

Temperature, an extremely important weather factor, contributes to the development and activity of *Aedes aegypti* populations. Temperatures below 0 °C are fatal to this species, thereby preventing the development of larvae. The number of days during winter months when temperatures are below 0 °C may indicate the degree to which a base population could decline, and would then have to rebuild during the subsequent warm season. Figure 1B shows the number of days in Memphis with a minimum temperature below 0 °C, from November through February. Note how the number of days with a minimum temperature below 0 °C is below average for the winter of 1877–1878 (labeled as 1878). The relatively mild winter and early spring temperatures likely contributed to the survival of many of the mosquito eggs through the winter months.

When temperatures fall below 10 °C, a prime temperature threshold, *Aedes aegypti* is incapable of moving. Figure 1C gives the number of days with a mean temperature below 10 °C from March through November. The year 1878 stands out as one with very few days with a mean temperature below 10 °C during the spring and summer. Thus, during that year, temperature conditions in Memphis were highly favorable for mosquito movement.

Table 1 Years with yellow fever epidemics in the US from 1793 through 1905. Major outbreaks (> 1000 deaths) are denoted by shaded cells. Data taken from Patterson (1992). El Niño years taken from Quinn (1992) and Quinn and Neal (1992).

Year	*El Niño Event*
1793	Yes
1979	Yes
1802-1803	Yes
1817	Yes
1837-1839	Yes
1847-1849	No
1852-1855	Yes
1867	No
1873	Yes
1876	No
1878	Yes
1879	No
1888	Yes
1897	Yes
1905	Yes

Climatic Conditions in Other Parts of the Southeast US, 1877 to 1878

Record or near-record temperature and precipitation anomalies were recorded in many parts of the world during 1877–1878 (Kiladis and Diaz 1986). In particular, the winter season (November through April) of 1877–1878 in the US was exceptionally warm in the interior states, and wet along the west and southeast coasts. In the middle and upper Mississippi Valley, temperatures were unusually warm in the spring of 1878. In the Southeast US, mean temperature departures for these months exceeded 1 °C in most areas, and 2 °C throughout the stem of the river. Summer temperatures were near normal or slightly above the mean, and the relative warmth extended into September. The summer of 1877 was very wet in the Memphis area, which recorded nearly 300% of average summer (June through August) rainfall that year. It was wet throughout the Southeast during the fall of 1877. Hence, climatic factors associated with the major El Niño episode of 1877–1878 may have contributed to the severe YF outbreak in the Southeast US by promoting the reproduction, survival, and propagation of *Aedes Aegypti*.

Other Yellow Fever Outbreaks in the US and El Niño

Table 1 lists the years with YF outbreaks in the US and any associated El Niño events. Since the late 18th century, nearly all of the major YF outbreaks in the US have been associated with El Niño events (73% of all outbreaks and 77% of major outbreaks). The 1905 YF episode was the last US epidemic of this disease.

It is beyond the scope of this study to consider the range of epidemiological and social factors that conspired to make the 1878 YF outbreak the national disaster that it was. (See the bibliographic references listed, in particular Bloom (1993), Duffy (1966), and Patterson (1992) for further study.) Undoubtedly, the YF epidemic of 1878 in Memphis and elsewhere along the Mississippi River was a result of both social, epidemiological, as well as climatic factors working simultaneously. Some of the more important of these non-climatic factors were a supply of infected individuals for the mosquito to feed on and propagate the virus, a relatively large population of non-immune individuals, and the absence of preventive public health actions (such as the removal of water containers where the mosquito could breed, mosquito eradication programs, or vaccines). Although El Niño events have continued to occur in this century, after 1905, with the discovery of the source of the infection in 1900 by W. Reed and his colleagues, there have been no YF epidemics recorded in the US. Nevertheless, the strong coincidence between severe YF outbreaks and the occurrence of El Niño events over the previous century suggests a climatic connection.

Conclusions

During 1878 one of the most virulent strains of YF had entered the Southeast. The prevalence of water-filled rain barrels and cisterns during an abnormally wet period provided ample breeding grounds for the mosquito, and the movement of people, mainly on boats along the Mississippi River, carried the disease to Memphis. The optimal climatic conditions allowed the *Aedes aegypti* to develop and spread the disease. Usually, Memphis lies north of the general poleward limit of *Aedes aegypti* distribution (Christophers 1960; Bruesch 1968; Smith and Gibson 1986). However, the 1877–1878 winter and the spring of 1878 were warmer than normal, which likely aided the early migration of the mosquito into the Memphis area. Much of the unusual weather was likely the result of the strong El Niño episode recorded in 1877–1878 (Kiladis and Diaz 1986).

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Documented Validation of Extreme Precipitation Events Reconstructed for Northwest Mexico (1860–1997)

Sara C. Díaz and César A. Salinas-Zavala

Abstract

The relation between climate change and human behavior is very closely linked in societies that depend primarily on agriculture. The history of drought in Mexico shows that the effects of climate change are broadcast to the whole society as food scarcities, hunger, epidemics, death, social disruptions, and political conflicts. Northwest Mexico is an arid zone with highly variable precipitation, and severe droughts are common. Rainfall is influenced by ENSOs in this region, resulting in increased winter precipitation. The keeping of instrument records started in a large way only around the 1950s; however, dendroclimatic techniques let us reconstruct winter precipitation from the region and identify drought periods from 1860 to 1997. Documentary evidence was used to validate the records.

Northern Mexico was very important in initiating the Mexican Revolution, the greatest Mexican social movement of this century. Prior to the Revolution there was a severe drought period documented in different parts of the region that lead to increased social discontent. Since 1949, despite some significant departures in precipitation amounts, the impact of climatic variation on the region's population has been moderated by technological innovation. The last two decades have been characterized by abundant rainfall associated with more frequent ENSO events.

Introduction

The relation between climate change and human behavior is very close in societies that depend significantly on agriculture. The lack of moisture due to a drought lasting more than two years greatly affects plant and animal development. The history of drought in Mexico shows the effects of climate changes are broadcast to the whole society as food scarcities, starvation, epidemics, death, social disruptions, migration movements, and political conflicts.

Northwest Mexico is a semiarid zone with variable precipitation and severe droughts. The indigenous people of arid northwest Mexico, as in other societies, settled primarily on the banks of the major rivers to obtain resources for their survival. On the peninsula, because of a lack of rivers, settlements were established primarily close to oases. This settlement pattern made them highly vulnerable to the yearly climatic phenomena. The most trying phenomena for the region were droughts, because of their long duration (Florescano and Swan 1995).

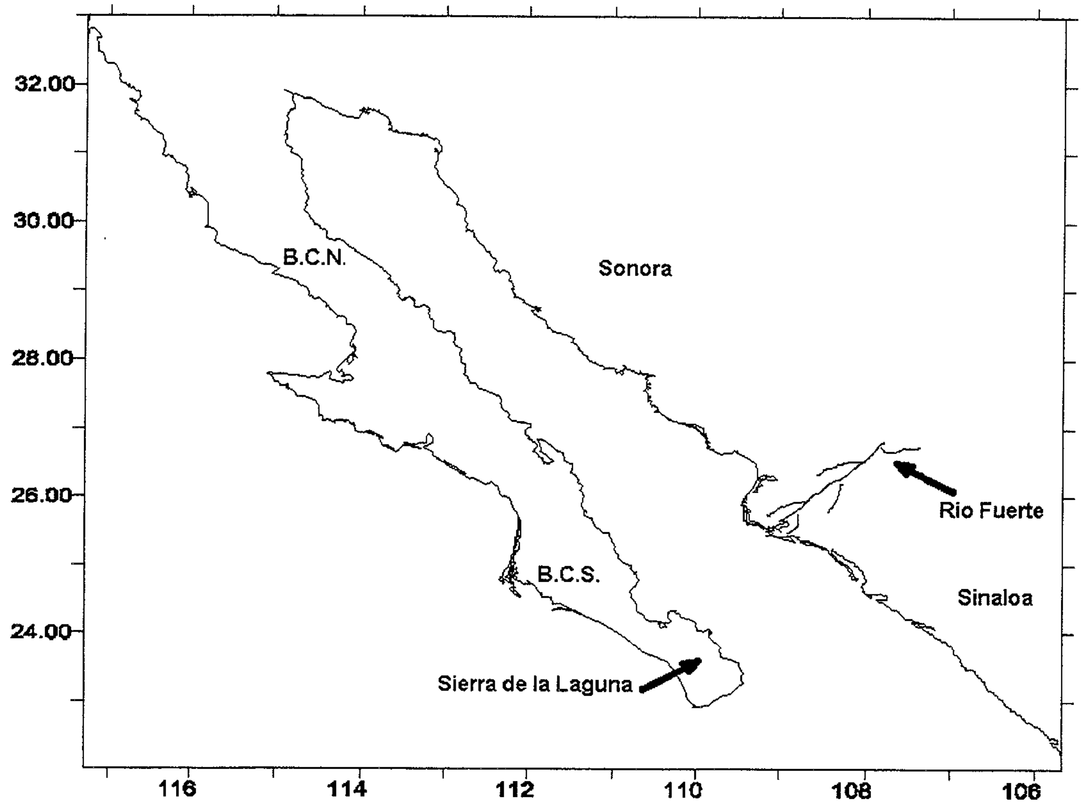

Figure 1 Northwest Mexico, Baja California (B.C.N.), Baja California Sur (B.C.S.), Sonora, and Sinaloa

Climatic impact assessment is a fairly new field of research, partly because of limited data on the frequency and intensity of environmental changes in the past (Eckstein 1990). Most of the instrumental climate data collection in northwest Mexico began largely around 1950 and so contains little information of variations over previous decades. Dendrochronological and dendroclimatological records developed from trees in Baja California Sur let us reconstruct the winter precipitation for a great part of the northwest Mexico region from 1860 to 1997.

The preliminary results from our analysis of the winter precipitation reconstruction series allow us to identify drought periods between 1860 and 1997 and explain the anomalous precipitation periods with documentary evidence to validate them.

Study Area

Tropical-subtropical northwest Mexico consists of four states surrounding the Gulf of California (Figure 1). The region is dominated by desert environments characterized by xerophilus scrub and thorn forest, but at the higher altitudes in the peninsula mountain, axes are deciduous-tropical and conifer-oak forests. Sierra de La Laguna is located in the southern part of Baja California Sur.

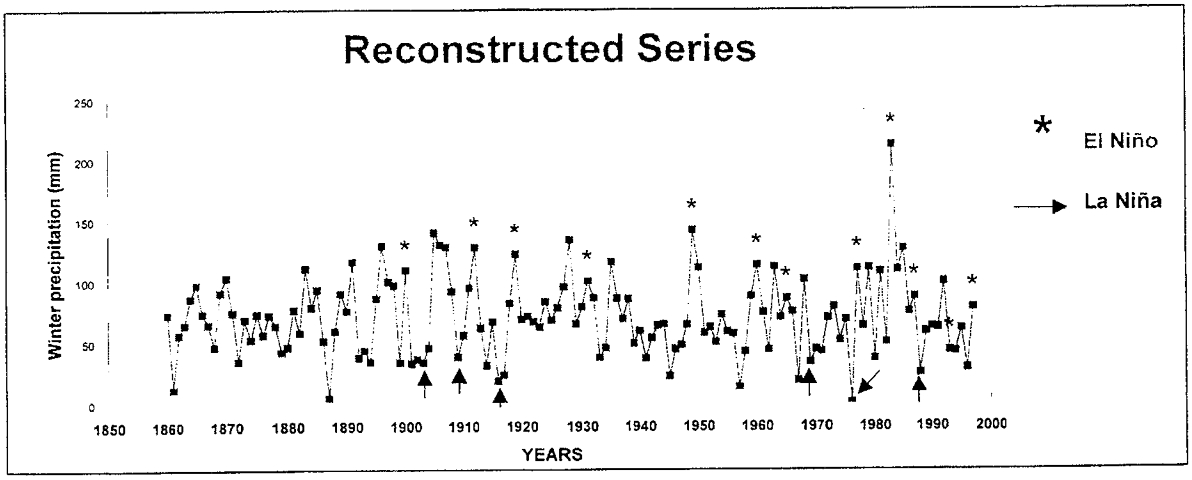

Figure 2 Winter precipitant reconstructed series. Asterisks (*) denote the El Niños and arrows denote the La Niñas. The horizontal line is the threshold of 80% of the mean.

Analysis of Reconstruction

The winter precipitation (November through February) reconstruction made by Díaz (unpublished data) extends from 1860 to 1997 and covers the greater part of Baja California Sur, Sonora, and Sinaloa. In accordance with Kiladis and Díaz (1989), the year zero of warm (El Niño) and cold events (La Niña) were identified in the precipitation series. The maximum precipitation was coincident with El Niño from 1982 to 1983, and the lowest was around 1975. This is considered the year of the Climatic Regime Change of the 20th century. The majority of El Niños correspond with moist years, whereas La Niñas coincide with drought years (Figure 2).

We summarized the short-term drought properties in this series by runs analysis (Sadeghipour and Dracup 1985) using an arbitrary threshold of 59.7 mm to define a drought year. This threshold is approximately 80% of the 1964 to 1986 mean observed from November through February precipitation. Using this method, we observed 32 drought periods in the precipitation series.

To determine the anomalies, precipitation was subtracted from the threshold. The anomalies were integrated and detrended, with the accumulated series obtained showing long-term precipitation change trends. The periodogram of the precipitation series shows us several significant frequencies. The most important is the six-year cycle.

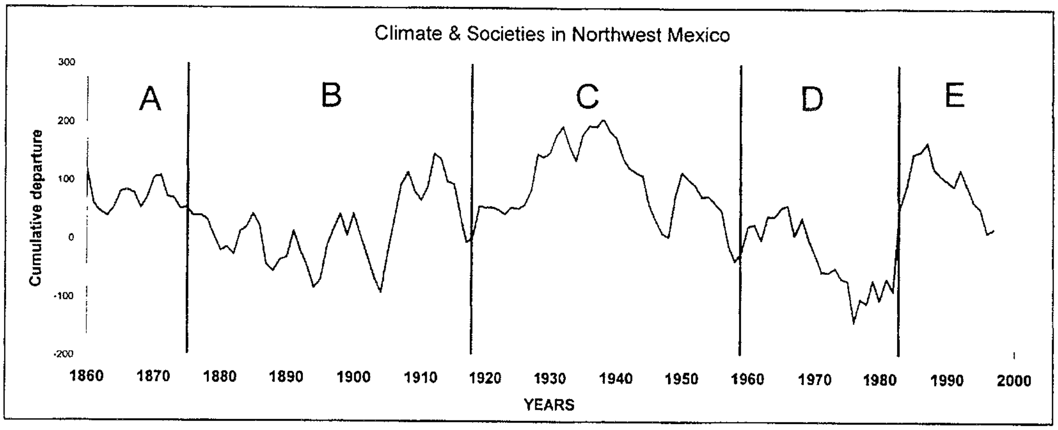

Figure 3 Cumulative departure from the threshold trends that are divided in epochs for the influence of climate in the northwest Mexico society

Documented Episodes

Different epochs are noted in the accumulated anomalies series. These are explained as follows (Figure 3):

A. Stable Climate Period (1860–1875).

In 1860 a great runoff event of Río Fuerte was reported, and in our graph we can see that this was a wet year (Delgadillo 1996). From 1861 through 1875 a period of stable climate without a severe precipitation event is noted.

B. Drought Period (1875–1918). A period of frequent droughts with a great social impact.

Between 1874 to 1906, a period with frequent droughts occurred as documented on a regional scale in the four states of northwest Mexico. The primitive development of agriculture made the region's populations very vulnerable to droughts. This drought period occurred just before the greatest Mexican social phenomenon of recent history, the Mexican Revolution, an event that was partially caused by the general discontent of the farmers and rural population (Florescano and Swan 1995). Although this was a national movement, the discontent in northern Mexico played an important initial role in the Mexican Revolution which later expanded as new discontented groups joined the movement.

C. Beginning of Lessening Vulnerability (1915-1955). This can be considered a moist period.

The period from the late 1920s through the late 1940s is characterized by positive accumulated winter precipitation. Thanks to the water resource facilities developed during the late 1940s through the late 1950s in Sonora and Sinaloa, the effects of climatic related disasters had been greatly reduced. Hydraulic constructions have controlled runoffs to supply water to the cities and, most significantly, to irrigate agricultural lands, thus minimizing drought effects (Delgadillo 1996). Even so, there were droughts reported for 1943 and 1951.

D. Climate-society Breaking (1959-1983). This was a period of droughts with the lowest values of accumulated anomalies.

In the early 1960s the implementation of the Green Revolution began, increasing the most important agricultural yields for corn and wheat (Michaels 1981). This "technological packet" decreased agricultural vulnerability to drought during this period. Flood years in northern Sinaloa were recorded in 1955, 1960, and 1979.

In 1963 there was another severe drought. As a result, 70% of the corn crop was lost in middle and southern Sinaloa (Sinagawa 1987). Because of the droughts and increasing population growth, the self-sufficiency for food in Mexico ended in 1975 (Urciaga 1993). However, during all these events during this epoch, there was social stability as the result of increased transportation and communication.

E. El Niño Period.

From 1983 to the present is characterized by the frequent influence of El Niños that bring more winter rains. Four events are recorded including the most intense El Niño of this century in 1983. (This period does not include the 1997-1998 ENSO.)

Conclusions

Northwest Mexico is a region where water is a restricted resource and the dynamic equilibrium between the environment and human life can be easily disrupted. The reconstructed precipitation values correspond to some of the documented climatic departures from normal that had an impact on the population of northwest Mexico that lead to social instability, loss of food supply, and economic problems.

The historic records of the calamities caused by the severe droughts and floods in the region show they were minimized because of economic development, which included communications and transportation development and a great increase in water resource management facilities in the region during the middle part of this century.The analysis of the precipitation reconstruction also confirms the effect of ENSO on the region.

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Alternative PCA-based Regression Techniques in Dendroclimatic Reconstructions

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Abstract

Principal Components Analysis (PCA) has been used extensively for reconstructing past climatic variability by regressing components derived from tree-ring chronologies onto the climatic variable (in other words, streamflow). However, this procedure leaves several choices to the researcher that may result in very different reconstructions. This study compares these options using the cross-validation standard error (CVSE) as a criteria to estimate the predictive skill of the model. Independent testing, or the optimization of the CVSE, is a way to identify the model that best represents the physical processes using the minimum number of variables (a parsimonious model), and that reduces the influence of unrelated noise.

This study uses 17 tree-ring chronologies from different sites in the upper Colorado River Basin to predict streamflow at Lee's Ferry, the legal point separating the upper and lower Colorado River basins. Combinations of up to seven variables with the lowest CVSE were selected from these 17 chronologies. This procedure was repeated using rotated components, using unrotated components, using all the modes, and by pre-selecting the modes with eigenvalues higher than one. Also, the final regression of the components, done traditionally by a stepwise regression, is compared with a new regression technique. Results show in some cases stepwise regression may not result in the most parsimonious models and alternative methods should be considered.

Finally, the model believed to give the best predictive skill is used to reconstruct the Lee's Ferry streamflow and it is compared to a previous reconstruction in the upper Colorado River Basin.

Introduction

Predictor variables used for streamflow generation forecasting or dendroclimatic reconstruction purposes are usually correlated with each other. This cross-correlation is particularly evident when using the same type data for different stations (or sites) at the same time (Garen 1992).

To overcome this problem one may transform the original variables using a Principal Component Analysis (PCA) technique. However, PCA and the regression of the resulting components allows several alternatives in the procedure that may result in significantly different results depending on choices made by the researcher. This study is a comparative analysis of the differences in the results obtained by choosing several alternatives when regressing components of standardized tree ring indices onto the streamflow variable. Different alternatives in the PCA and in the final regression, as well as different subsets of the predictor variables, are compared using cross-validation standard error (CVSE). The better models are assumed to be the ones having smaller CVSE, regardless of their coefficient of determination (Rsqr) for the calibration period.

The case study will be the upper Colorado River Basin (UCRB), which is the most important river basin in the southwestern US in terms of water resource usage (Figure 1). A previous dendrohydrological reconstruction of the UCRB flow by Stockton and Jacoby (1976) is available. Their results will be compared with our estimates of the streamflow for the UCRB.

Data Sources

The tree-ring chronology data set used in this study was obtained in 1997 from the International Tree-Ring Data Bank (ITRB), maintained by the NOAA Paleoclimatology Program and World Data Center-A for Paleoclimatology (Table 1). The streamflow data set used for the upper Colorado River Basin is the Lee's Ferry record, immediately downstream of the Glen Canyon Dam, measured at the legal dividing point between the upper and lower basins. The period used was 1896 to 1962 and does not reflect streamflow beyond the construction of the Glen Canyon Dam in 1963. These data were obtained from the US Bureau of Reclamation (USBR 1994).

Methods

A common problem in dendroclimatological reconstructions is the presence of multicollinearity between predictors (tree ring chronologies). When all the chronologies and their lag values are included in the analysis, the problem of multicollinearity may become worse. It may also result in the undesirable effect of "overfitting" the model, thus, making the model able to predict even the smallest variations in the observed data, but with a low predictive skill for unobserved cases (Jackson and Chan 1980; Cureton and D'Agostino 1983; Jennrich 1995). When these highly intercorrelated predictors are used in a multiple linear regression model, multicollinearity can become the cause of statistically imprecise and unstable estimates of regression coefficients, incorrect rejection of variables, and numerical inaccuracies in computing the estimates of the model's coefficients (Cureton and D'Agostino 1983; Weisberg 1985; Fritts 1991; and Jennrich 1995).

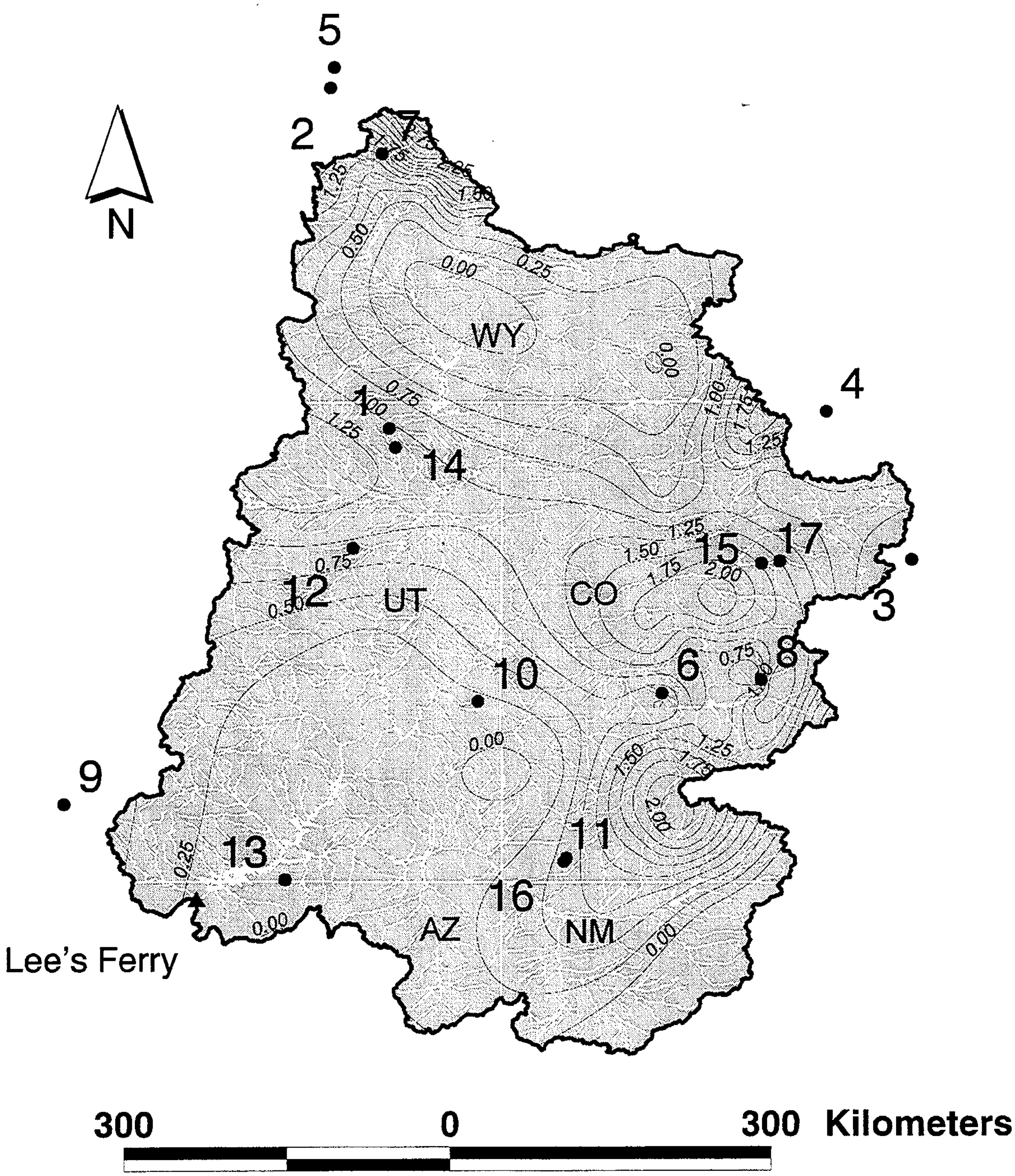


Figure 1 The location of the 17 tree ring site chronologies used in this study in the upper Colorado River Basin. Annual water yield contours in ft/yr are also shown.

Table 1 List of tree ring chronologies used in this study. S.D. is the standard deviation. $r_1 lag_1$ is the lag+1 autocorrelation coefficient. Correl. Criterion is the correlation between the tree ring index and streamflow. M.S. is the mean sensitivity (Fritts 1976). All the statistics are computed for the period from 1493 to 1963, except the correlation criterion which is computed from 1914 to 1963. PCEN - *Picea engelmannii*, PIFL - *Pinus flexilis*, PSME - *Pseudotsuga menziesii*, PILO - *Pinus longaeva*, PIED - *Pinus edulis*.

#	*Site Name, State*	*Researcher*	*Year*	*ID #*	*Species ID*	*Elev.*	*Correl. Criterion*	*S.D.*	*r_1 lag_1*	*M.S.*
1	Uinta Mountain A, UT	Harsha, Stockton, Jacoby	1972	277550	PCEN	3353	0.14	0.14	0.67	0.11
2	Gros Ventre, WY	Ferguson, Loope	1972	316597	PIFL	2179	0.17	0.28	0.47	0.26
3	Chicago Creek, CO	Stokes, Harlan	1965	115549	PSME	2835	0.22	0.39	0.26	0.40
4	New North Park, CO	Stokes, Harlan	1965	110549	PSME	2469	0.31	0.37	0.54	0.31
5	Uhl Hill, WY	Ferguson	1972	318599	PIFL	2225	0.36	0.29	0.52	0.27
6	Black Canyon of the Gunnison River, CO	Stokes, Harlan	1965	117549	PSME	2426	0.41	0.35	0.52	0.31
7	Wind River Mountains, Site D, WY	Harsha Stockton, Jacoby	1972	283590	PIFL	2500	0.47	0.26	0.51	0.21
8	Upper Gunnison, CO	Stokes, Harlan	1965	116549	PSME	2530	0.54	0.34	0.38	0.38
9	Mammoth Creek (for 21), UT	Graybill	1990	MAM519	PILO	2590	0.56	0.37	0.17	0.41
10	La Sal Mountains, Site A, UT	Harsha, Stockton	1972	285620	PIED	2323	0.57	0.33	0.42	0.34
11	Bobcat Canyon, CO	Dean, Robinson, Bowden	1972	61099	PSME	2042	0.62	0.43	0.25	0.47
12	Nine Mile Canyon (High), UT	Stokes, Harlan	1965	123549	PSME	1920	0.64	0.41	0.41	0.39
13	Navajo Mountain, UT	Dean, Bowden	1972	133099	PIED	2286	0.66	0.44	0.21	0.51
14	Uinta Mountains, Site D, UT	Harsha Stockton, Jacoby	1972	280620	PIED	2289	0.69	0.32	0.46	0.31
15	Eagle, CO	Stokes, Harlan	1965	112549	PSME	1951	0.69	0.35	0.62	0.28
16	Schulman Old Tree #1, Mesa Verde, CO	Schulman	1964	640106	PSME	2103	0.69	0.45	0.30	0.51
17	Eagle East (Job 105 reworked), CO	Stokes, Harlan	1965	113629	PIED	2164	0.77	0.29	0.34	0.31

To reduce multicollinearity in the original variables, the original data set can be transformed into linear combinations of the original variables by using PCA. These linear combinations, or components, are characteristically independent of one another (orthogonal) and the resulting components (predictors) are then regressed onto streamflow (predictand) to form a reconstruction model. This type of data-reduction technique minimizes the redundancy in a set of intercorrelated variables and forms a smaller set of "composed" (latent) variables or components where the number of components is equal to the number of variables.

Even though the intention of PCA is to remove the intercorrelation between independent variables by forming independent components, there is usually some degree of overlap between components. If the intercorrelation were entirely removed (usually not the case), the components will be completely independent and the eigen-vector coefficients for each original variable will be one or zero (hard coefficients). This shows the importance of component selection in determining the skill of the resulting models. The usual procedure for component selection in PCA-based dendroclimatic reconstructions is the stepwise regression.

An undesirable effect of stepwise regression is that it allows selection of non-consecutive components (Garen 1992). For example, the first, second, fifth, and tenth components could be selected for a regression model according to stepwise regression procedures. Non-consecutive component selection may result in regression coefficients for some of the original predictor variables that have the opposite sign of their initial correlation with the predictand. This suggests that some of the confounding intercorrelation between the predictor variables, which PCA intended to remove, is reintroduced into the regression model. A model of this type may give results that are not consistently accurate over time and is not conceptually acceptable.

Garen (1992) based on McCuen (1985), gives an alternative procedure to stepwise regression for component selection. This procedure results in a more parsimonious model that better represents the physical system being modeled and has better predictive skill than a model created using stepwise regression. This procedure uses the "*t*-test" and a "sign test" as the criteria for retaining variables. The *t*-test is used to test the significance of the coefficient of the predictor variable in the regression equation. The sign test is passed if the algebraic signs of the regression coefficients (in terms of the original variables) match the algebraic signs of the correlation coefficients of the original variables with the dependent variable.

The following discussion summarizes the alternative procedure for principal component (PC) selection. First, test PC1 according to the *t*-test. If PC1 passes the *t*-test, then perform a sign test. If both the *t*-test and sign test are passed, then accept PC1. Next, test PC2 as non-consecutive components are not allowed.

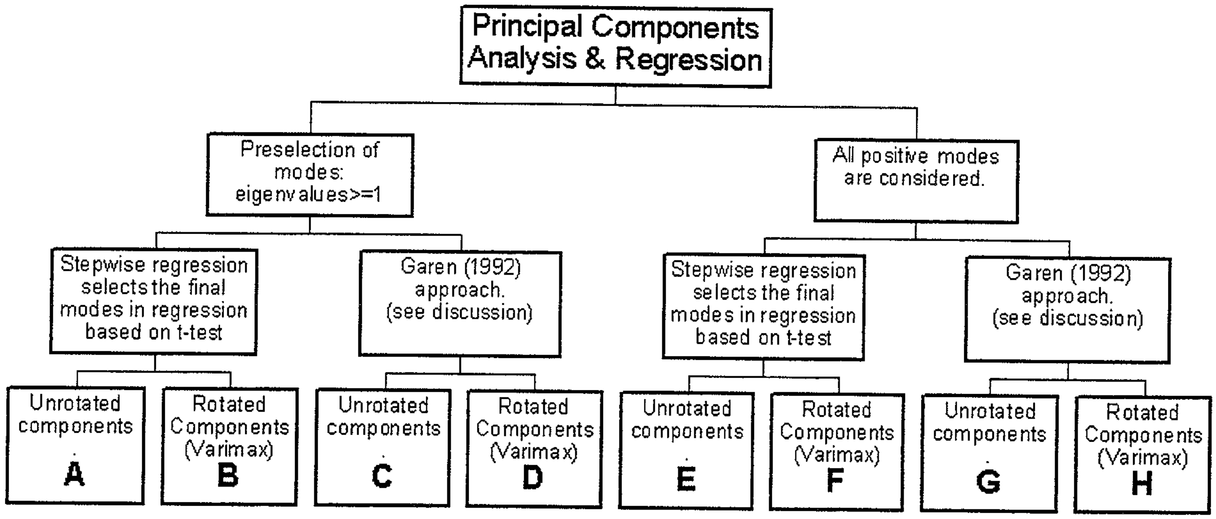
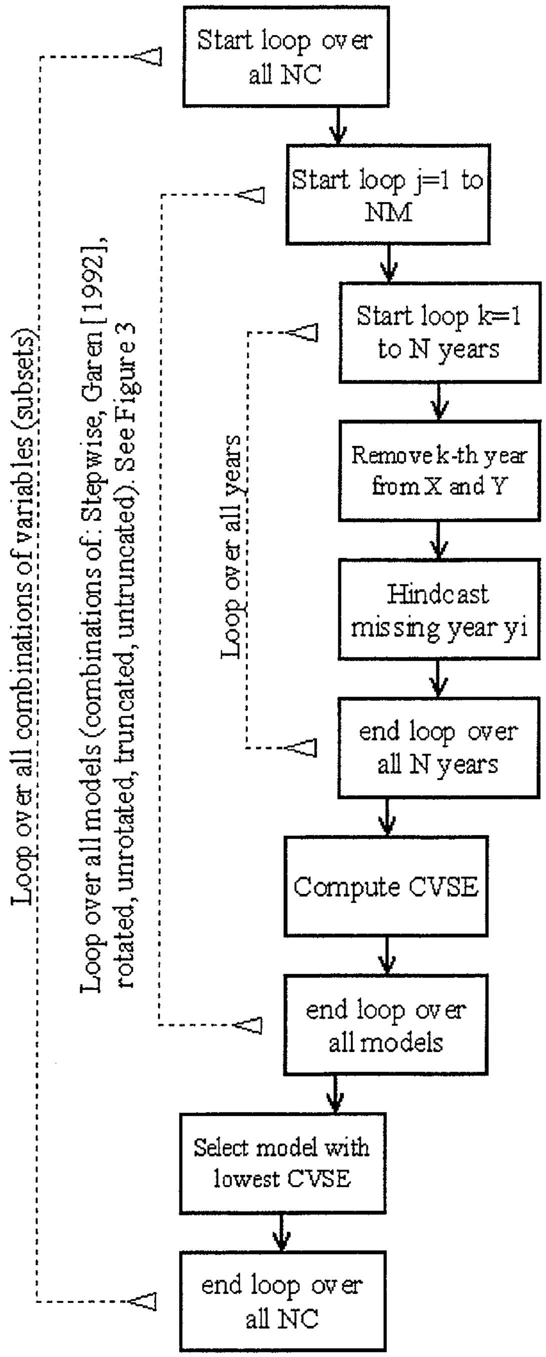


Figure 2 Schematic of the eight different modeling approaches investigated in this study. All models are tested using the cross-validation standard error.

If PC2 does not pass the *t*-test, then only retain PC1. If PC2 passes the *t*-test and the sign test, then retain PC1 and PC2 and test PC3. If PC2 passes the *t*-test, but fails the sign test, then retain PC2 temporarily and test PC3. If PC3 fails the *t*-test, then only retain PC1. If PC3 passes the *t*-test and the sign test, then retain PC1, PC2, and PC3. If PC3 passes the *t*-test, but fails the sign test, then retain PC3 temporarily and test PC4. The procedure continues until the next PC does not pass both the *t*-test and the sign test.

The effect of rotating components in PCA is also examined in this study. Rotation is intended to make sharper distinctions between components (in other words, making the coefficients closer to one or zero). A thorough discussion of reasons for rotation of components is given in Richman (1986). In this study, both rotated and unrotated PCA are presented and compared. The method of rotation used here is based on the Varimax criterion for factor rotation (Kaiser 1958) and includes the modifications suggested by Nevels (1986) and ten Berge (1995).

The possible combinations of these alternative models are shown of Figure 2. The models were tested using the algorithm in Figure 3. The criteria for determining the skill of the model is based on the CVSE (Michaelsen 1987). This algorithm selects the model with a subset of tree ring variables that has the highest skill (lowest CVSE). First, the algorithm finds the lowest CVSE for combinations of one variable. Next, the lowest CVSE for the two variable combination is found. The procedure is continued up to the total number of variables. If the minimum CVSE for combinations with an added variable is larger than the previous CVSE, the program stops, and the extra variable is not included. This procedure is similar to the one used by Garen (1992), although it may not necessarily find the optimum of all combinations of variables. Instead, the procedure tends to select a near-optimal parsimonious model (Garen 1992).



Given:
NC: number of subsets of predictor variables, stored in matrix X(1..N,1..p), where p=maximum number of predictor variables, and N is the number of years.
Y: Predictand variable matrix, Y(1..N,1).
NM: Number of different models, in this case the eight models shown in Figure 3.
CVSE: Cross Validation Standard Error.

Figure 3 The algorithm used for identification of the optimal model parameters

Results

Table 2 presents the results of the models identified in Figure 2. The CVSE is compared with other verification statistics commonly used for tree ring reconstruction models (Fritts 1991). The components and the variables that are used to form the different components are also shown in the second and last columns. The "complete" model (using all variables) is shown as a comparison with more parsimonious models for each of the alternative procedures. In all cases, the complete model resulted in a higher CVSE than the other models.

Table 2 Summary of the results for the models identified in Figure 2. PC is the principal component included in each model. The CVSE is the cross-validation standard error. Rsqr is the square of the correlation coefficient. AdjRsqr is the adjusted Rsqr. RMSE is the root mean square error. RE is the reduction of error statistic. Variables are the chronologies used in the reconstruction model.

Model	*PCs*	*CVSE*	*Rsqr*	*AdjRsqr*	*Cp/10*	*RMSE*	*Sign Z*	*RISK*	*BIAS*	*COVAR*	*RE*	*Variables*
A												
Stepwise	1,3	2.101	0.798	0.775	0.646	1.923	0.493	-0.985	1.857	0.112	0.984	17, 16, 14, 13, 5
Unrotated	1,5	3.132	0.722	0.574	4.756	2.258	0.655	-0.979	1.854	0.099	0.974	1 to 17
B												
Stepwise	1,2	2.141	0.790	0.771	0.299	1.963	-1.391	-0.987	1.859	0.111	0.983	17, 14, 13, 6
Rotated	2,4,8	3.254	0.744	0.607	5.658	2.191	1.190	-1.001	1.876	0.097	0.972	1 to 17
C, G												
Garen (1992)	1	2.156	0.771	0.756	-0.477	2.027	-0.825	-0.983	1.857	0.109	0.983	17, 14, 13
Unrotated	1	3.057	0.680	0.509	3.806	2.397	0.825	-0.979	1.861	0.093	0.975	1 to 17
D, H												
Garen (1992)	1	2.586	0.734	0.717	0.559	2.183	-0.780	-1.002	1.892	0.085	0.975	17, 14, 13
Rotated	1	3.195	0.640	0.448	3.653	2.542	-0.825	-0.976	1.861	0.088	0.973	1 to 17
E												
Stepwise	1	2.586	0.734	0.717	0.559	2.183	-0.780	-1.002	1.892	0.085	0.975	17, 14, 13
Unrotated	1	3.195	0.640	0.448	3.653	2.542	-0.825	-0.976	1.861	0.088	0.973	1 to 17
F												
Stepwise	1,3	2.100	0.795	0.777	1.352	1.938	0.493	-0.987	1.860	0.111	0.984	17, 14, 13, 6
Rotated	2,4,9,13	3.003	0.806	0.703	6.382	1.926	-0.024	-0.976	1.847	0.105	0.976	1 to 17

All the models based on the Garen (1992) approach use only the first component. This suggests that the size of the upper Colorado River Basin is small enough that the climate signal common to all variables belongs to a single climate regime that influences most of the basin. In contrast, the stepwise regression selected one to four components. Note that the correlation coefficients are similar for both approaches.

Truncation of the components did not influence the models based on the Garen (1992) approach, which only selects the first component. For stepwise regression, however, better results are obtained when all the components (in other words, no truncation) are considered in the model. The results also suggest that the Garen (1992) methodology has a preference for the unrotated PCA, but that the stepwise regression approach gives better results using rotated PCA. This is logical since the rotation of the components distributes the variance of the original time series more equally among the components. The unrotated solution has a large portion of the variance in the first component and the amount of variance in the following components drops off much faster than in the rotated solution. The rotation of components diminishes the high contribution placed on the first component and this affects the Garen (1992) method, which favors the first component. The opposite effect is observed in the stepwise regression selection, which gives importance to some of the latter components.

The rotated stepwise regression model has the lowest CVSE [2.100 million acre feet (maf)] among all the models in Table 2; however, it is not the most parsimonious model. The method suggested by Garen (1992) selected the model with the fewest variables (one less variable than the stepwise regression) and had a CVSE that was just slightly higher (2.156 maf) than the rotated stepwise regression model.

The effect of using two components in the best stepwise regression model is shown in Figure 4. In Figure 4, the loadings for the first component (PC1) and third component (PC3) are presented. It is clear that PC1 and PC3 are highly correlated (correlation coefficient = 0.74). This high correlation between components contradicts the intent of PCA, which is to form independent variables that represent different modes of variability. In this example, PC3 is providing similar information to PC1. It is not clear if there is an increase in "real" skill by including PC3. Therefore, it is concluded that the Garen (1992) unrotated PCA models are more parsimonious and maintain the independence between the predictor variables.

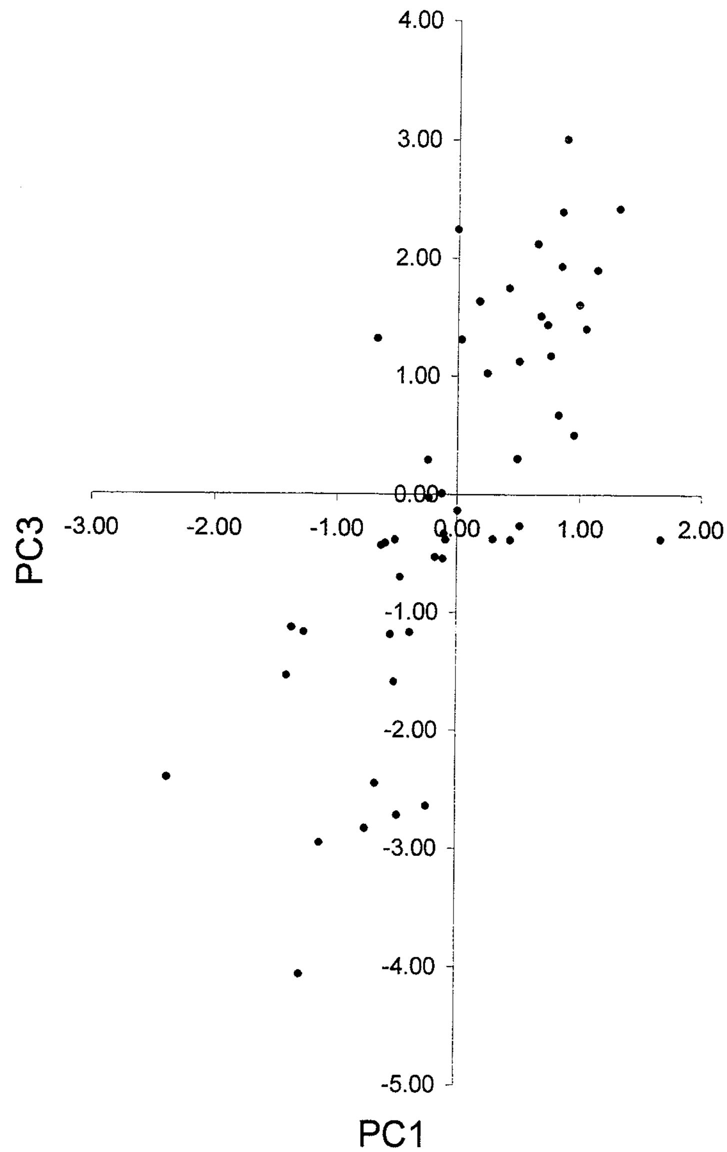


Figure 4 Plot of the principal component loadings for the first and third principal components (PC1 and PC3) used in the best stepwise regression model

Comparison with Stockton and Jacoby's (1976) Previous Reconstruction

In this section, the Lee's Ferry streamflow reconstruction using the "optimized model" based on the Garen (1992) unrotated PCA approach is compared with the streamflow reconstruction done by Stockton and Jacoby in 1976 using a stepwise regression model that allowed non-consecutive components. The calibrated models use lagged (–1,0,+1,+2) chronologies. Tables 3 and 4 present the results of the model developed in this study using the Garen (1992) approach. Figure 5 compares the results of a traditional stepwise regression model and the model formed with the procedures from this study.

Table 3 The statistical characteristics of the model formed using the Garen (1992) approach for the reconstruction of the Colorado River flow at Lee's Ferry

PC Used	*CVSE (maf)*	*Rsqr*	*AdjRsqr*	*RMSE (maf)*	*RISK*	*BIAS*	*COVAR*	*RE*
1	1.901	0.824	0.803	1.75	-0.982	1.86	0.109	0.987

Table 4 Statistical characteristics of the chronologies used in the model selected with the Garen (1992) approach that had the lowest cross-validation standard error. The numbers in parentheses are the decreasing rank based on the original 68 chronologies (including lag chronologies).

Site Name Calibration Period	*Nine-Mile, #12 Lag 0*	*Uinta, #14 Lag 0*	*Eagle East, #17 Lag 0*	*New No. Pk., #4 Lag -1*	*Chicago Ck., #3 Lag +1*	*Up.Gunnison, #8 Lag +1*
Tree Rings						
Lag+1 Auto Correlation	0.16 (41)	0.47 (20)	0.11 (57)	0.23 (32)	0.12 (52)	-0.13 (67)
Correlation with Streamflow	0.64 (5)	0.70 (3)	0.79 (1)	0.32 (21)	0.30 (24)	0.35 (20)
Mean	1.30 (11)	1.04 (56)	1.03 (60)	1.09 (43)	1.24 (15)	1.09 (46)
Standard Deviation	0.44 (7)	0.34 (34)	0.26 (60)	0.27 (57)	0.38 (22)	0.34 (38)
Mean Sensitivity	0.46 (11)	0.33 (45)	0.35 (31)	0.28 (51)	0.38 (26)	0.43 (18)
Standard Deviation/Mean	0.34 (15)	0.33 (18)	0.25 (57)	0.25 (58)	0.31 (30)	0.31 (27)
Streamflow						
Lag+1 Auto Correlation	0.30					
Mean	15.00 maf					
Standard Deviation	4.13 maf					
Mean Sensitivity	0.28					
Standard Deviation/Mean	0.28					

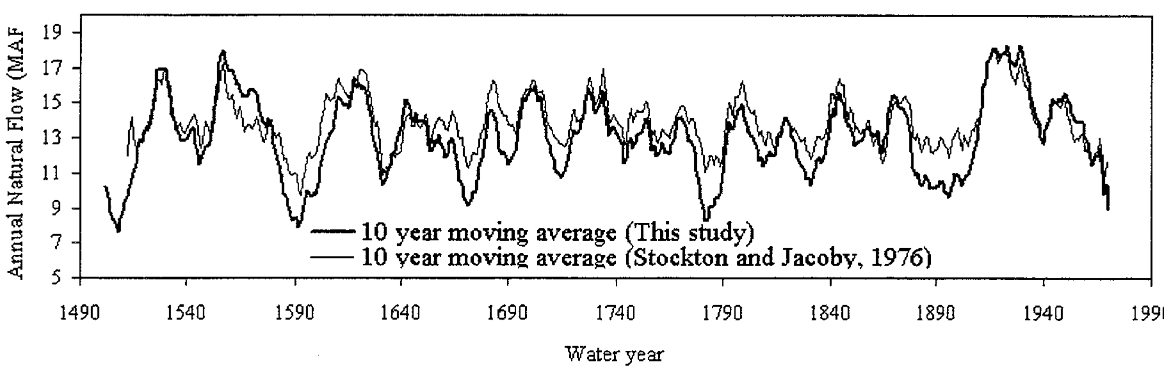


Figure 5 Comparison of the reconstruction results obtained using the Stockton and Jacoby (1976) approach and the alternative approach from this study. Annual flows are millions of acre-feet (maf) measured at Lee's Ferry.

As expected, the sites selected by the model using Garen's (1992) approach are located in the upper part of the Colorado River Basin where the runoff yield is high. Note that the very high yield sites in the upper part of the Green River, Wyoming, (sites 2, 5 and 7) were not selected by the model over sites with similar yield in the upper part of Colorado (sites 3 and 4). This suggests that tree species may play some role in the identification of the best chronologies for streamflow reconstruction in this particular basin. In general, the model preferrs the species *Pseudotsuga menziesii* and *Pinus edulis* over *Pinus flexilis* and *Picea engelmannii*.

In Figure 5, the optimized model has more sensitivity to below average streamflow (droughts) than is found in Stockton and Jacoby's model. The Stockton and Jacoby (1976) model used six components (representing an unknown number of tree ring chronologies) that were not consecutive. The Rsqr from the Stockton and Jacoby reconstruction was 0.860, slightly higher than the optimized model presented here (Rsqr = 0.824). However, the six components used in the Stockton and Jacoby study may not be truly independent, and with the additional components, there may be some duplicate information and artificial skill added to the model.

Conclusions

Comparison of several alternative PCA regression techniques presented in this paper is intended to provide guidelines about the relative accuracy of these models for streamflow reconstruction.

The models using Garen's (1992) methodology for selecting unrotated components resulted in the most parsimonious models having a low CVSE. These methods produce parsimonious models that are more physically consistent with the underlying physical processes than those calibrated using stepwise regression.

Compared to traditional methods, significant differences were obtained using these optimized calibration models. Specifically, the magnitude of dry periods tends to be more intense when these models are used. The results show that minimization of the cross-validation standard error is a good tool for determining the most parsimonious model, one with a low mean standard error that continues to retain consistency with the underlying physical processes.

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Comparison of Tree-species Sensitivity in Streamflow Reconstructions in the Colorado River Basin

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Abstract

Tree-ring-based hydrologic reconstructions have often been based on multi-species data sets of moisture-sensitive tree species to obtain an adequate spatial coverage of the study basin. However, it is known that sensitivity to climatic forcing varies for different species and growing conditions at different sites. Biologically controlled differences in physiological water demands and the starting date and length of the species' growth period, as well as differences in the hydrological sensitivity of the site type and substrate favored by different species, make some species better potential predictors of a particular hydroclimatic parameter (such as streamflow). The identification of the most hydrologically sensitive species in the basin under study is important for the appropriate selection of tree-ring sites and paleohydrological model construction. Careful selection of tree ring species and sites will reduce error in the reconstruction model and in the resulting streamflow estimates.

Introduction

The work presented in this study focuses on hydrologic reconstructions in the upper Colorado River Basin (UCRB), based on a multi-species tree-ring data set. Our goal is to identify the most hydrologically sensitive tree species and sites in the UCRB. Ring width chronologies studied were selected from six species, *Pseudotsuga menziesii* (PSME), *Pinus flexilis* (PIFL), *Pinus edulis* (PIED), *Pinus longaeva* (PILO), *Pinus ponderosa* (PIPO) and a juniper species (JUSP). The varying relationships between the Lee's Ferry streamflow record (the lowest point of the upper basin) and these different species' ring width indices will be analyzed. The study is based on tree ring sites for each species that displayed significant correlation coefficients with streamflow. It is known that sensitivity to climatic forcing varies for different species and the growing conditions at different sites. The information gained from this analysis is important not only in the selection of future tree ring sites, but also in paleohydrological model construction.

A careful selection of tree ring chronologies will reduce error in the reconstruction model and in the resulting streamflow estimates. This research will have important future implications in the identification of the duration and magnitude of severe sustained drought in the upper Colorado River Basin, the most important river basin in the arid Southwest.

Data Sources

The tree ring chronology data set used in this study was obtained in 1997 from the International Tree-Ring Data Bank (ITRB), maintained by the NOAA Paleoclimatology Program and World Data Center-A for Paleoclimatology. Standard site chronologies (growth indices for a site) were selected using coordinates of lat 35°N to 44°N and long 105°W to 113° W. These coordinates were chosen to encompass the upper Colorado River Basin and include parts of five states: Wyoming, Utah, Colorado, Arizona, and New Mexico. The tree-ring data set available for the upper Colorado Basin on the ITRB consisted of 62 sites representing 8 tree species: 23 *Pseudotsuga menziesii* sites (Douglas Fir); 11 *Pinus ponderosa* sites (Ponderosa Pine); 9 *Pinus flexilis* sites (Limber Pine); 6 *Pinus aristata* sites (Bristlecone Pine); 5 *Pinus edulis* sites (Colorado Pinyon); 5 *Picea engelmannii* sites (Engelmann Spruce); 2 *Pinus longaeva* sites (Great Basin Bristlecone Pine); and 1 *Juniperus* site (Juniper).

From an original 62 chronologies, we selected the 23 tree ring sites in this study based on their correlation with streamflow (Table 1). For those species with more than five sites represented in the UCRB, *Pseudotsuga menziesii*, *Pinus ponderosa*, and *Pinus flexilis*, the five chronologies with higher correlation with streamflow were selected. *Pinus edulis*, *Pinus longaeva*, and *Juniperus* had five or fewer sites; therefore all chronologies for these species were used. Two species representing 11 sites within our study area in the UCRB were not used in this study due to non-significant or negative correlation with streamflow. Species not used were *Picea engelmannii* with 0.04 correlation and Pinus aristata with -0.01 correlation.

Sites for our selected species ranged in elevation from 1,920 to 3,200 m. In Figure 1, elevations are grouped by species and appear from left to right in descending order of correlation with streamflow.

The streamflow data set used for the upper Colorado River Basin is the Lee's Ferry record, immediately downstream of the Glen Canyon Dam, measured at the legal dividing point between the upper and lower basins. The period used was 1896 to 1962 and does not reflect streamflow beyond the construction of the Glen Canyon Dam in 1963. This data was obtained from the US Bureau of Reclamation (USBR 1994).

Table 1 Characteristics of 23 tree ring chronologies selected for inclusion in this study based on correlation with Lee's Ferry streamflow. ID # is the identification number from the International Tree-Ring Data Bank. Species ID abbreviations are PIED - *Pinus edulis*, PSME - *Pseudotsuga menziesii*, PIPO - *Pinus ponderosa*, PILO - *Pinus longaeva*, JUSP - *Juniperus* spp., and PIFL - *Pinus flexilis.*

ID #	*Site Name*	*State*	*Lat*	*Long*	*Elevation (m)*	*Species ID*	*Researcher*
113629	Eagle East (Job 105 reworked)	CO	39.67	-106.72	2164	PIED	Stokes, Harlan
423000	Milk Ranch Point	UT	37.62	-109.73	2286	PIED	Dean, Robinson
280620	Uinta Mountains, Site D	UT	40.62	-109.95	2289	PIED	Harsha, Stockton, Jacoby
133099	Navajo Mountain	UT	37.02	-110.85	2286	PIED	Dean, Bowden
473629	Dolores	CO	37.58	-108.55	2195	PIED	Harlan
640106	Schulman Old Tree N 1, Mesa Verde	CO	37.20	-108.50	2103	PSME	Schulman
75854W	Spruce Canyon DB0417	CO	37.18	-108.48	2115	PSME	Cleveland, Harlan
061099	Bobcat Canyon	CO	37.17	-108.52	2042	PSME	Dean, Robinson, Bowden
112549	Eagle	CO	39.65	-106.87	1951	PSME	Stokes, Harlan
123549	Nine Mile Canyon (High)	UT	39.78	-110.30	1920	PSME	Stokes, Harlan
132000	Navajo Mountain	UT	37.03	-110.85	2377	PIPO	Dean, Bowden
012000	Ditch Canyon	NM	37.00	-107.82	2073	PIPO	Dean
130649	Water Canyon, Bryce Canyon National Park	UT	37.67	-112.10	2098	PIPO	Stokes, Harlan
182649	Walnut Canyon National Monument	AZ	35.18	-111.52	2073	PIPO	Stokes, Harlan
WCP549	Walnut Canyon	AZ	35.17	-111.52	2057	PIPO	Graybill
WHR519	Wild Horse Ridge	UT	39.42	-111.07	2805	PILO	Graybill
MAM519	Mammoth Creek	UT	37.65	-112.67	2590	PILO	Graybill
951000	Dead Juniper Wash	AZ	36.17	-110.50	1920	JUSP	Dean
283590	Wind River Mountains, Site D	WY	43.08	-110.07	2500	PIFL	Harsha, Stockton, Jacoby
ISLSTD	Island Lake Standard	CO	40.03	-105.58	3200	PIFL	Woodhouse
552590	Gros Ventre + Uhl Hill	WY	43.70	-110.52	2179	PIFL	Ferguson, Loope
318599	Uhl Hill	WY	43.80	-110.47	2225	PIFL	Ferguson
316597	Gros Ventre	WY	43.63	-110.50	2179	PIFL	Ferguson, Loope

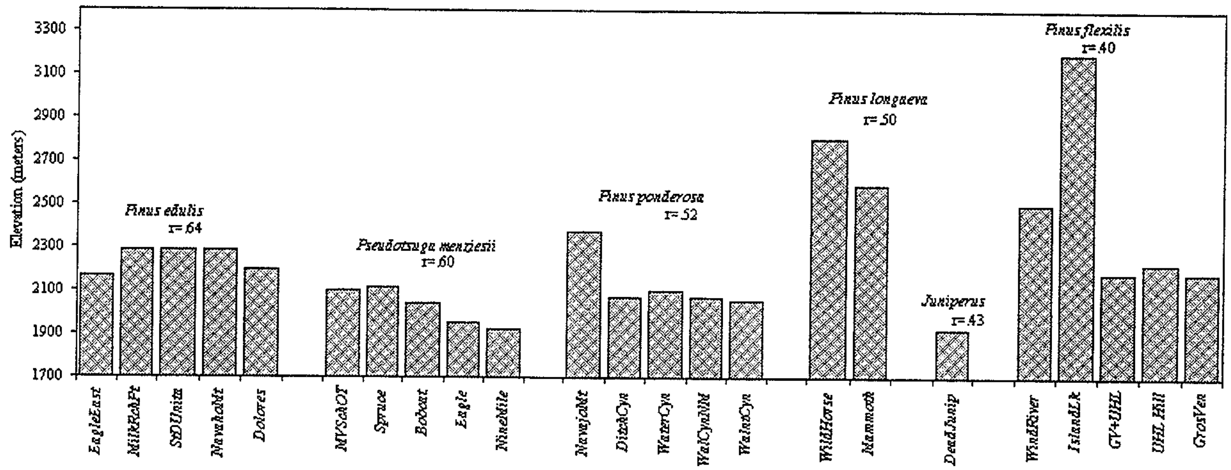

Figure 1 Tree ring chronology site elevations grouped by species in descending order of average correlation with Lee's Ferry streamflow. Average correlation coefficient is also shown.

Heteroskedasticity and Non-linearity

Figure 2 shows partial correlation graphs (at lag 0) between the annual natural flow at Lee's Ferry and standardized tree ring indices for the six selected species. The figure shows more scatter in the upper values, or years of higher growth, of the tree ring width index (heteroskedasticity). This indicates that a suitable transformation or weights may be needed in some cases to guarantee homoskedasticity of the residuals. This increase in scattering is especially evident for *Pinus flexilis* chronologies. This species' lower sensitivity to high precipitation may result in an underestimation of the high flows or the over-representation of mid-flows in streamflow reconstructions.

Additionally, for dry years of extreme low growth, there is evidence that the relationship of streamflow to the tree ring index is non-linear. For *Pseudotsuga menziesii*, *Pinus edulis* and *Pinus ponderosa*, the results suggest a different streamflow/ tree ring relationship when ring width is small due to low soil moisture conditions. As the Colorado River's base flow from ground water reserves and spring contributions is not reflected by ring width in dry years, it may result in an underestimation of low flows during severe drought periods, and an overestimation of flows greater than the base flow.

Species' Response to Different Climate Conditions

Using the historical Lee's Ferry streamflow record from 1896 to 1962, we categorized the years in Figure 3 based on the following percentile limits: the lowest 33% were considered "dry" years (26 years), from 34% to 65% were considered "normal" years (26 years), and above 66% were considered "wet" years (16 years).

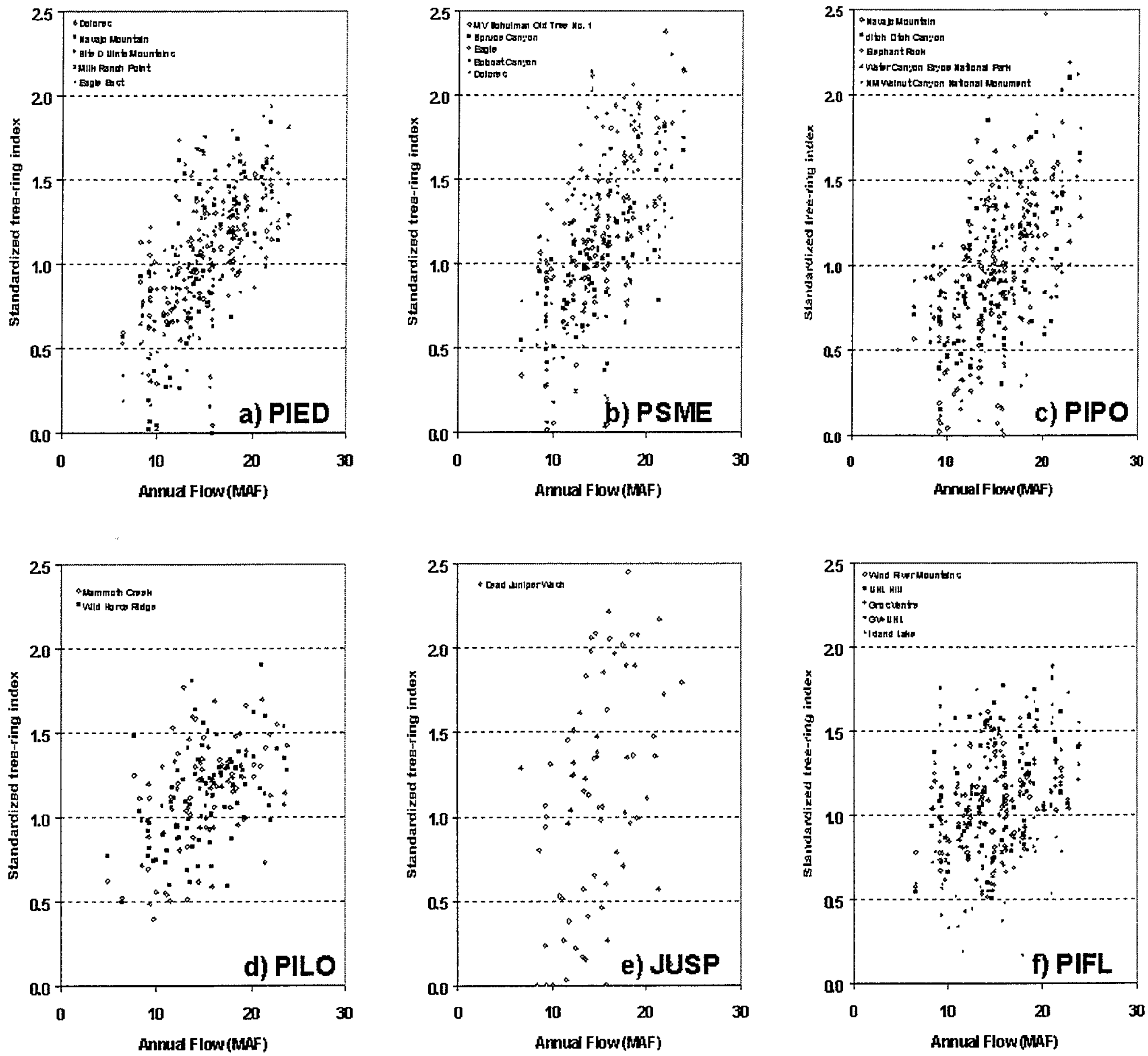

Figure 2 Annual natural flow at Lee's Ferry, Arizona, compared with standardized tree ring width indices for chronologies within the Upper Colorado River Basin for a) *Pinus edulis* **(PIED), b)** *Pseudotsuga menziesii* **(PSME), c)** *Pinus ponderosa* **(PIPO), d)** *Pinus longaeva* **(PILO), e)** *Juniperus* **spp. (JUSP), and f)** *Pinus flexilis* **(PIFL)**

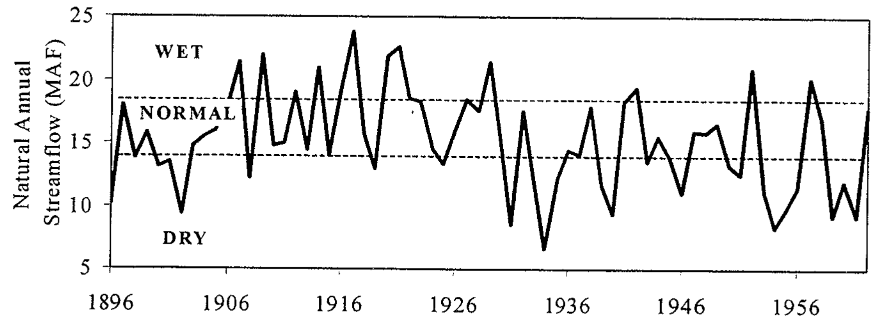

Figure 3 Lee's Ferry streamflow record categorized into wet, normal, and dry years based on percentile limits. Wet years are 66% and above of normal streamflow, normal years are between 34% and 65% of normal streamflow, and dry years are 33% and below of normal streamflow.

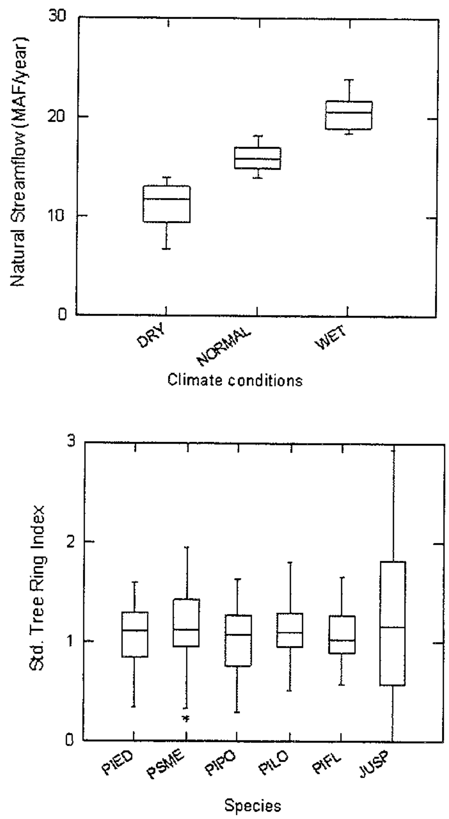

Figure 4 Box plots summarizing the distribution of data for streamflow and tree ring width indices by species. The middle lines of the boxes are the species index medians, the bottom of the boxes is the 25% value, and the top of the boxes is the 75% value. The height of the box is the H spread, equal to the interquartile range. Lines extending above and below the boxes include values within one step, or H spread, away from the boxes. Values outside one and within two steps away from boxes are marked with an asterisk (*).

In Figure 4, boxplots for streamflow and for each species used in our study summarize the distribution of the data. Boxplots for PILO and PIFL species show lower variability. Compared to the other four species used, the JUSP species showed very high variability, but this may be because it is represented by only one chronology.

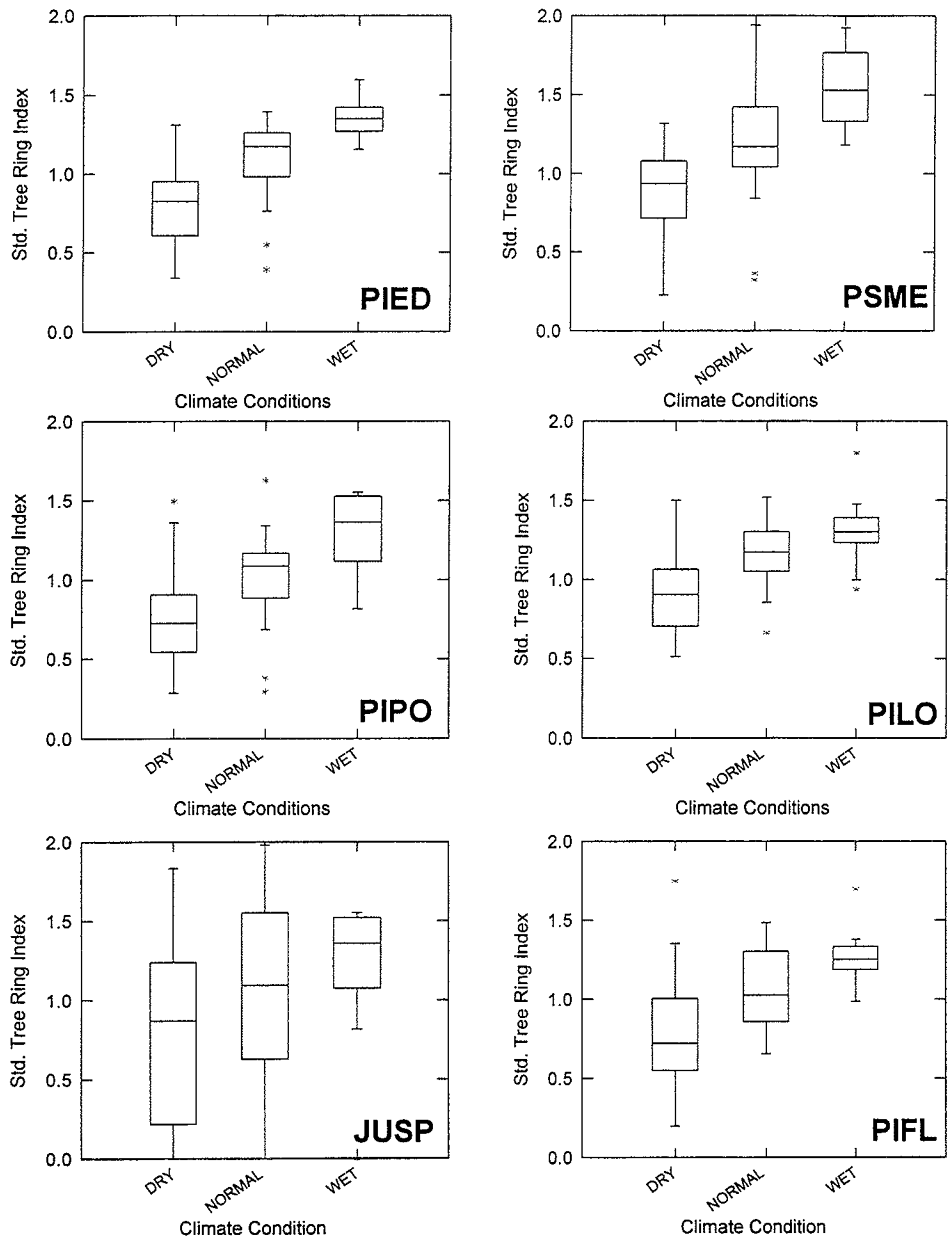

Figure 5 Probability distributions for tree species for dry, normal, and wet conditions as described in Figure 3. Box plot data is distributed as described in Figure 4.

Figure 5 shows the shifts in probability distributions for each tree species for the conditions defined in Figure 3 as dry, normal, and wet. With the exception of PSME and PIPO, the species exhibit more variability for dry conditions than for normal conditions, and more variability for normal than for wet, consistent with the discussion of the previous section. Except for PSME, the difference between the median for normal and the median for wet conditions tends to be smaller than the difference between the median for normal and the median for dry conditions. These suggest a non-linear relationship between streamflow and tree ring index, also consistent with the previous section results.

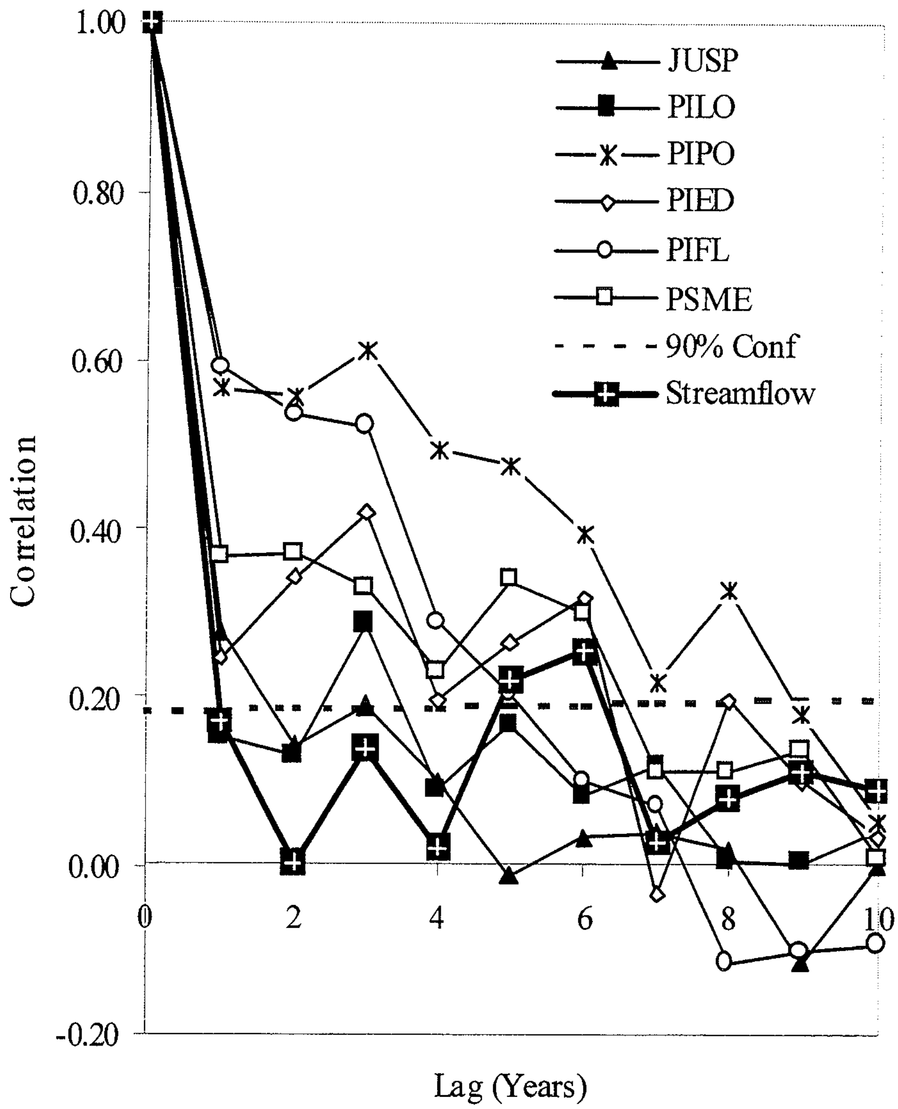

Figure 6 Auto correlation coefficients, computed for ten lags, plotted from average site indices by species and streamflow

Autocorrelation Structure

Figure 6 shows the autocorrelation coefficient, computed for the first ten lags. For most of the species the lag+3 autocorrelation coefficient is higher than the lag+1 and lag+2 coefficients. This lag+3 coefficient is probably amplified by a slight increase in the forcing (streamflow) for lag+3 compared to lag+2. This suggests the utility of inclusion of the lag+3 series for reconstruction model building. After lag+3, the autocorrelation coefficients remain significant for some of the species up to lag+6, again amplified by a five- to six-year periodicity in the climate forcing signal, probably linked to El Niño Southern Oscillation (ENSO).

Future Work

A previous work on the basin (Hidalgo and others, this volume) identified PSME and PIED as the species that produced models with the lowest cross validation standard error (CVSE) estimates. Moreover, species' type was found to be the only parameter that suggested some insight for selection of chronologies based solely on the CVSE as selection criteria.

PSME and PIED are more suitable than PIFL because of the higher heteroskedasticity of the latter species, which is consistent with what we found in this study. For some species, the inclusion of lag+3 in the CVSE models, as mentioned in the previous section, may reveal an increased potential as a climatic indicator.

A more complete study is needed that includes the suitability of incorporating nonlinear effects into reconstruction models, as well as the effects of transformation and filtering of the data in the accuracy of the reconstruction estimations.

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Southwest Climate and the Quasi-Biennial Oscillation, the El Niño-Southern Oscillation, the Arctic Oscillation and Tidal Resonance

Thor Karlstrom

Abstract

Southwest instrumental and tree ring precipitation records are analyzed to further test regional responses to atmospheric circulation systems: the Quasi-Biennial Stratigraphic oscillation (QBO), the El Niño-Southern Oscillation (ENSO), the Arctic Oscillation (AO) and modulating Tidal Resonance (TR). Winter precipitation from Pacific sources dominate the climate of the west part of the Southwest; summer precipitation primarily from the Gulf of Mexico dominates that of the eastern sector. Half-cycle analyses of additional tree ring records from the US, Mexico, and South America continue to reveal differing response functions to harmonic elements of the TR model. Some phase with the 278–year Subphase cycle or to higher frequency components of the model. The QBO, SO, and Southwest precipitation phase most strongly with the 120/1 (2.3–year) resonance, but show little correlation with the AO and El Niño years. High resolution records of culture from the US, Southwest, Egypt, and Iceland appear to directly reflect changes in climate and the physical environment. Correlations of the Iceland and other paleoclimatic records with Resonance and Sunspots strengthen the empirical basis for linking climatic change to tidal and solar activity.

Introduction

Southwest instrumental precipitation records and more widely spaced tree ring-precipitation records are analyzed to further test regional responses to atmospheric circulation systems, including the Quasi-Biennial Stratospheric Oscillation (QBO), the El Niño-Southern Oscillation (ENSO), the Arctic Oscillation (AO) and modulating Tidal Resonance (TR).

Analytical procedures used in this and previous papers emphasize half-cycle smoothing with temporal placements on theoretical cycle turning points to test for their presence. It is assumed that because of variable amounts of non-climatic noise in most climate time series, 70% or more matching of trends represent significant coefficients of correlation for those cycles identified within parentheses by wavelength in years, such as R = 0.83 (278). As a first approximation it is further assumed that cycle turning points, as defined by sinusoidal trends, are positioned on maximum and minimum values (respectively crests and troughs).

Regional Distribution of Southwest Precipitation, Seasons and Primary Sources

Winter precipitation from Pacific sources dominate the climate of the western sector of the Southwest. Summer precipitation primarily from Gulf of Mexico sources dominate that of the eastern sector. Precipitation generally increases and temperature decreases with increasing elevations ranging regionally from sea level to over 14,000 feet. Regional precipitation gradients and elevation relations along S–N, W–E and SW–NE profiles across the central and eastern part of the Southwest are shown in Figures 1, 2, and 3.

Tree Ring Precipitation Records and the TR Climate Model

Half-cycle analyses of additional tree-ring records continue to reveal differing response functions to elements of the TR Climate Model. These differences are evidently dependent on site location in relation to changing regional circulation patterns or to differing physiological sensitivities and signal/noise ratios. Some tree-ring records phase predominantly with the 278–year Subphase Cycle; others predominantly with one or more of the higher frequency sub harmonics including the 2/1 (139–year) Event Cycle, the 4/1 (69.5–year) Subevent Cycle, the 8/1 (34.8–year) Bruckner Cycle, and the 12/1 (23.2–year) Hale Cycle.

Tree-ring records from Arkansas (Figure 5), Texas (Figure 10), Mexico (Figure 11) and South America (Figure 13) phase predominantly with the Subphase Cycle. Others from Colorado (Figure 6), New Mexico (Figure 8), and Mexico (Figure 9) phase predominantly with the Event Cycle. The remainder, one from Utah (Figure 4), one from Colorado (Figure 7) and one from Mexico (Figure 12), show no significant positive correlations with the above elements of the Resonance Climate Model.

For comparison, the original tree-ring evidence for the Event Cycle is shown in Figure 14 and for the Subevent Cycle in Figure 15.

Correlations between the QBO, ENSO, AO, TR, and Southwest Precipitation

Figure 16 shows levels of correlation for QBO, SO, El Niño, and TR. At these higher frequencies, the QBO phases most strongly with the 60/1 (2.3–year) resonance of the Event Cycle. In turn, it correlates more weakly but significantly with the SO. In contrast, the El Niño series correlates poorly with the SO, suggesting factors other than tropical air pressure and ocean temperatures are involved (see discussion in Karlstrom 1996).

Figure 17 shows averaged precipitation for the main watersheds of the Colorado Plateaus along with a regional average. The regional average correlates weakly but apparently significantly with the 60/1 (2.3–year) resonance of the 139–year Event Cycle.

As shown in Figure 18, no significant correlations are evident between the AO, QBO, ENSO and instrumental regional precipitation records. This is consistent with other analyses of Southwest climate and hydrology that also indicate great spatial and event-to-event variability in regional responses to El Niño years that seriously compromise the use of El Niño (and alternating La Niña) recurrence patterns in predicting future trends. In fact the presented data indicate that the Resonance Climate Model may better serve as a predictive basis for estimating future long- and-short term climatic trends in the Southwest.

Culture, Social Process and Climate

A central theme of this 1999 Paclim Workshop is the possible influence of climate on social process and culture. Thus, I add three figures that correlate climate and physical environmental changes with cultural history. Figure 19, based on more than 20 years of multidisciplinary research in the Black Mesa region, correlates precipitation and hydrology reflecting the 139–year Event Cycle with Southwest cultural changes in a semiarid region where moisture is the dominant limiting subsistence factor. Figure 20 correlates the long Egyptian dynastic history with the same event cycle that apparently affected Nile flood levels and therefore the dominant socioeconomic base of this culture. Figure 21 correlates Iceland history with limiting temperature changes inferred from changing shoreline ice conditions. Finally, Figure 22 correlates Iceland's record of temperature with Sunspots (Friis-Christensen and Lassen 1991) and with harmonic elements of the TR Model. Figure 22 includes two other paleoclimatic records (one a marine record, the other a tree ring isotope-temperature record) that also correlate well with the TR Model and Sunspots and which, therefore, substantially contribute to the empirical base for linking solar and tidal activity to climatic change.

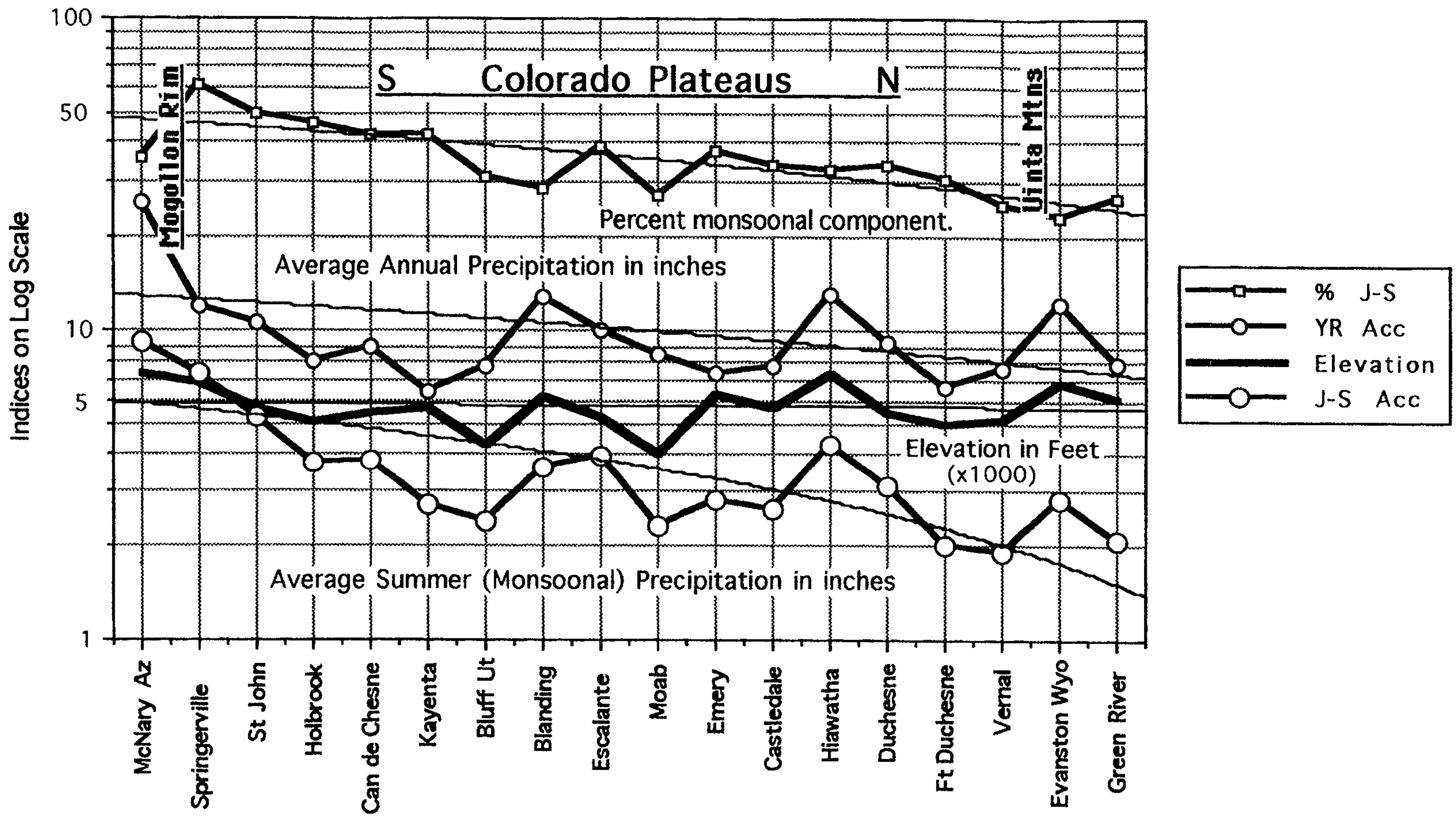

Figure 1 Elevation and precipitation gradients of the Colorado Plateaus along a N-S transect through the indicated meteorological stations. Regional trends by simple regression. Averaged from station data in Richmond (1987). Note that both summer and winter precipitation generally decrease northward but also increase with increased elevation across the plateaus. The regional northward decrease in precipitation evidently results mainly from increasing distance from principal precipitation sources located to the south, particularly the southwest.

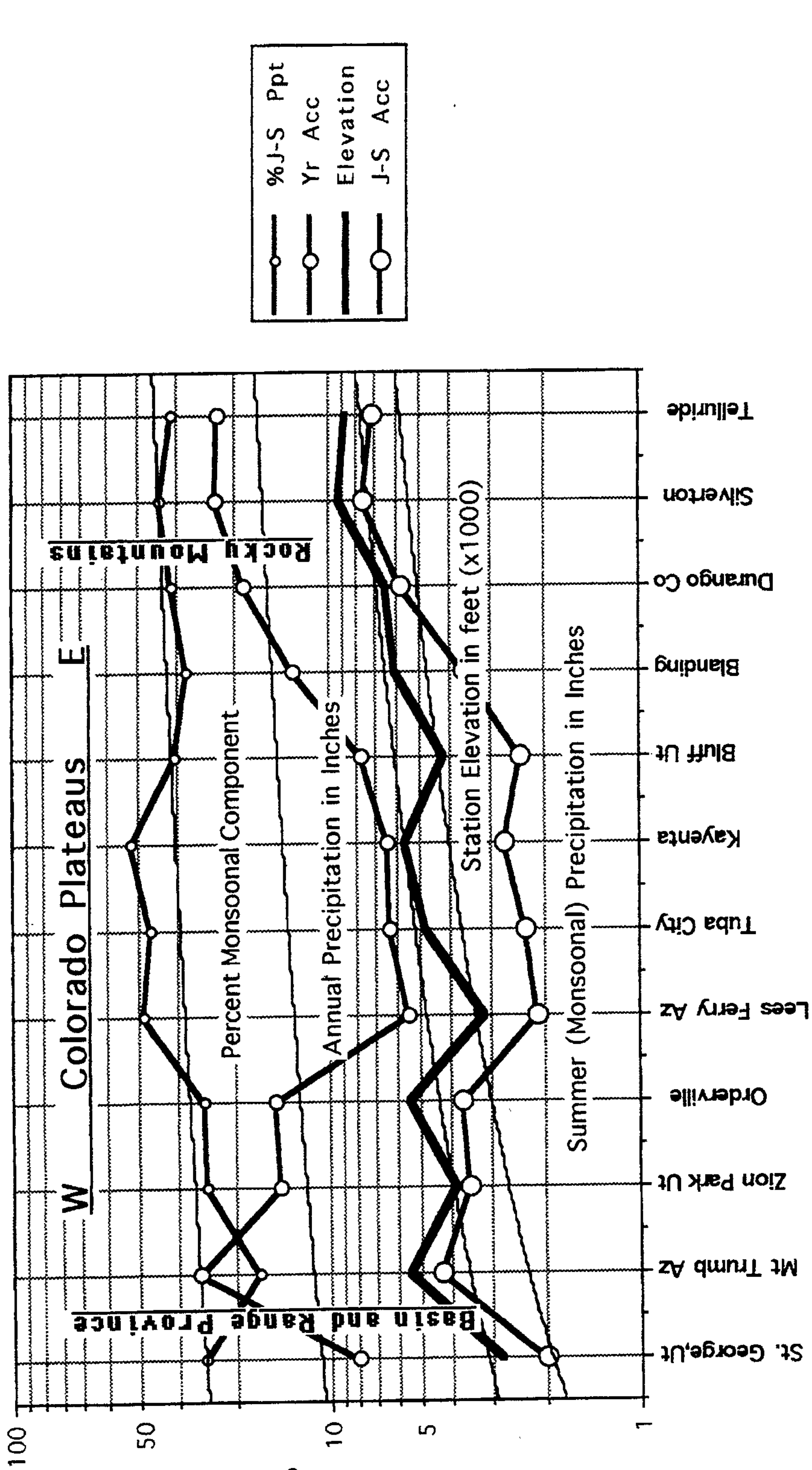

Figure 2 Elevation and precipitation gradients of the Colorado Plateaus along an E-W transect through the indicated meteorological stations. Regional trends by simple regression. Averaged from data in Richmond (1987). Both winter and summer components increase from west to east and with increasing elevation.

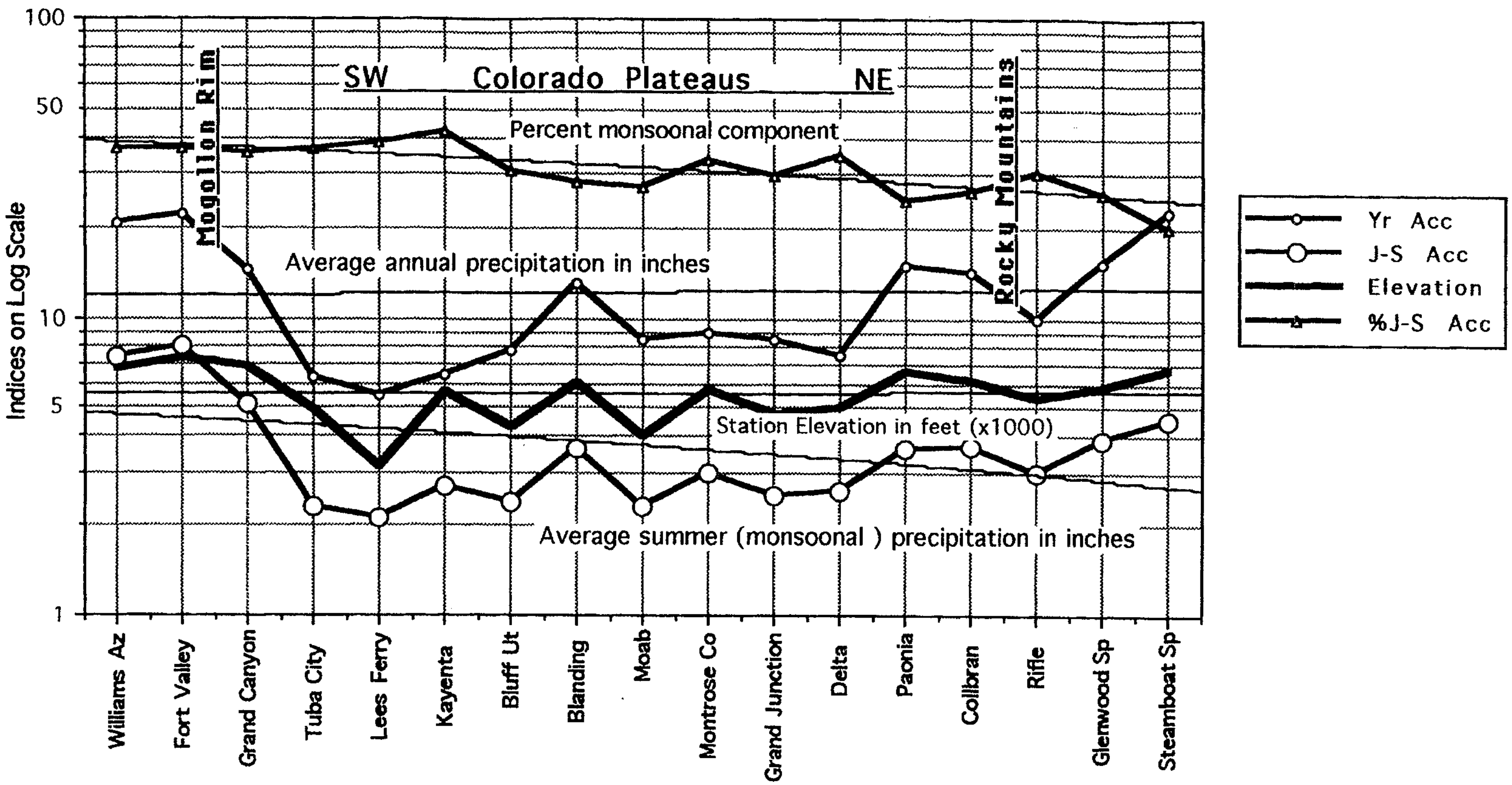

Figure 3 Precipitation and elevation gradients of the Colorado Plateaus along a SW-NE transect through the indicated meteorological stations. Regional trends by simple regression. Averaged from station data in Richmond (1987). Transect along direction of prevailing regional winds and storms from Pacific Ocean precipitation sources. Note general increase toward the northeast in winter rains accompanied by a decreased summer-rain component away from the hotter south. Both winter and summer rains increase with increasing elevation along the transect.

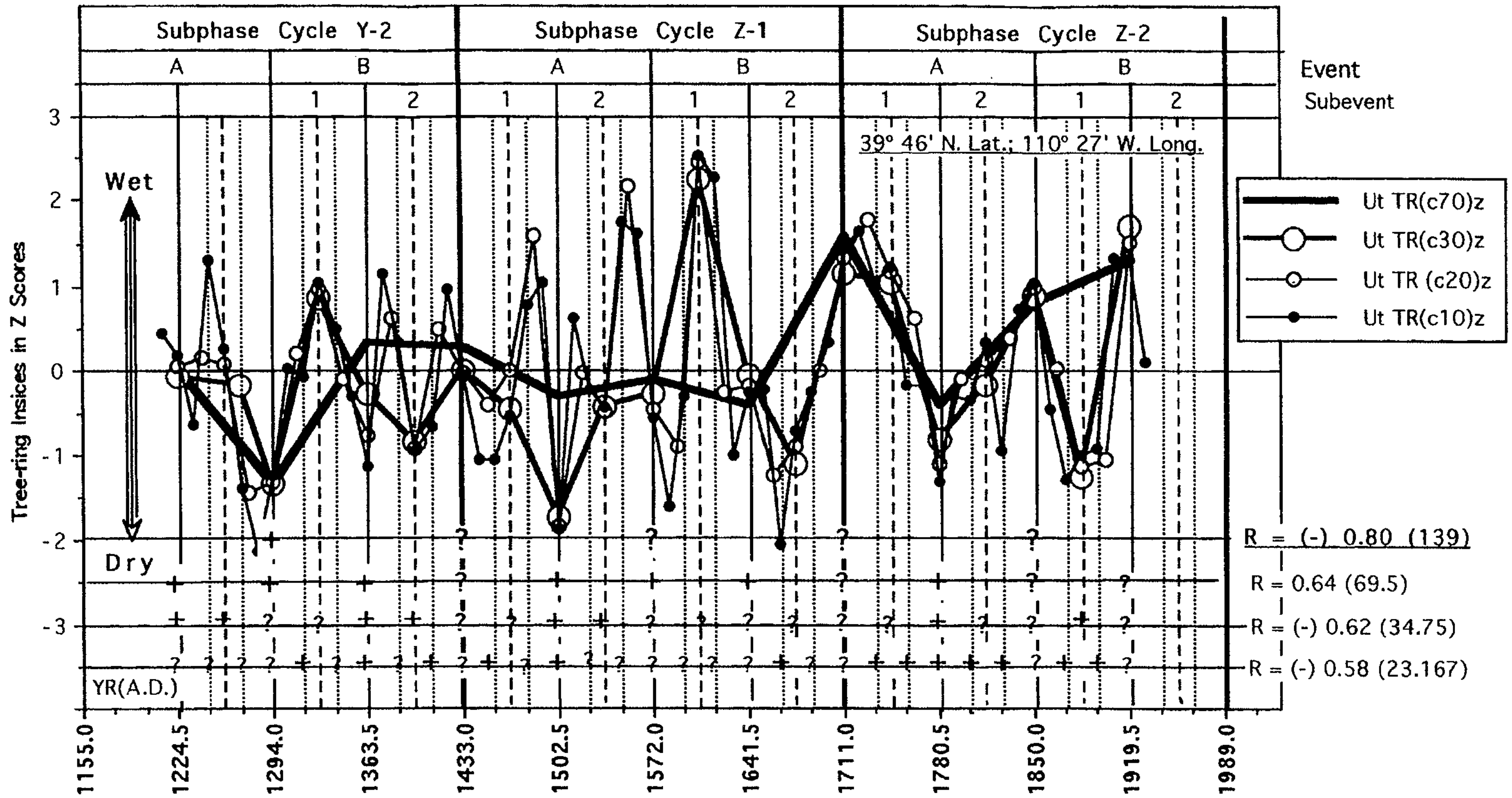

Figure 4 Nine Mile Canyon, Utah, tree ring record on time scale of the 69.5–year Subevent Cycle and its 2/1 (34.75–year) and 3/1 (23.167–year) resonances. Douglas fir indices from Table 1 in Fritts (1967). Note the strong negative phasing with the Event Cycle after 1433 and the generally poorer correlations (positive as well as negative tendencies) with the analyzed higher frequency components.

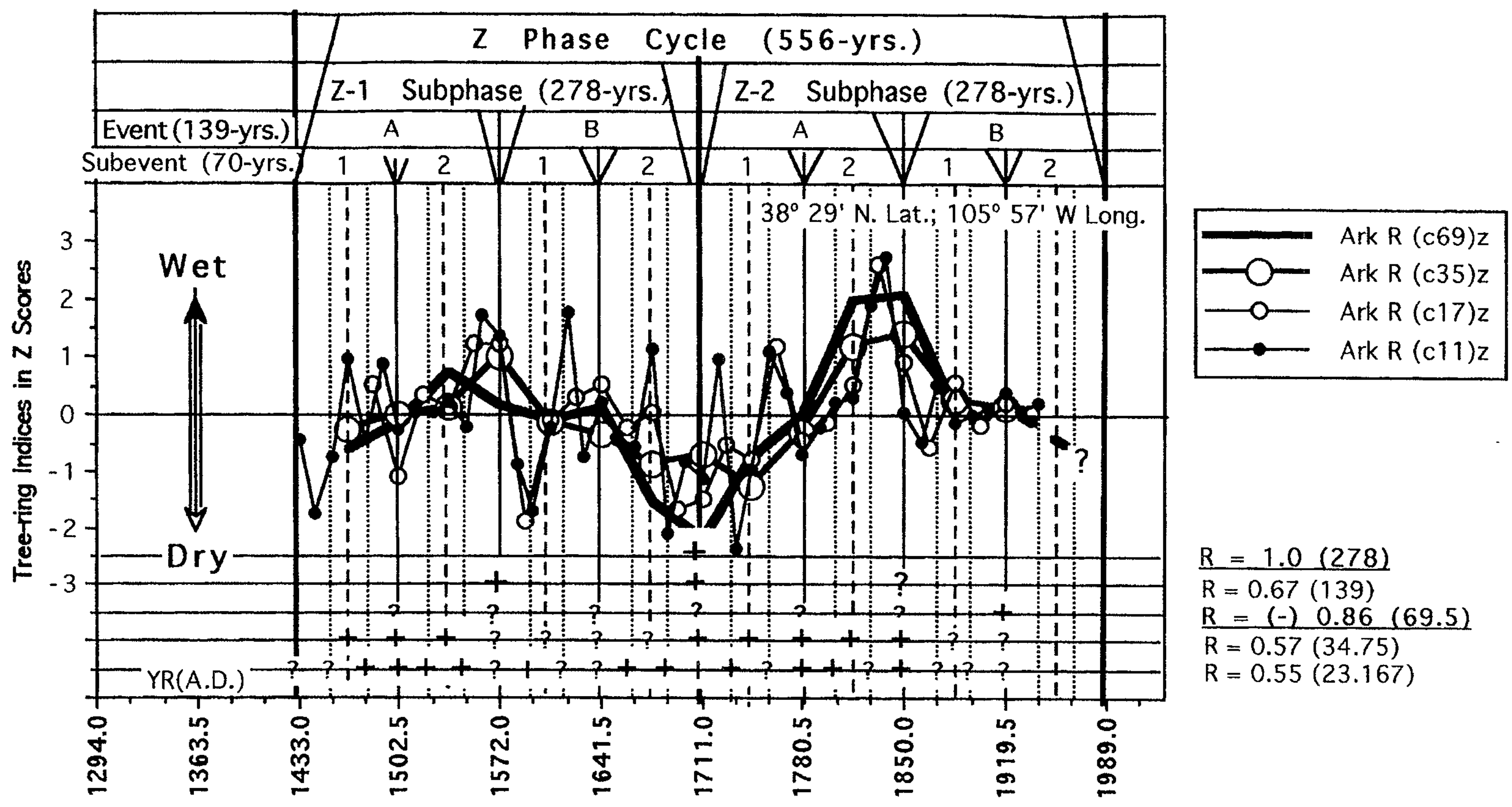

Figure 5 Arkansas River tree ring record on time scale of the 65.9–year Subevent Cycle and its 2/1 and 3/1 resonances. Douglas fir indices from Table 45 in Schulman (1956). The record is dominantly in phase with the 278–year Subphase Cycle but also shows a strong tendency to phase negatively with the ca. 70–year Subevent Cycle.

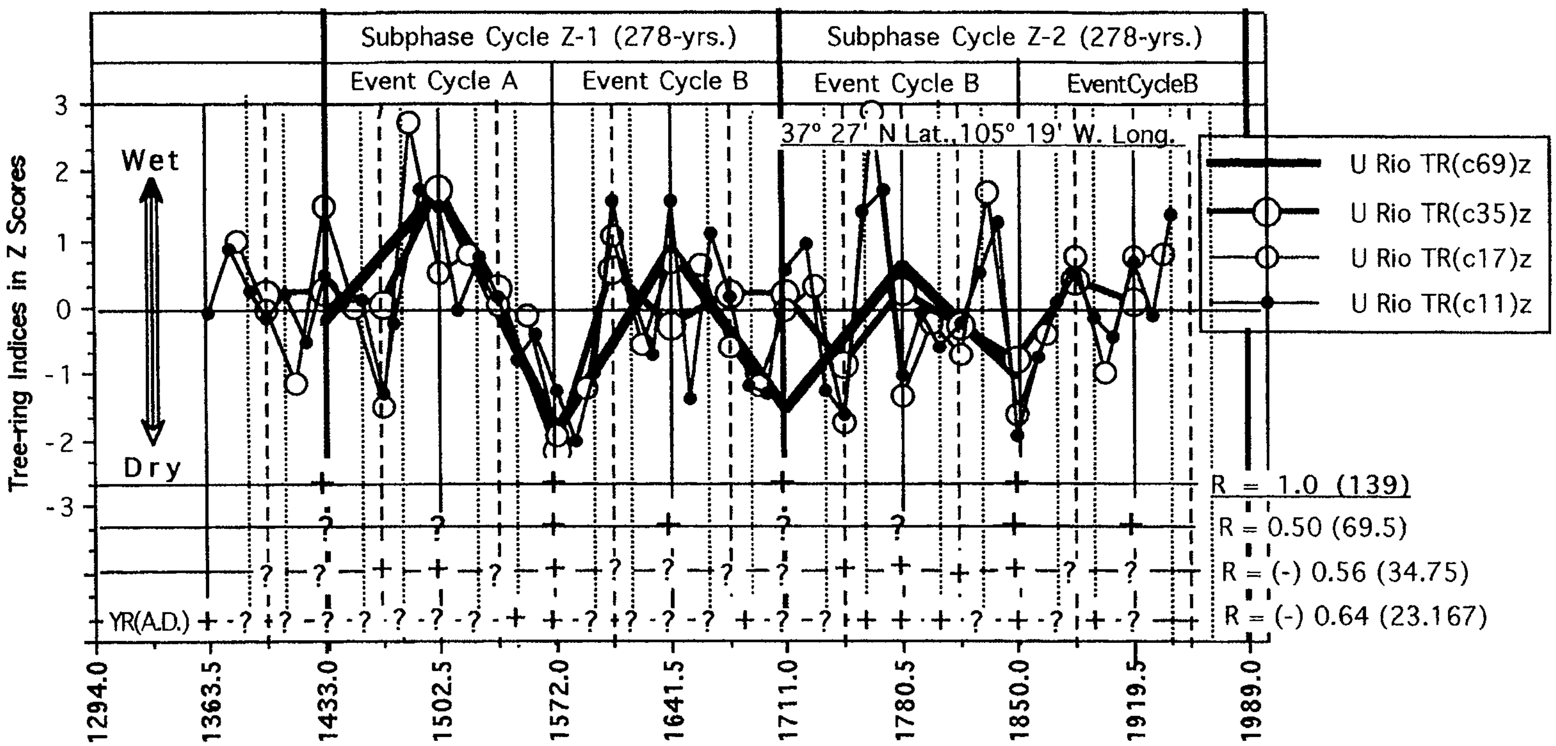

Figure 6 Upper Rio Grande tree ring record on time scale of the ca. 70-year Subevent cycle and its 2/1 (ca. 35-year) and 3/1 (ca. 23-year) resonances. Note the strong correlation with the Event Cycle, or similar to the robust pattern of cyclical atmospheric changes over much of the western part of the Southwest (see also Figure 11).

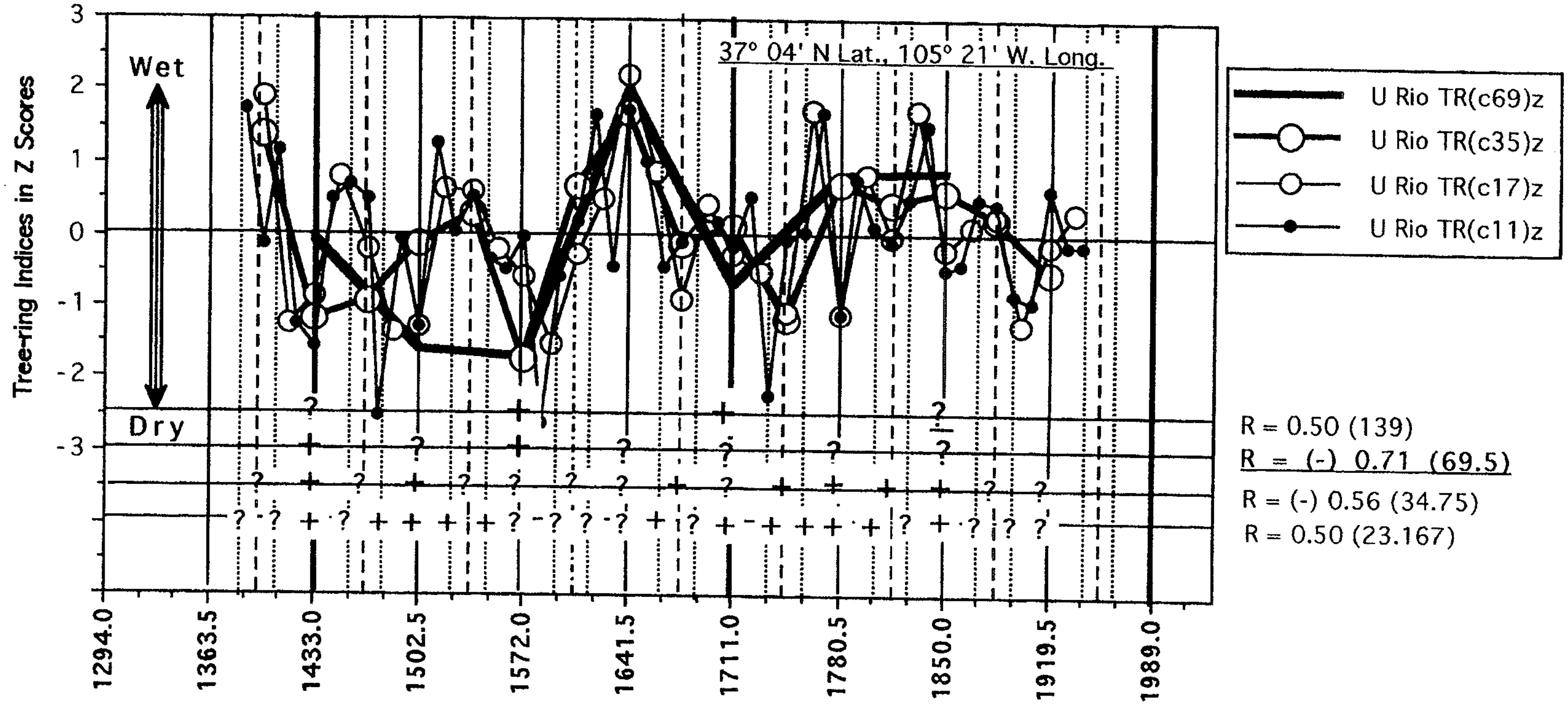

Figure 7 Upper Rio Grande tree ring record on time scale of the ca. 70-year Subevent Cycle and its 2/1 (ca. 35-year) and 3/1 (ca. 23-year) resonances. Douglas fir indices from Table 70 in Schulman (1967). Note generally poor or negative correlations with the Resonance Model, in striking contrast to the nearby Pinyon Pine record in Figure 3 that phases strongly with the Event Cycle.

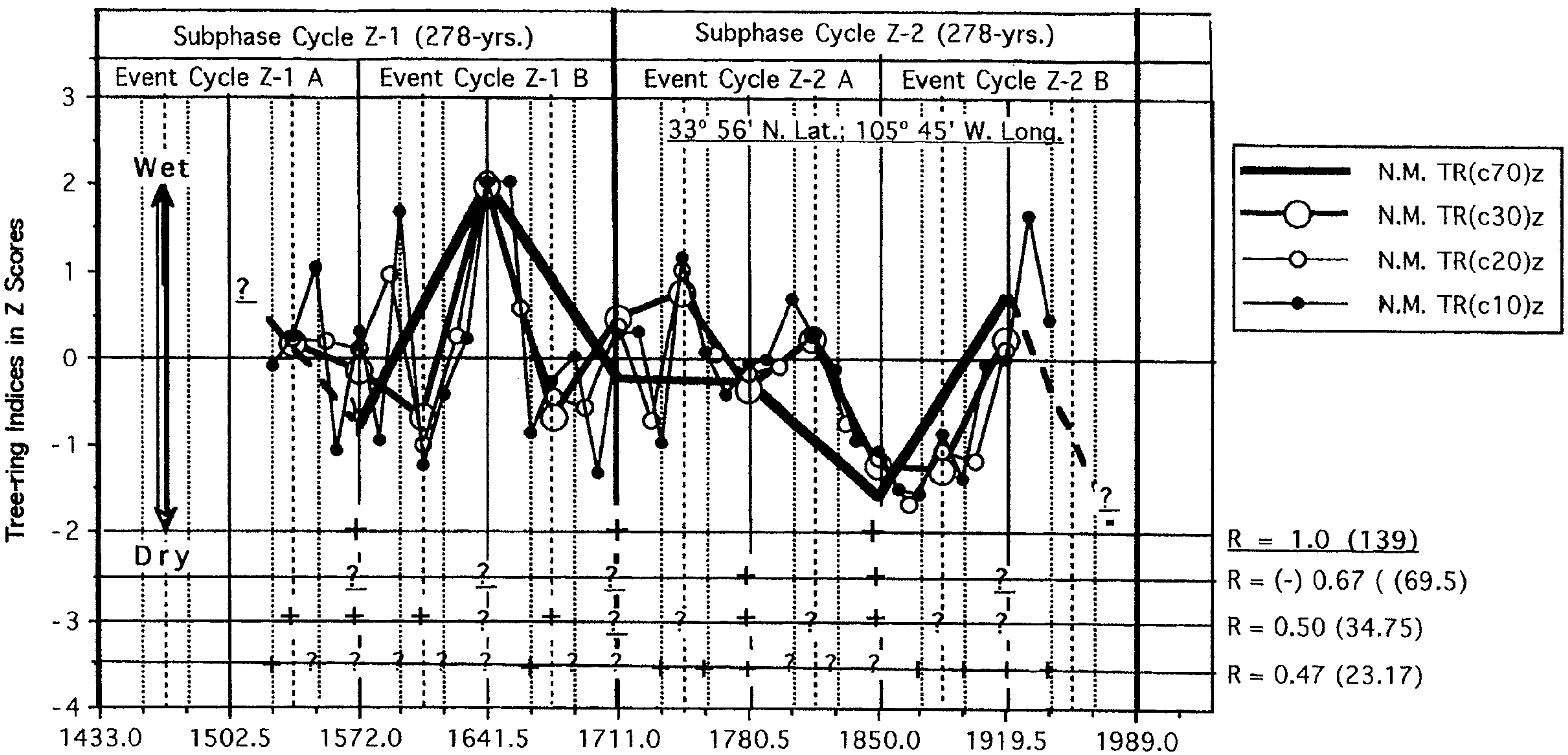

Figure 8 Cloudcroft, New Mexico, tree ring record on time scale of the 69.5-year Subevent Cycle and its 2/1 (ca. 35-year) and 3/1 (ca. 23-year) resonances. Douglas fir decadal indices from Table 2 in Fritts (1967). Note strong phasing with the 139-year Event Cycle, but poor or insignificant correlations with the analyzed higher frequency components. Main phase reversals of the analyzed higher frequency components occur near 1711 and 1850.

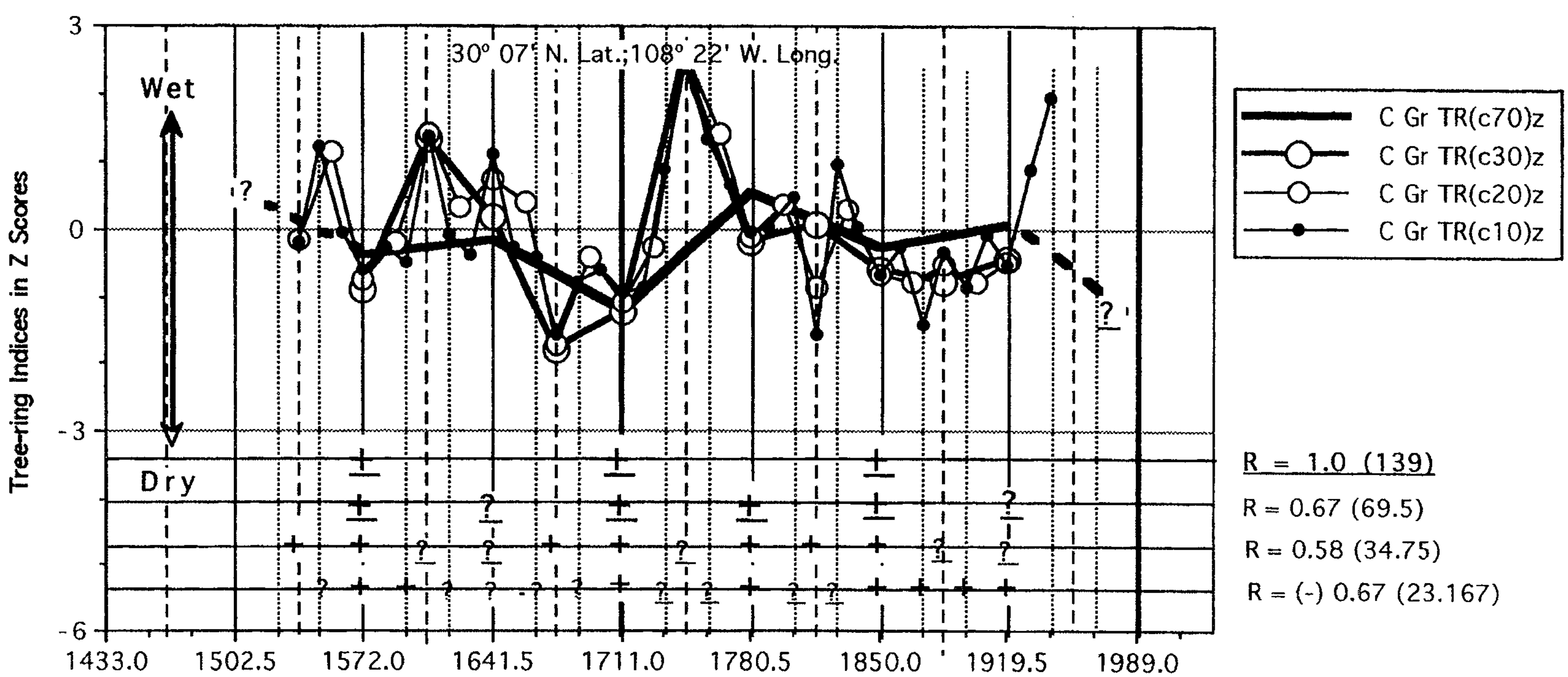

Figure 9 Casa Grande, Mexico, tree ring record on time scale of the 69.5-year Subevent Cycle and its 2/1 (34.75-year and 3/1 (23.167-year) resonances. Decadal indices from Table 2 in Fritts (1967). Note strong tendency to phase with the 139-year Event Cycle but with only short cycle runs of the higher frequency components. Main phase reversals occur near 1572, 1641, 1711, 1780, and 1850.

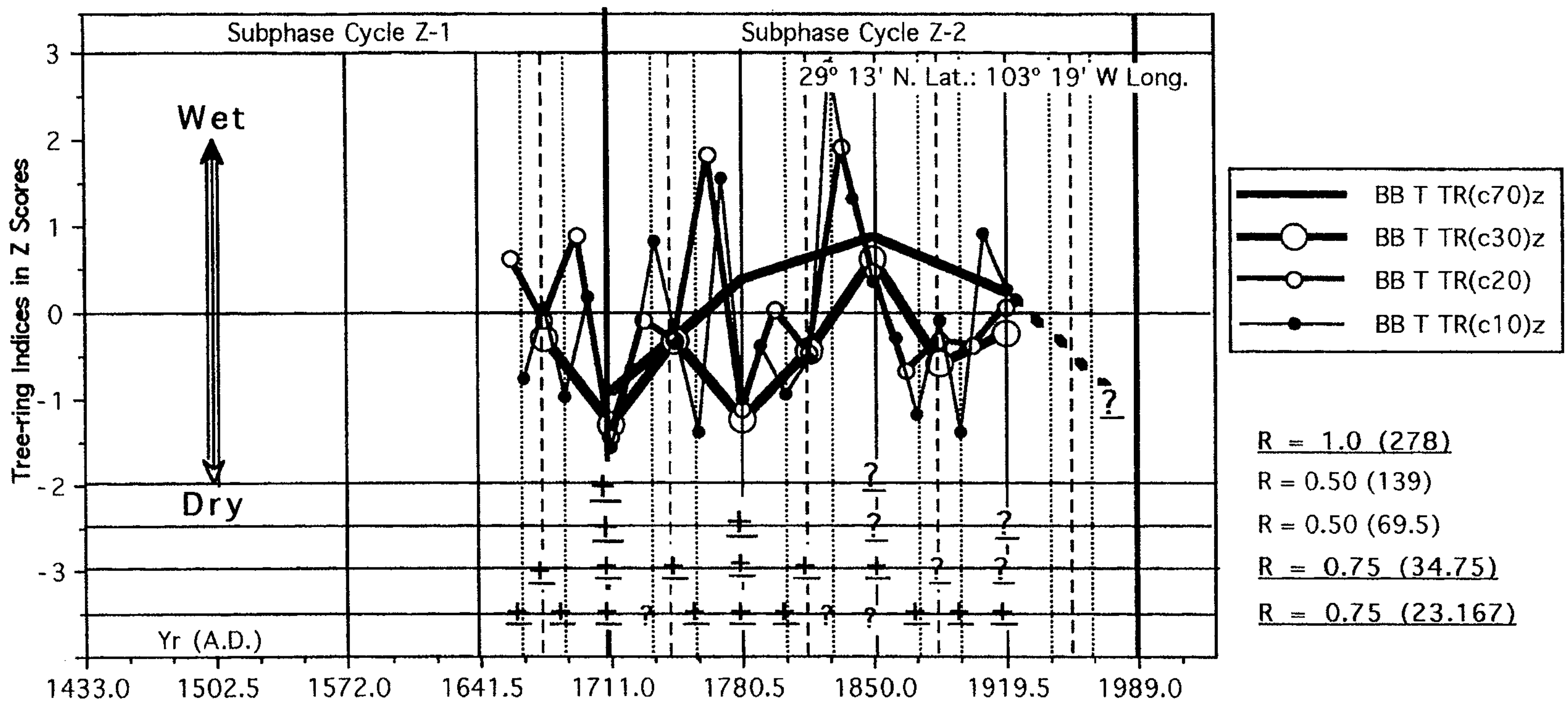

Figure 10 Big Bend, Texas, tree ring record on time scale of the 69.5 Subevent Cycle and its 2/1 and 3/1 resonances. Decadal indices from Table 2 in Fritts (1967). This record is similar to the Arkansas River record in that it predominantly phases with the 278-year Subphase Cycle. It also shows weak but significant tendencies to phase with the ca. 35-year Bruckner Cycle and the ca. 23-year Hale Cycle.

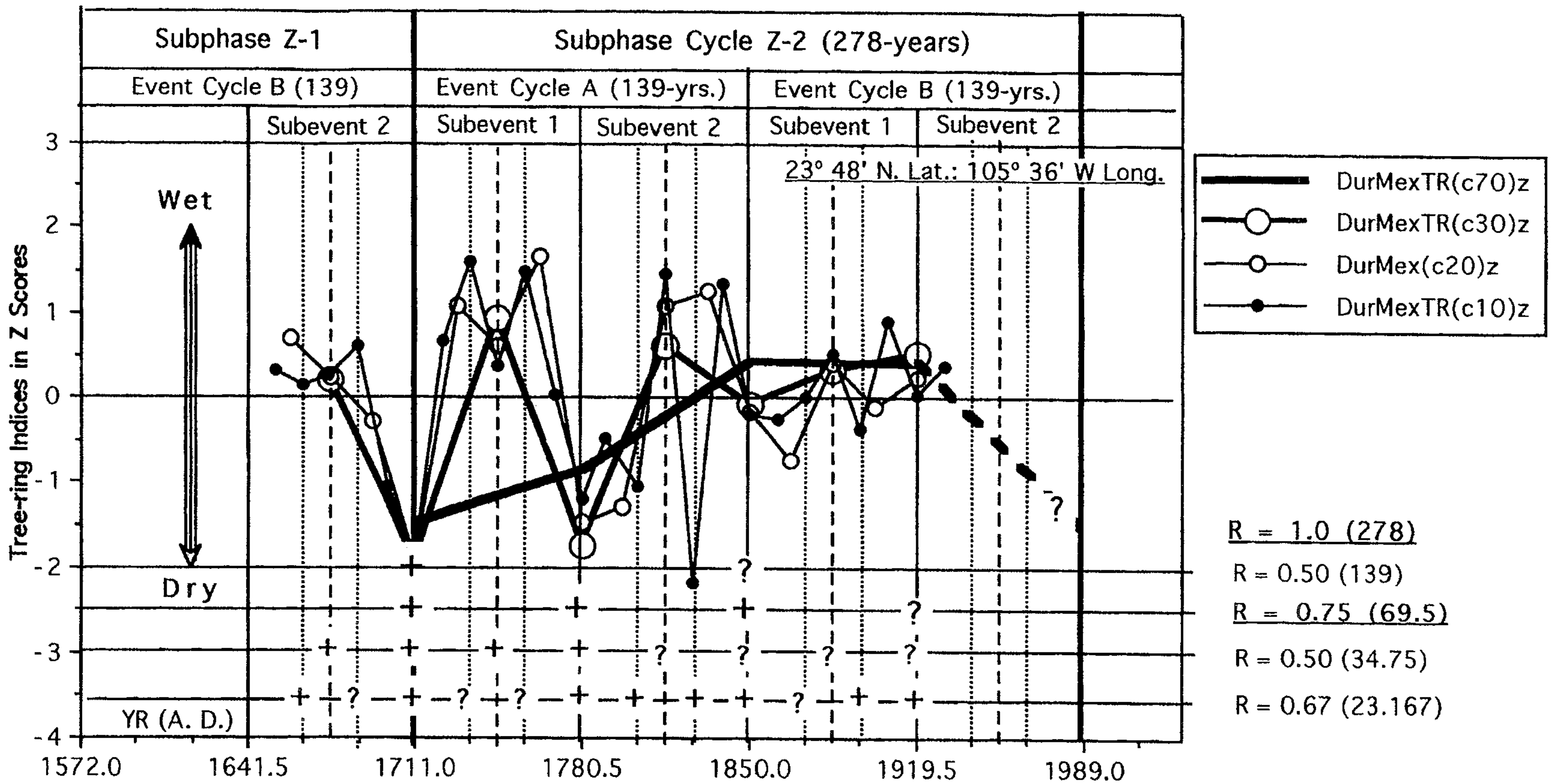

Figure 11 Durango, Mexico, tree ring record on time scale of the ca. 70-year Subevent Cycle and its 2/1 (ca. 35-year) and 3/1 (ca. 23-year) resonances. Douglas fir decadal tree ring indices from Table 2 in Fritts (1967). Record appears to phase predominantly with the 278-year Subphase Cycle, but also shows a fairly strong tendency to phase with the ca. 70-year Subevent Cycle. Note also the strong tendency, as in Figure 4, for abrupt sign reversals to take place at the beginning of the AD 1780s, suggesting a shift from doubling to tripling of resonances—a characteristic suggestive of complex systems in transition to chaos.

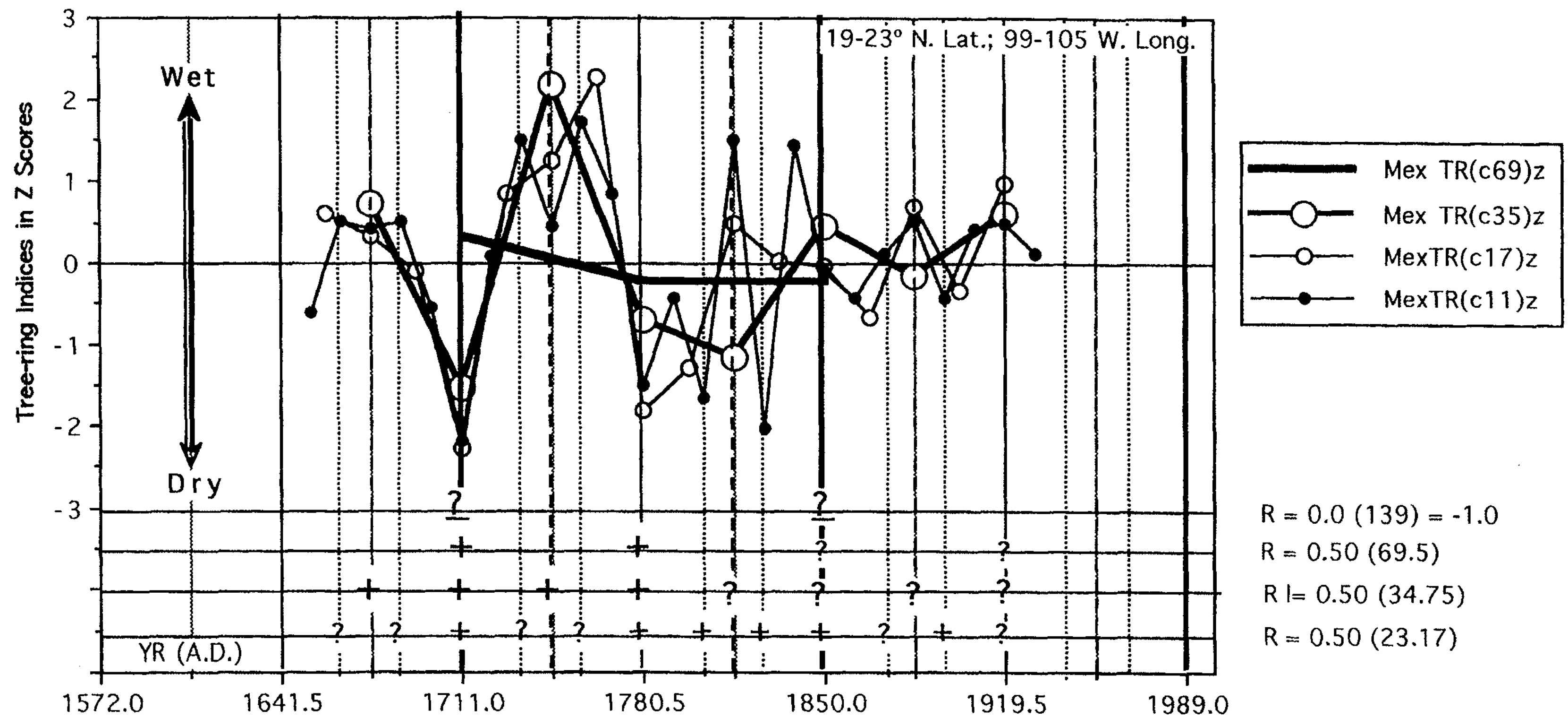

Figure 12 Mexican tree ring record on time scale of the 69.5-year Subevent Cycle and its 2/1 and 3/1 resonances. Douglas fir indices of west central Mexico from Table 81 in Schulman (1956). Poor correlation with all analyzed elements of the Resonance Model. Note, however, the interrupted series of cycle runs and the tendency for abrupt reversals in sign to take place at the larger cycle turning points—a common characteristic of many paleoclimatic records.

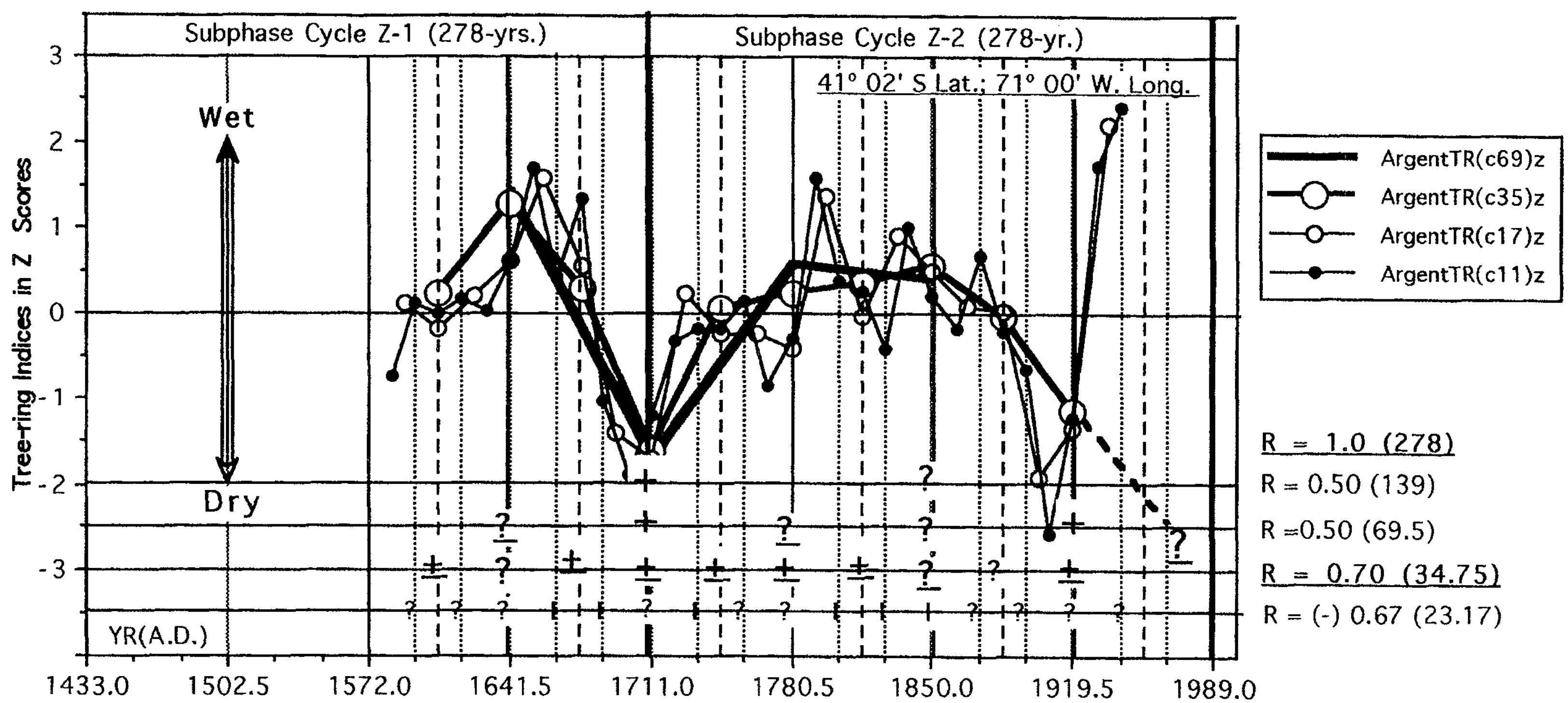

Figure 13 Argentina, South America, tree ring record on time scale of the ca. 70-year Event Cycle and its 2/1 (ca.35-year) and 3/1 (ca. 23-year) resonances. Cypress indices from Table 85 in Schulman (1956). This Southern Hemisphere record evidently phases with the 278-year Subphase Cycle and in part with the ca. 35-year Bruckner Cycle or consistent with the interpretation of interhemispheric synchrony of shorter-term climatic changes. Compare with Figure 10.

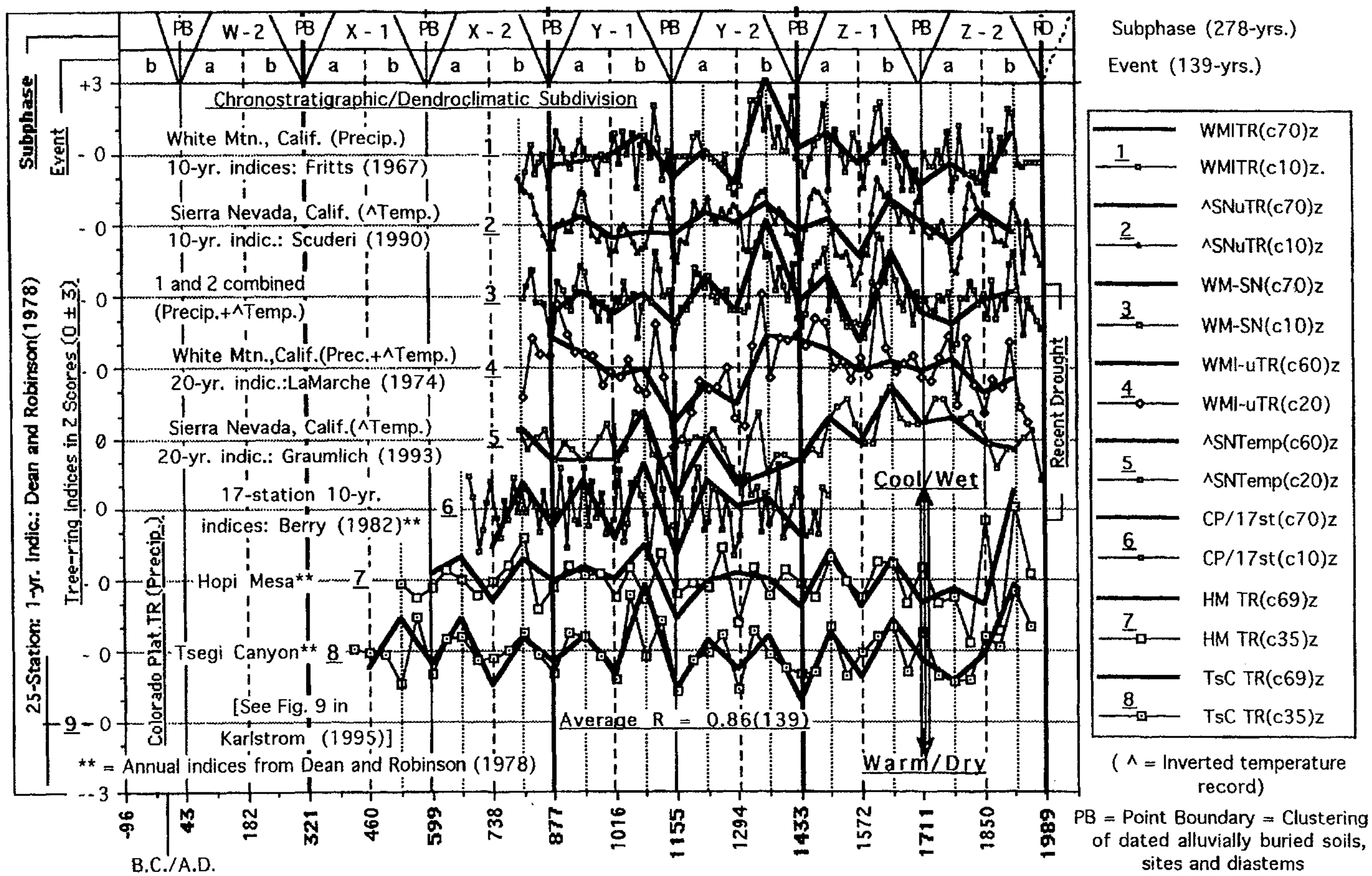

Figure 14 Summary evidence for a dendroclimatic cycle in phase with the 139-year Event Cycle. Trend analyses of both inferred temperature and precipitation records provide correlations ranging from 0.75 to >0.90, or within the correlation range (<0.60 to >90) of published tree ring/climate calibrations. This suggests that the cycle is real, regionally robust and evidently related to changing atmospheric circulation patterns. Similar half-cycle analyses of other high-resolution records may define differing regional patterns and local response functions, providing clues leading to a better understanding of the basic climatic/biologic processes involved (modified from Figure 10 in Karlstrom [1995]). Additional analyses of tree ring records, as provided in the above figures and as discussed (see Figure 12), fortify the expectation of different regional response patterns, however, it remains unclear whether these differences result primarily from atmospheric dynamics or from differing response functions (sensitivities) of the trees.

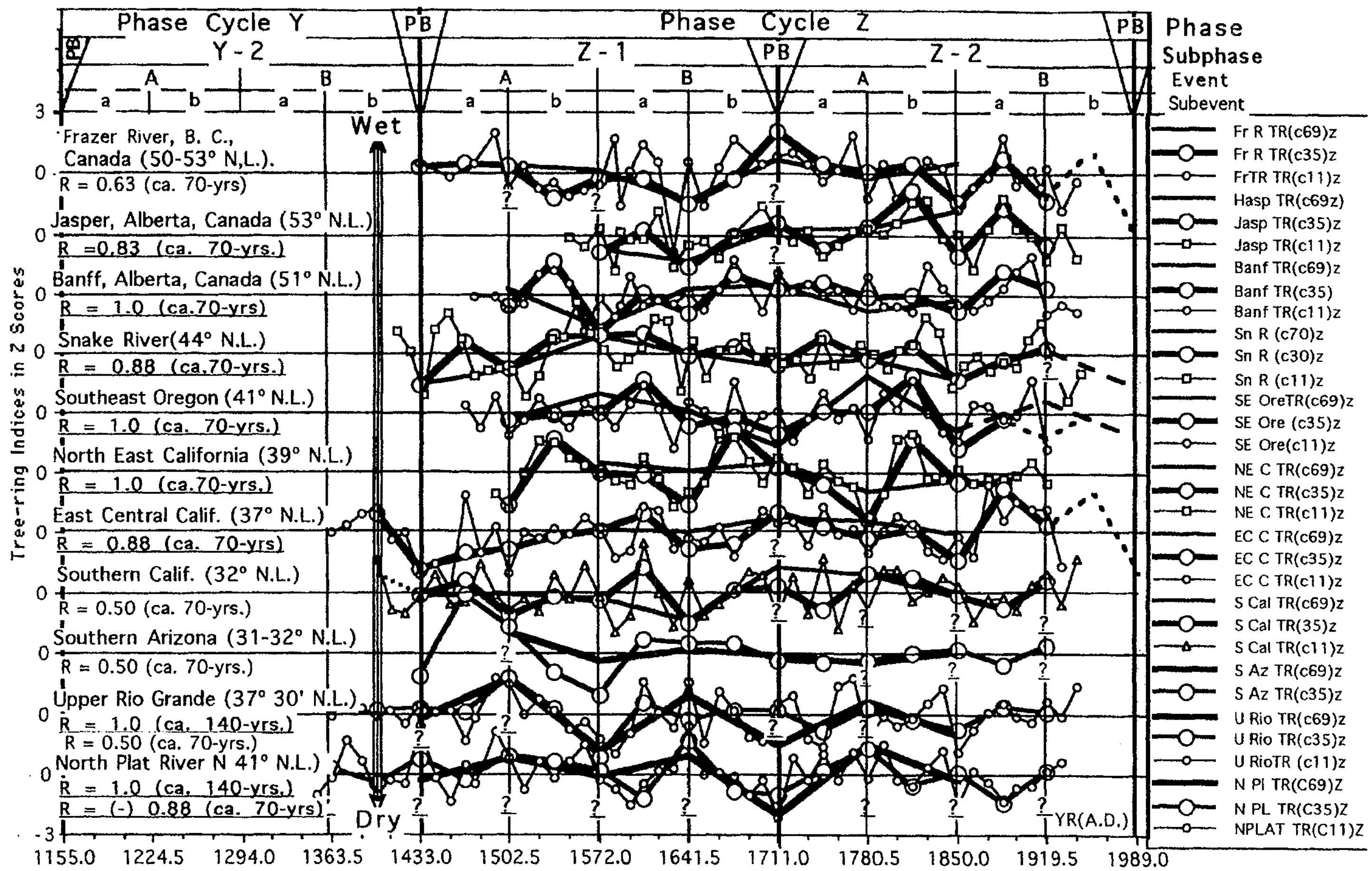

Figure 15 Tree ring records from western North America on time scale of the ca. 70-year Subevent Cycle and its 3/1 (ca. 23-year) resonance. Half-cycle smoothing of annual tree ring indices from Schulman (1956). Note strong tendency for the northernmost records to phase with the ca. 70-year Subevent Cycle, whereas the more southerly and interior records tend to phase with the longer, 139-year Event Cycle. Compare with Figure 11.

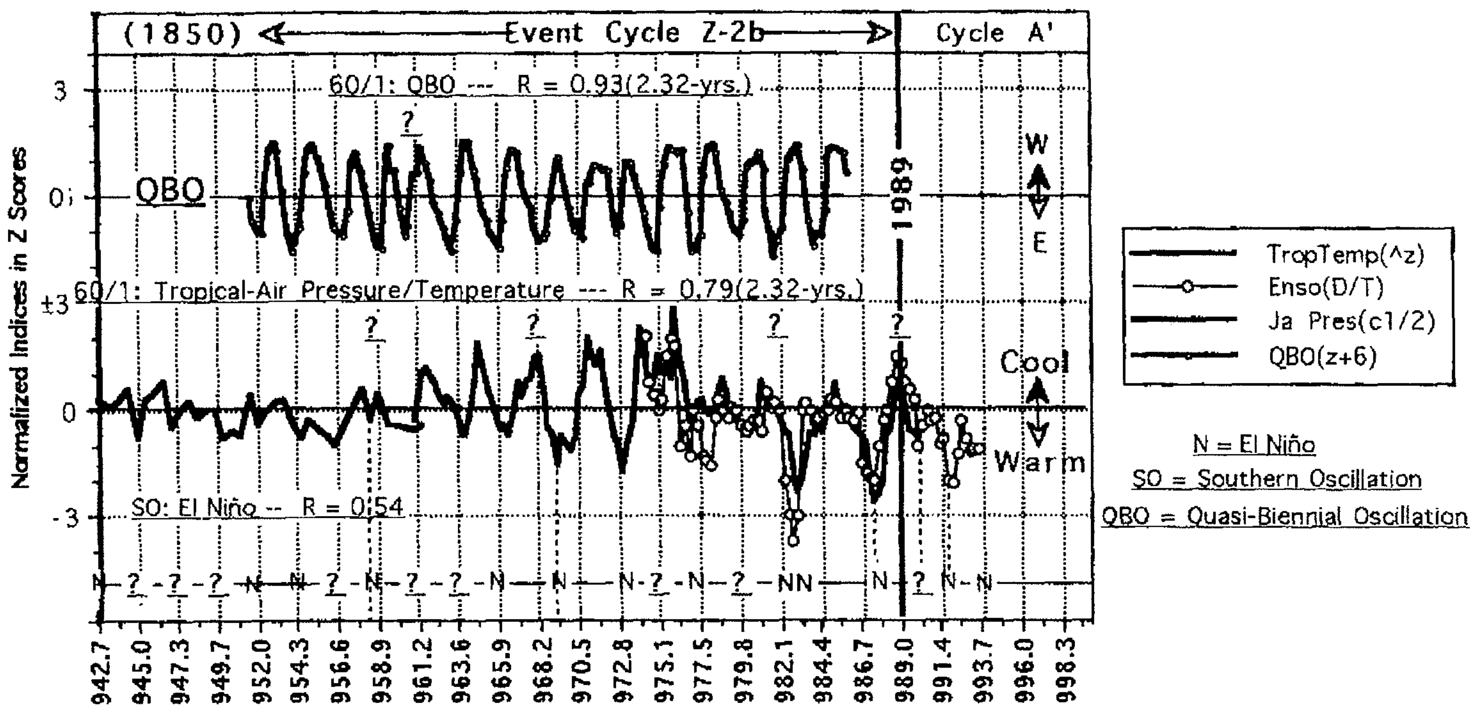

Figure 16 The QBO, tropical air pressure and temperature, and El Niño records on time scale of the 60/1 (2.32-year) resonance of the 139-year Event Cycle. Tropical temperature indices from Burroughs (1992); ENSO indices from Kerr (1993); Jakarta air pressure indices from de Boer (1967); and El Niño dates from Quinn and others (1987). The generally strong correlation of the QBO and SO temperature with the 60/1 resonance strongly suggests resonance modulation of one or both of these stratospheric and tropospheric oscillatory systems. The El Niño-Southern Oscillation correlation is strikingly weaker, suggesting that other critical variables are involved, including possible nonlinear phase reversals near 1961 and 1989 in the QBO and near 1958, 1968, 1982, and 1989 in the air pressure and temperature records, or alternatively, nonlinear response of ENSO to the superposed annual cycle.

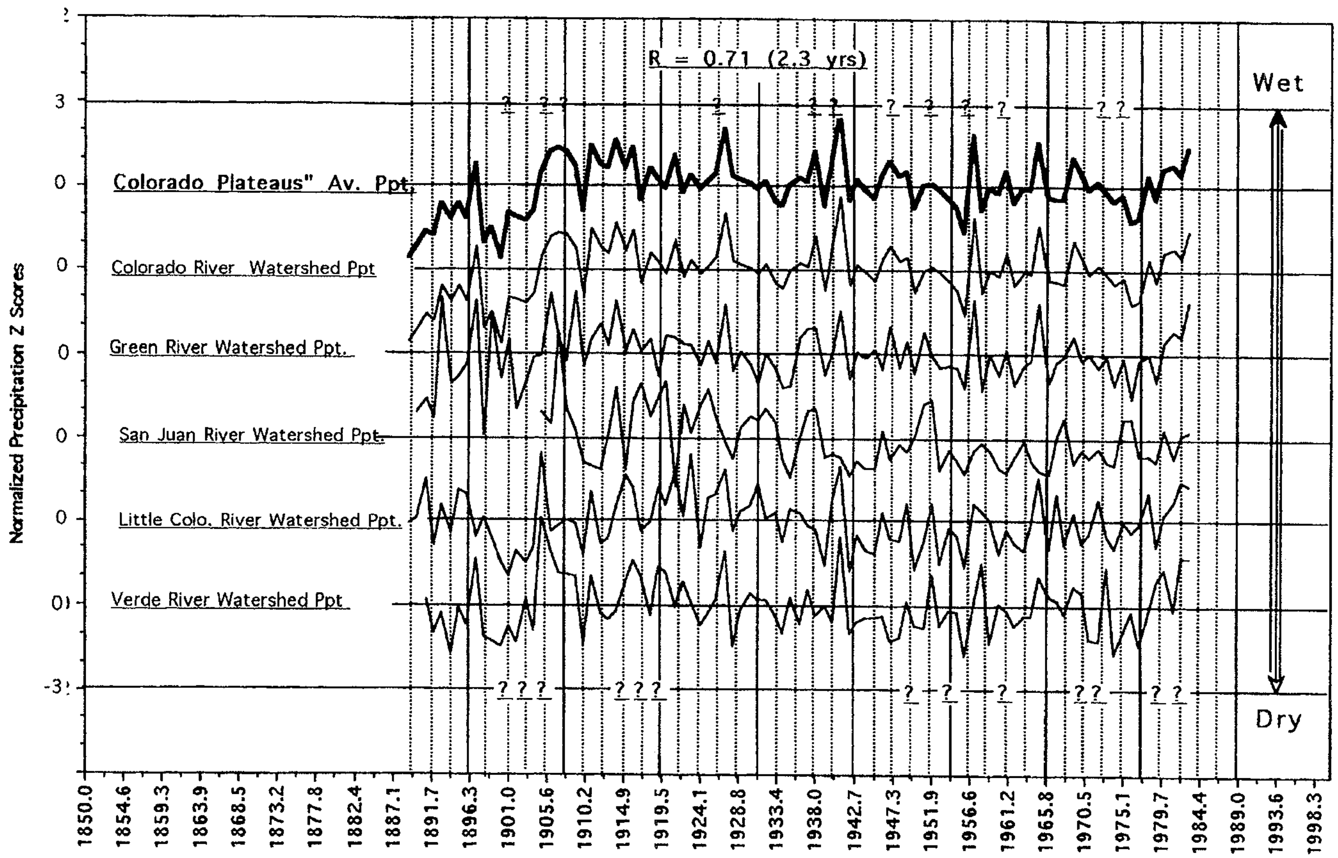

Figure 17 Colorado Plateaus precipitation records on time scale of the 60/1 (2.3-year) resonance of the 139-year Event Cycle. Precipitation indices from Richmond (1987). Note the nearly significant correlation between regionally averaged precipitation and a high frequency of component of the Resonance Model.

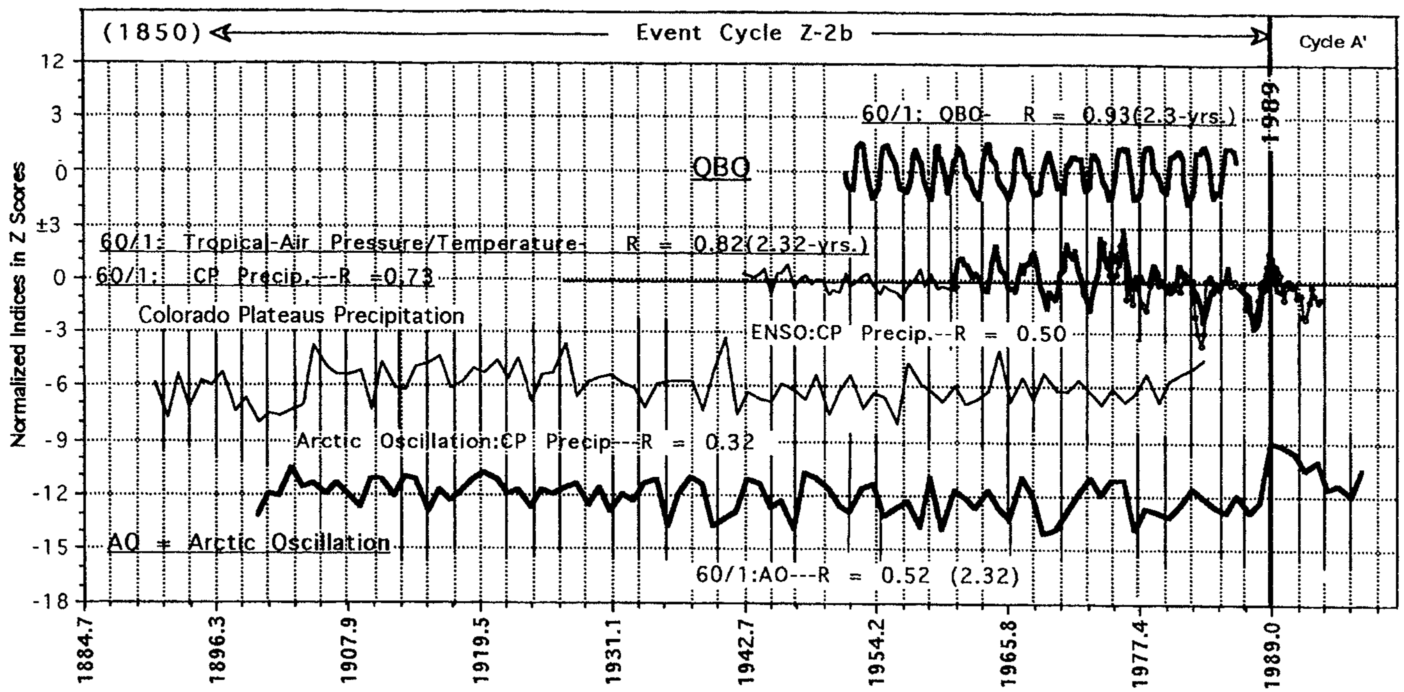

Figure 18 The QBO, tropical air pressure and temperature, Arctic Oscillation and Colorado Plateaus precipitation records on time scale of the 60/1 (2.32) resonance of the 139-year Event Cycle. Tropical temperature indices from Burroughs (1992); ENSO indices from Kerr (1993); jakarta air pressure indices from de Boer (1967); average Colorado Plateaus (CP) precipitation indices from Figure 17; and Arctic Oscillation indices from Kerr (1999). Note that whereas there is fairly good to strong correlations between the 60/1 resonance and the QBO, SO and Colorado Plateaus precipitation, the correlations with the Arctic Oscillation are weak or insignificant. This appears consistent with the evidence of precipitation gradients, indicating primary source areas to the south, as well as the tropical location of the strongest QBO stratospheric winds.

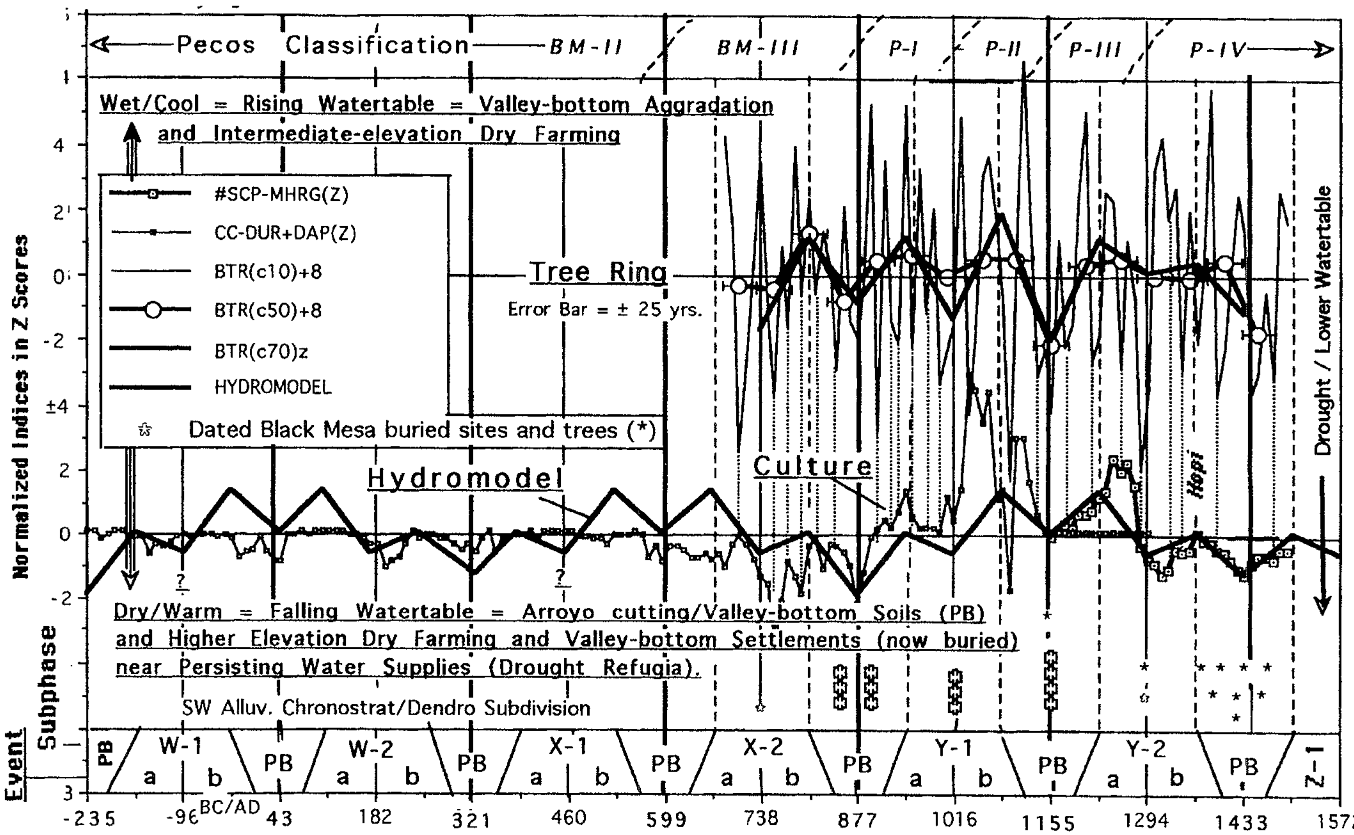

Figure 19 Colorado Plateaus dendroclimate, hydrology, and culture on time scale of the 139-year Event Cycle and its 2/1 resonance. Decadal tree ring indices from Berry (1982), 50-year and half-cycle smoothing. Tree ring and radiocarbon-dated buried archaeological sites and trees and chronostratigraphic and subdivision from Karlstrom (1976a, 1988). PB = clustering of basal-contact dates. Tree-ring-dated surface sites from Euler and others (1979), Berry (1982), and Breternitz and others (1986). Note striking parallelisms between longer-term tree ring trends, inferred hydrology, and number of tree-ring-dated surface sites (rough approximations of population size and regional movements). Modified from Figure 1 in Karlstrom (1997). Culture designations: SCP = S. Colorado Plateaus sites; MHRG = Mogollon Rim sites; CC = Chaco Canyon sites; DUR = Durango sites; and DAP = Dolores Archaeological Project sites. To satisfy the paleoclimatic equation, higher elevation sites as potential drought indicators are subtracted from the intermediate elevation sites (SCP and CC): (+) scores = predominantly intermediate elevation sites and (–) scores = predominantly higher elevation sites.

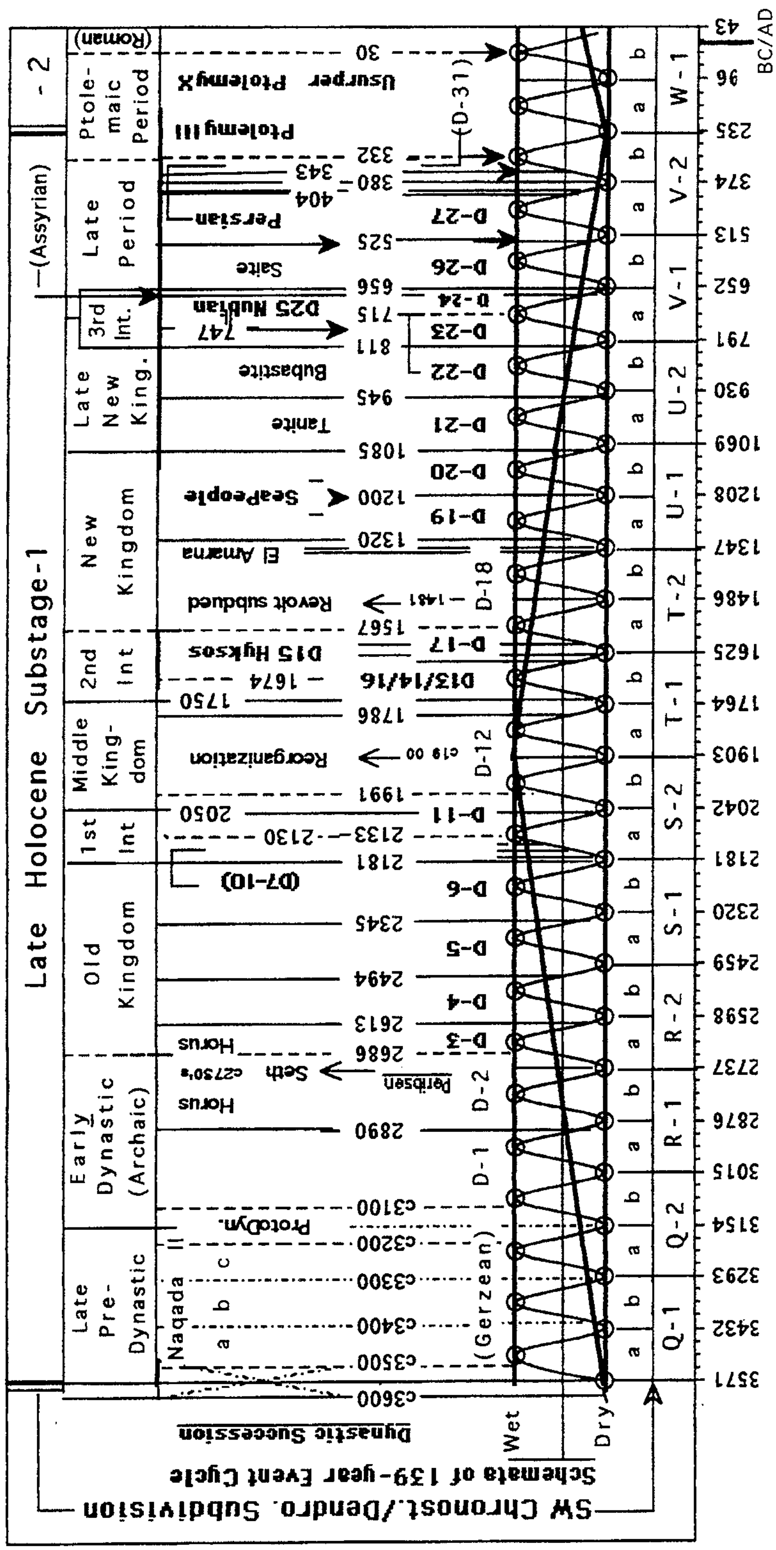

Figure 20 Correlation of Egyptian dynastic history with schemata of the 139-year Event Cycle. Reconstruction of dynastic record from James (1979) who notes that the dating is approximate and increasingly so towards the beginning of the record. Most dated boundaries (solid vertical lines) fall within the dry epicycles, the remainder (dashed vertical lines) within the wet epicycles, suggesting that environmental stress (lower Nile levels) played a contributory role in dynastic succession. If so, empirical evidence for the Event Cycle is extended back to the mid-Holocene. Similarly, instrumental global temperature evidence of the Event Cycle's ca. 70-year half cycle is projected back to the mid-Holocene through correlation with dated beach ridges of Lake Michigan (Delcourt and others 1996). Modified from Figure 11 in Karlstrom (1995).

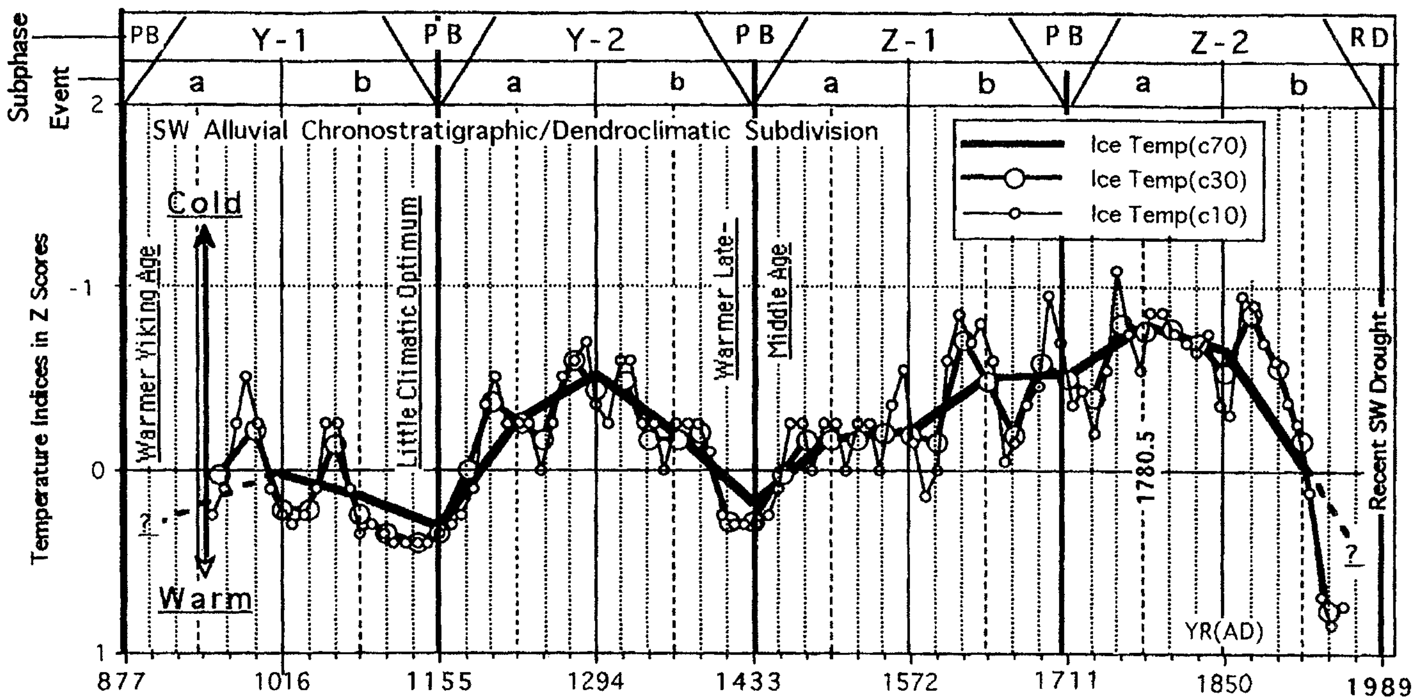

Figure 21 Iceland temperature record on time scale of the 139-year Event Cycle and its 2/1 (69.5-year) and 6/1 (23.166-year) resonances. Ten-year temperature indices from Bergthorson (1969). Half-cycle smoothing as before. Note the strong tendency to oscillate in phase with the 278-year Subphase Cycle and the lesser tendencies with the 139-year Event Cycle and its 2/1 (69.5-year) and 6/1 (23.17-year) resonances. The Medieval Warm Period (MWP) placed from approximately AD 900 to 1300 by Lamb (1972) appears to include cooler intervals as well, as these are defined in higher resolution records from Europe, the Southwest, and elsewhere. For correlation of the post-AD 1700 Iceland temperature record with sunspots see Friis-Christensen and Lassen (1991) and Figure 22. Figure 22 includes a tree-ring-dated isotope record and a marine record that also closely phases with the Sunspot-Resonance record, and thus, substantially strengthens the empirical case for probable solar-resonance-climate cause and effect.

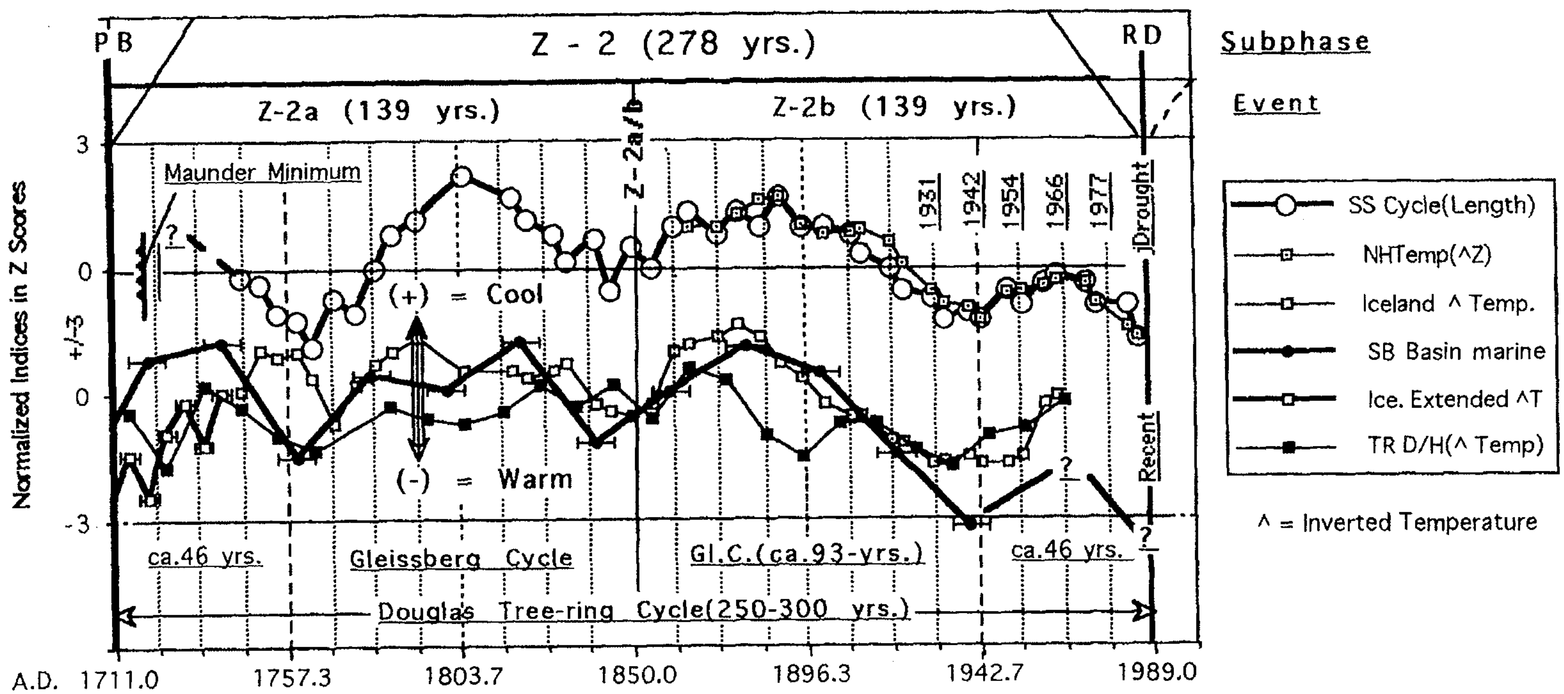

Figure 22 Sunspot and climate records on time scale of the 139-year Event Cycle and its 3/1 (46.3-year) and 12/1 (11.5-year) resonances. Sunspot, hemispheric temperature, and Iceland indices to 1745 from Friis-Christensen and Lassen (1991), extension of Iceland temperature record by indices from Bergthorsen (1969). Santa Barbara marine indices from Pandolfi and others (1980), and tree-ring-dated isotope indices from Epstein and Yapp (1976). Sunspots and collated climatic records appear to be related to the Tidal Resonance Model through in-phase relations with the ca. 46-year resonance and its double Gleissberg Sunspot Cycle. There is some tendency for sunspots and the higher resolution climate records to oscillate in phase with the 11.5-year resonance. Figure modified from Figure 5 in Karlstrom (1996).

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Natural Variability and Human Effects in the San Francisco Estuary and Watershed

Noah Knowles

Abstract

Understanding of Bay-Delta processes is complicated by both natural and human effects on freshwater inflows. To investigate implications for the estuary, changes in inflows due to major reservoirs and freshwater diversions (Delta exports) in the watershed were inferred from available data. Effects on Bay-Delta salinity were estimated by using the reconstructed Delta flows to drive a numerical salinity model. Both natural and human-induced signals show strong interannual variability. Though reservoir effects are anti-correlated with both natural variability and Delta exports overall, relative effects vary strongly within the average year. Human effects combine to raise salinities during the wet season, with maximum impacts occurring in spring. On average, May is the time of both greatest human impacts and lowest correlation between human and natural effects. While year-to-year variations in all signals are very large, natural interannual variability can greatly exceed the range of human effects on water quality in the estuary.

Introduction

The San Francisco Bay-Delta estuary has been the subject of intense scientific scrutiny in recent decades, due to its economic and aesthetic value to the region and its importance as a unique ecosystem. Like all estuaries, behavior of the Bay-Delta is linked to the coastal ocean and to the inland rivers, resulting in high variability at many scales. Also, the estuary has undergone extensive human development over the past 150 years, as has its upstream watershed. Current attempts to understand and restore the Bay-Delta's valuable ecosystems are complicated by both natural and human effects on freshwater inflows. Freshwater flow through the Delta of the Sacramento and San Joaquin rivers (Figure 1) is the most significant single factor affecting water quality in the estuary. These inflows flush seawater from the Bay-Delta, determining the levels of salinity throughout the estuary. Salinity levels in turn determine water density and flow patterns, which affect nutrient concentrations and so on. Salinity conditions are also directly crucial to the survival of some plants and animals in the estuarine ecosystem, and certain salinity regimes favor invasive species (Nichols 1985). The freshwater inflows that drive these processes have a well-known seasonal cycle, but seasonal to interannual deviations from this cycle can be immense. Understanding this variability in flow patterns is essential to a comprehensive understanding of the estuary.

Figure 1 San Francisco Bay and surroundings, 1999. Most of the bay's freshwater arrives through the Delta (upper right).

The importance of freshwater inflows links the fate of the Bay-Delta to its upstream watershed, the area of land that sources flows into the Delta (Figure 2). The San Francisco Bay-Delta watershed stretches from the western slopes of the coastal range to the Sierra Nevada, and from the Cascades to the Kings river basin in the south, covering an area of about 400,000 km^2. Processes in and over the watershed determine the timing and amount of inflow to the bay. Annually, about 30 km^3 of freshwater enter the bay from the watershed, with peak flows coming in early March, on average. Interannual variation in both timing and amount can be significant and is due to both natural and human-induced effects.

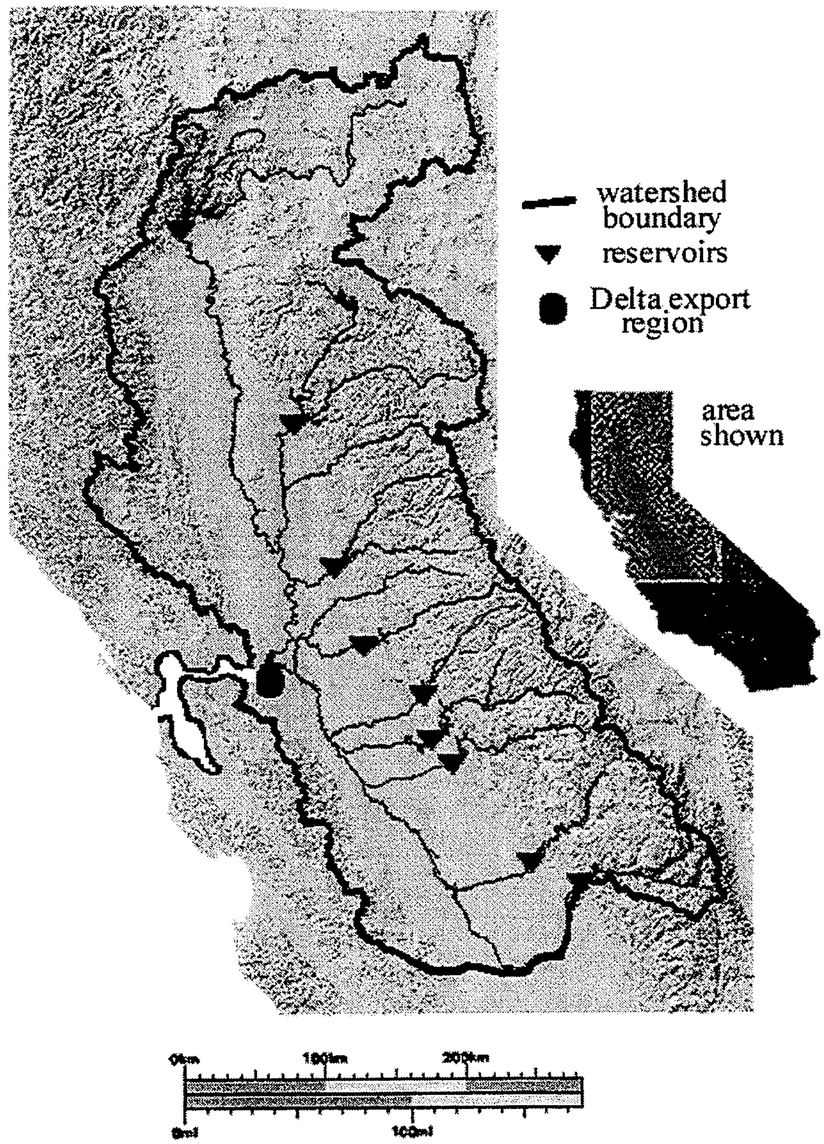

Figure 2 Location of major human effects within the San Francisco Bay watershed

Figure 2 shows locations in the watershed where human effects significantly impact flow patterns. Reservoirs with a combined capacity of over 35 km^3 (roughly equal to the bay's total annual inflow) substantially alter the magnitude and timing of river flows throughout the watershed (DWR 1998). Also, freshwater is exported from the Delta region for municipal, industrial, and agricultural uses. The combined effect of reservoirs and Delta exports constitute the bulk of human-induced changes in bay freshwater inflows (other effects include return flows, groundwater pumping, river confinement and land use changes). These effects take place in the shadow of the watershed's large natural hydrologic variability, resulting in a complex managed watershed-estuary system. The present study is a first attempt to quantify the implications of human effects, in the context of natural variability, for water quality in the estuary.

Delta Flow Variability and Human Effects

Data

The first step in exploring the estuarine impacts of reservoirs and Delta losses is to quantify their effects on Delta flow rates. To this end, daily time series of estimated data provided by two agencies proved invaluable. First, the DAYFLOW data program administered by the California Department of Water Resources (DWR 1999) offers, among other values, estimates of flows into and out of the Delta. Subtracting outflows from inflows gives an estimate of losses, primarily due to freshwater exports, in the Delta region. These losses are shown in Figure 3 (bottom) for water years 1965–1987, and are hereafter referred to as the "Delta export effect." Next, the California-Nevada River Forecast Center provided estimates of "unimpaired" river flows below nine major reservoirs throughout the watershed. These data were calculated using reservoir storage data and out-of-basin diversion rates above the outflow point to infer what flows would have been without these impairments. Subtracting the unimpaired flow data from observed flow rates at the same locations and summing the differences to yield one time series results in daily estimates of the "reservoir effect" on Delta flow rates, also shown in Figure 3 (middle). Finally, the observed flows just below the major reservoirs were subtracted from the DAYFLOW Delta inflow values to estimate flow contributions from the foothills and valleys. These contributions were then added to the total of the CNRFC "unimpaired" flow time series to yield estimates of unimpaired Delta outflow, shown at the top of Figure 3. This quantity is intended to represent what freshwater inflows to the San Francisco Bay estuary would have been without shifts in flow timing and magnitude caused by reservoir effects and Delta exports. Though this estimate does not account for such effects as increased in-basin losses due to irrigation, it is nonetheless an approximation to the watershed's outflow in its undeveloped state. (Accounting for the valleys in this manner also allows return flows from redistributed Delta diversions to be included in the analysis, so the Delta export effect is not overestimated.) Adding the three series yields actual Delta outflow.

Analysis of Delta Flow Components

Several facts are apparent from a cursory examination of Figure 3. First, the year-to-year variability of both the natural signal and the human effects is significant; extreme events provide notable examples. The signature of the 1976–1977 drought is evident in all three signals, while years of major abundance, such as water year 1983, are reflected most clearly in the unimpaired and reservoir signals. The Delta export effect, consistently negative (occasional positive spikes are in-Delta storm runoff), became noticeably stronger over the period of record. It is also apparent from Figure 3 that each of these signals has a strong annual cycle, though the exact timing is not clear. To explore this further, Figure 4 shows the mean annual cycles (standardized, with smoothed versions added for clarity) of the flow contribution time series from Figure 3.

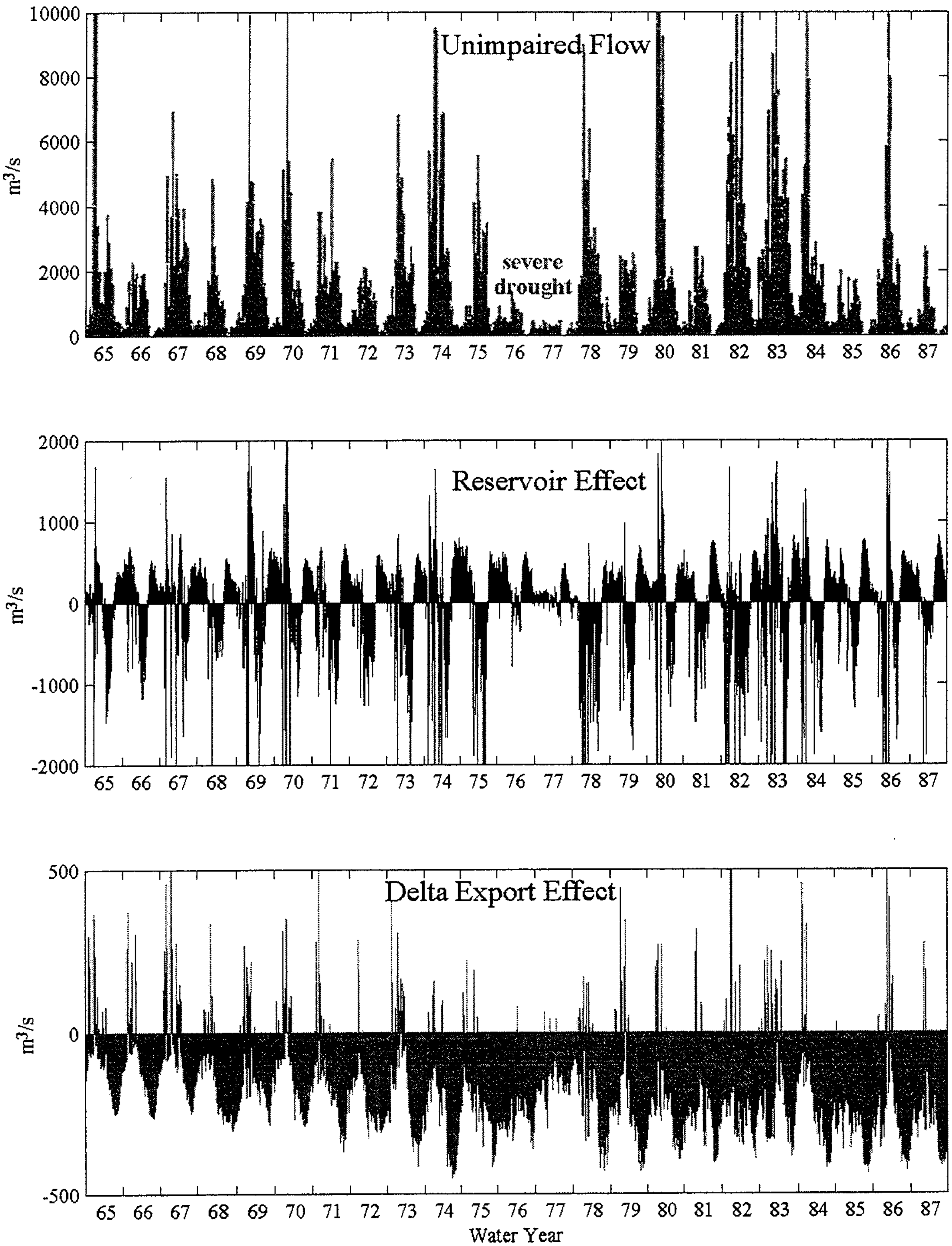

Figure 3 Natural and human-induced contributions to bay freshwater inflows through the Delta

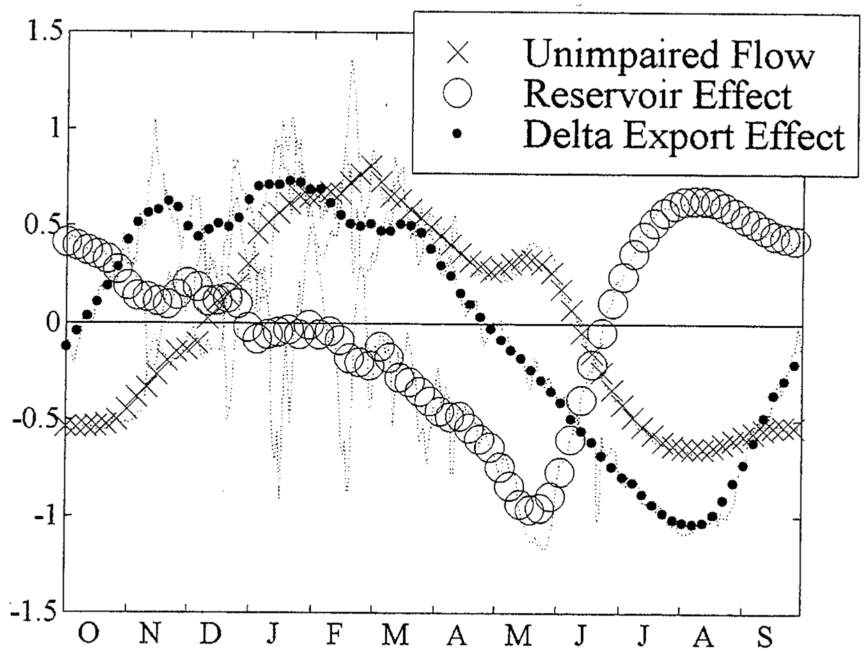

Figure 4 Mean annual cycles of flow contributions (standardized, with 30-day smoothed versions)

The average yearly timing of natural and human effects are clear in Figure 4. Natural flows reach a peak in February and March, with the low flows of the dry season extending from July through October. On average, reservoirs remove water from Delta flow from February through early June, returning it during the dry season. The sharp peak in the negative reservoir effect in May is due primarily to reservoirs in the southern Sierra capturing snowmelt runoff. Figure 4 also shows Delta exports to be at their maximum during June, July, and August, with the lowest diversions occurring from November through May. Though these human effects are clearly related to natural variability, the strength of these connections is not apparent from Figure 4. The results of an empirical orthogonal function analysis of these time series are shown in Figure 5. This method provides a more quantified representation of the relationships between human effects and natural variability.

This analysis yields three modes which explain 60%, 27%, and 13% of Delta flow variability. The first and third modes represent flow variability which is directly due to, or a management action correlated with, concurrent (at the daily scale) natural variability. These "nature-correlated" modes capture a total 73% of Delta flow variance. The dominant mode shows that reservoir effects and Delta export effects tend to be anti-correlated. This is no surprise as reservoir releases are often scheduled to meet export demands. The remaining 27% of variability captured by the second mode represents human effects that are either unrelated to natural variations, or that are correlated but with a time lag. This may represent, for example, changes in demand unrelated to natural variability or management actions based on the flow history or on runoff forecasts.

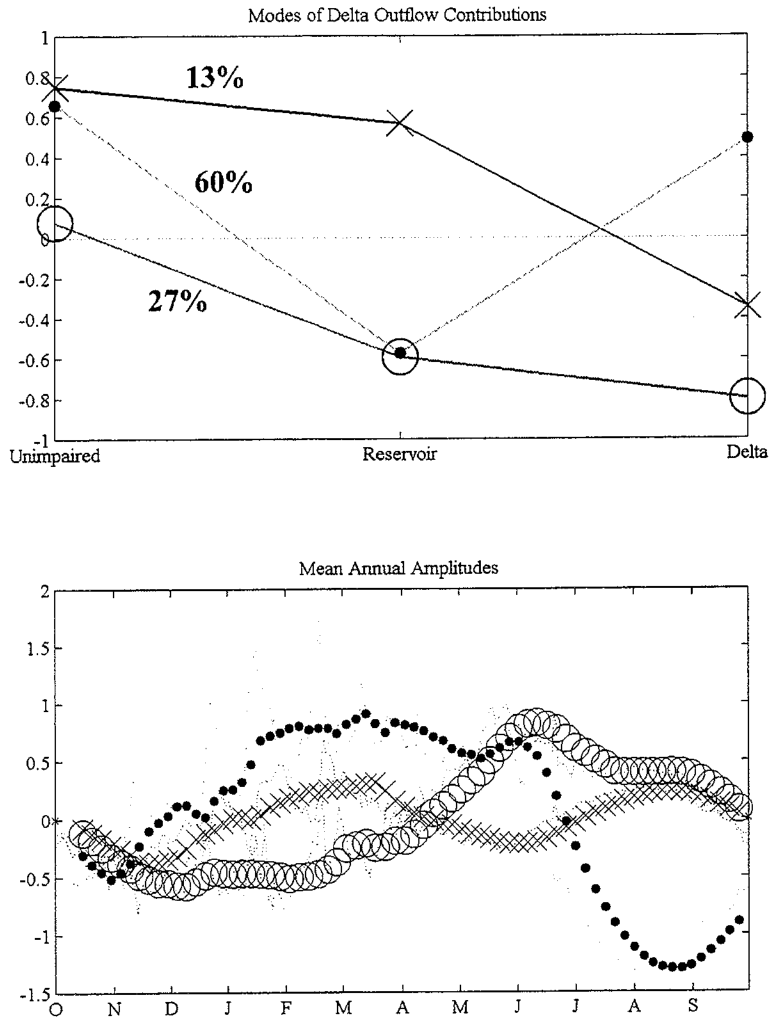

Figure 5 Modes and their mean annual cycle amplitudes for daily Delta flow contributions

Two key results are that human effects are strongly dependent on the large natural variability, and that reservoir effects tend to be anti-correlated with both natural variability and Delta export effects. These will be shown to have significant implications for the Bay-Delta estuary.

Simulating the Estuarine Response

The next step in evaluating human impacts is to develop simulations of the salinity field's response to the reconstructed flows. The model used here is the Uncles-Peterson (UP) model, an advective-diffusive intertidal box model whose dominant inputs are tidal state (a measure of the spring-neap tidal status) and freshwater inflows (Uncles and Peterson 1995). Other data used to force the model are coastal ocean salinity and local precipitation and evaporation. The model divides the bay horizontally into 50 segments, shown in Figure 6, and vertically into two layers (not shown).

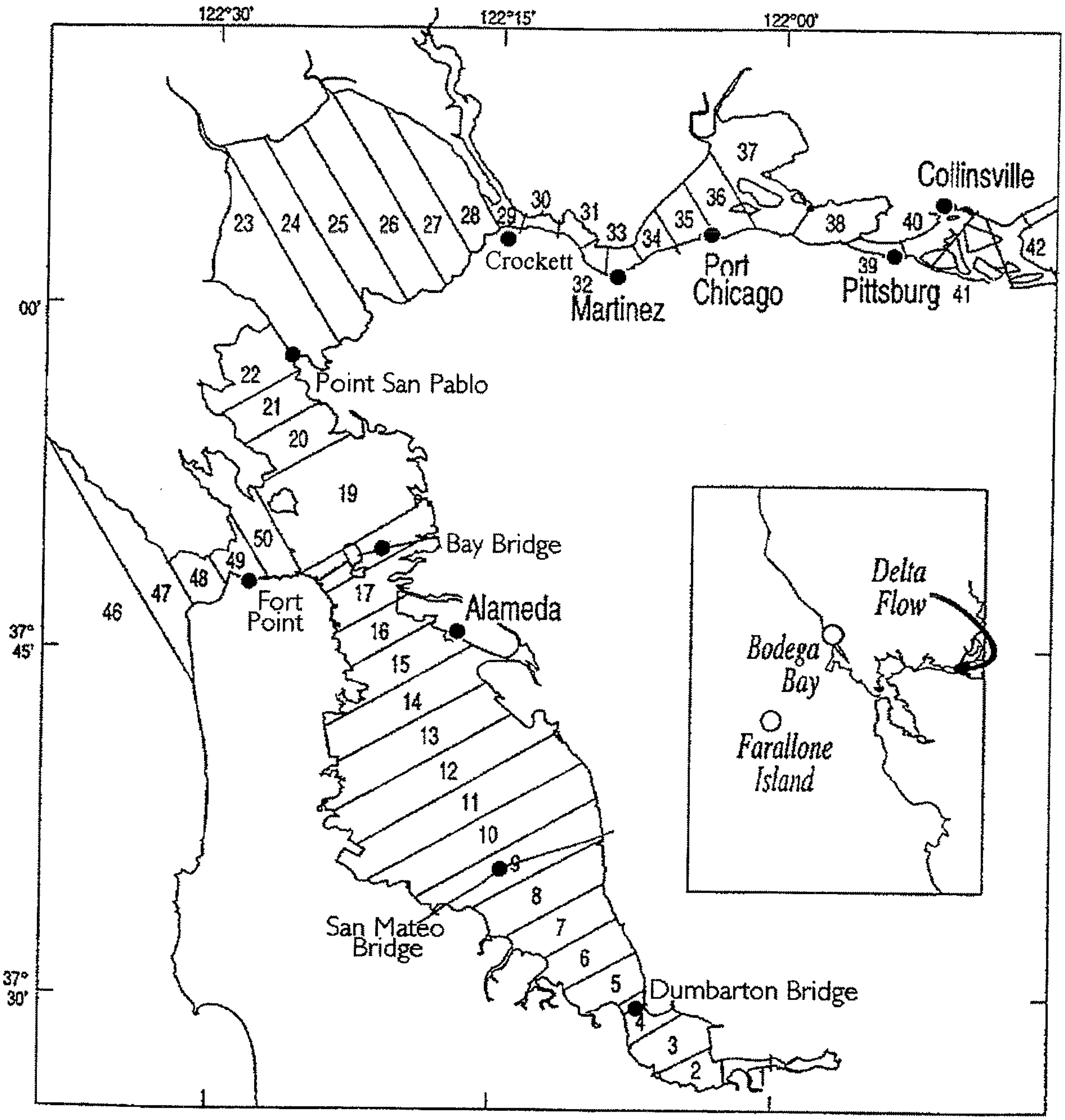

Figure 6 Segmentation of the UP estuary model used to simulate salinity

This model simulates San Francisco Bay's daily and laterally averaged salinity and current fields with a very low computation load, making it ideal for applications requiring long-term, multiple simulations such as this study. It has been applied in several previous studies of the bay and has been shown to accurately reproduce salinities at weekly to interannual time scales over a wide range of flow regimes (Peterson and others 1995; Knowles and others 1997, 1998).

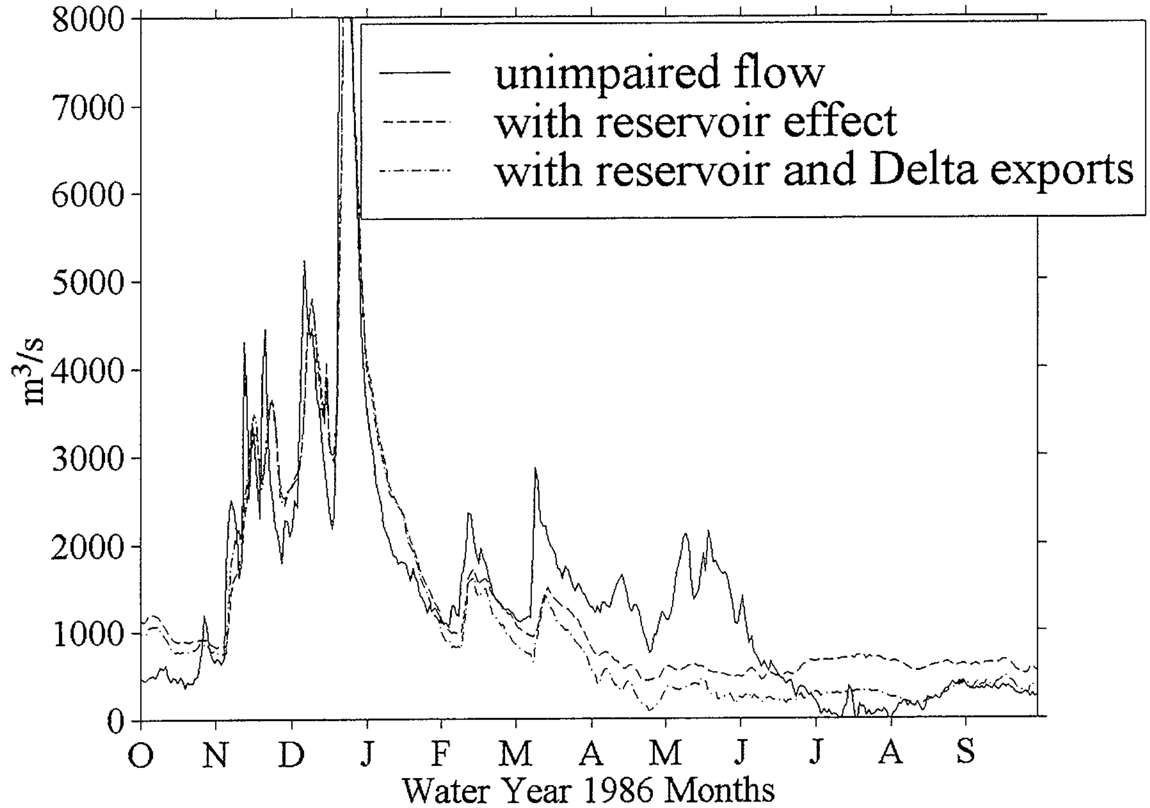

Figure 7 Sample time series for reconstructed flows with differing levels of human impacts

To drive the model, tidal hindcasts were used along with reconstructed Delta flows. The flow components of Figure 3 were summed sequentially to generate three hypothetical time series (a sample year is shown in Figure 7). The three series are as follows: unimpaired Delta flow, Delta flow with reservoir effects only, and Delta flow impaired by both reservoirs and Delta exports—the last series being identical to observed flows.

These three time series were used to force the UP model over the 21 water years from October 1966 through September 1987 to provide estimates of salinity under the three reconstructed levels of impairment.

Impacts on Salinity

Long-Term Statistics

Figure 8 shows two simple measures of the influence of reservoirs and Delta pumping on salinity throughout the estuary—the mean and standard deviation of the daily salinity field.

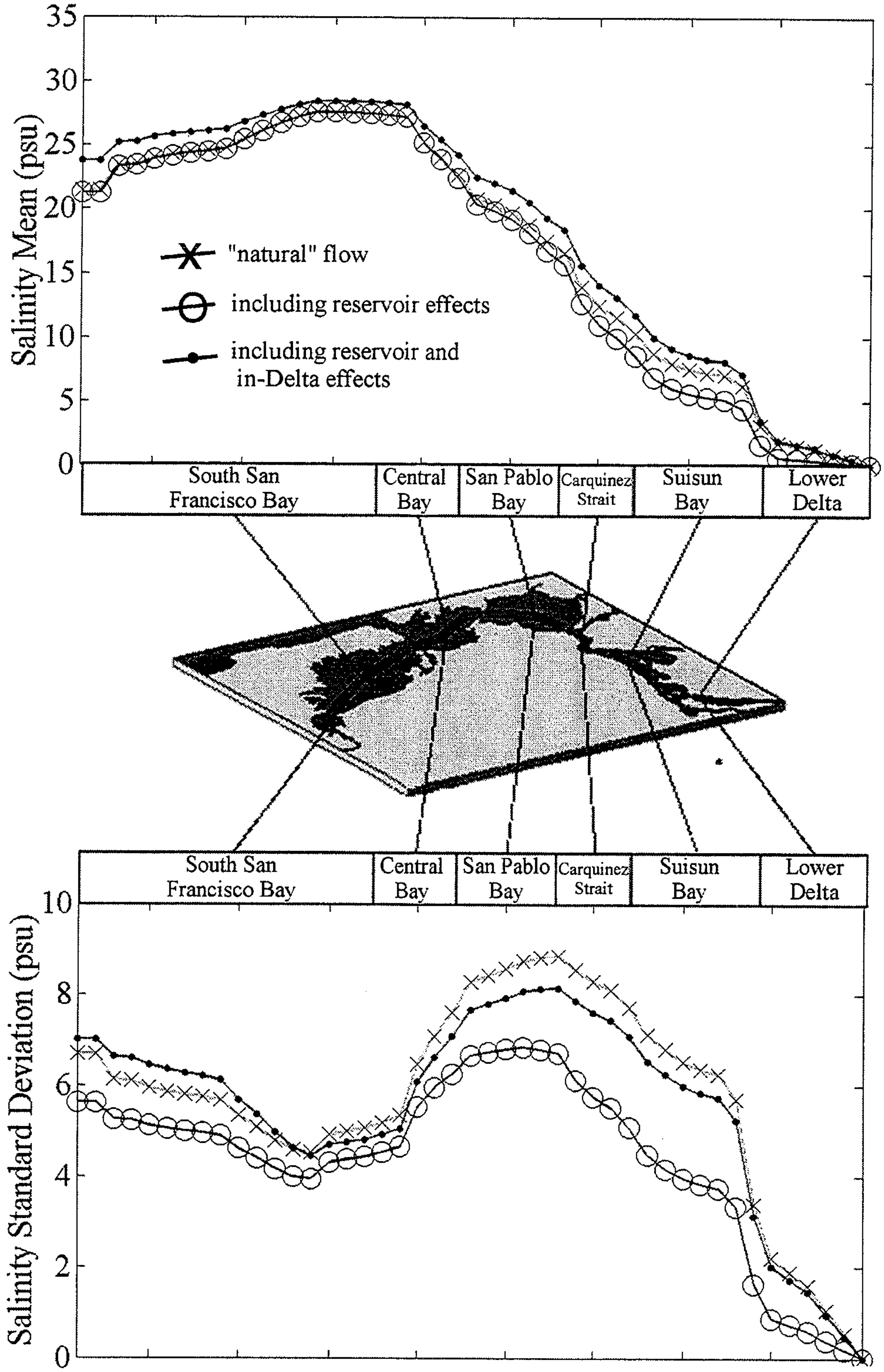

Figure 8 Average salinity response, over 21 years, to human impacts

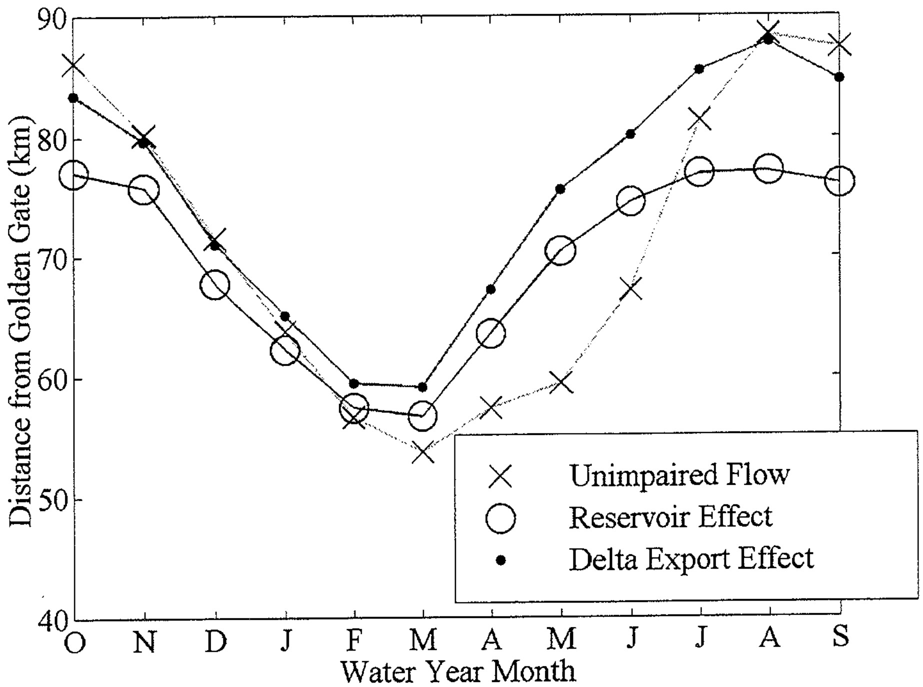

Figure 9 Average annual cycle of human effects on salinity. See Figure 10.

It is apparent, first of all, that the effects on the mean salinity field are quite small, though the final result of all human impacts is to raise mean salinity 1 to 2 psu throughout the estuary. Reservoirs alone tend to lower average salinity by up to 2 psu in the North Bay region, an indication of the practice of repelling salt water from the export region during the dry season. Reservoirs also reduce the variability of salinity, lowering the standard deviation by 1 to 2 psu from unimpaired levels. Delta exports have the opposite effect, restoring variability to well within 1 psu of unimpaired levels throughout the bay. The competing effects of reservoirs and Delta exports on the statistics of the salinity field are a result of their anti-correlation, as discussed in the results of the modal analysis (see Figure 5). It is also worth noting that since North Bay is near 0 psu in most wet seasons, human effects on salinity there are largely restricted to the dry season months. In the South Bay, on the other hand, salinity tends to reach a maximum in the dry season, and is relatively unaffected by human impacts on Delta flow except during the wet season.

Mean Annual Cycle and Interannual Variability

Though human effects on the long-term statistics are small, the changes in the mean annual cycle are much more significant. Figure 9 shows human impacts on the monthly mean annual cycle of the salinity field's position as indicated by X2. X2 is a commonly used salinity index, which is defined as the distance of the near-bottom 2 psu isohaline from the Golden Gate (Jassby and others 1995). High values of X2 correspond to saline conditions, while low values signify fresh conditions and higher inflows.

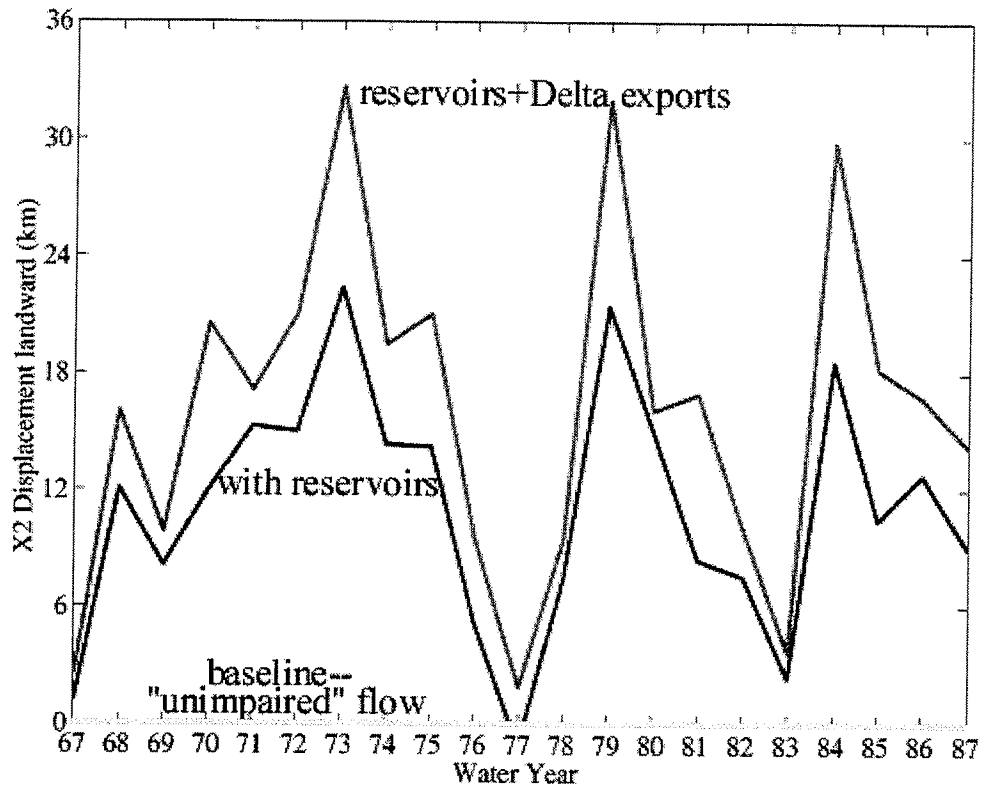

Figure 10 May residual management effects on salinity intrusion. See Figure 9.

Although in the long-term, reservoir and Delta export effects are anti-correlated and have competing effects on salinity relative to unimpaired conditions, Figure 9 shows that this is not true year-round. From February through mid-June, the two effects combine to increase monthly mean salinity levels, shifting the mean X2 position a maximum of over 15 km up the estuary in May, on average. During the dry season, reservoir effects move X2 as much as to 10 km downstream relative to unimpaired conditions, while competing Delta export effects restore the salinity to near-unimpaired levels.

Considering the significant average impact of humans in the spring, it is useful to examine the year-to-year variability of these effects. Figure 10 shows the relative average May effects for each year of the record. X2 displacements due to reservoir and Delta export impacts vary hugely, particularly at five- to ten-year intervals. Reservoir effects displace May X2 from 0 km to 22 km landward of unimpaired values. Delta export effects increase this displacement as much as 10 km. Despite the huge variability of these impacts over the record, reservoirs and Delta exports consistently act in concert during this time of year. Both displace X2 landward in every year of the record, the only exception being the slight seaward displacement due to reservoirs in May 1977, the second year of an extreme two-year drought.

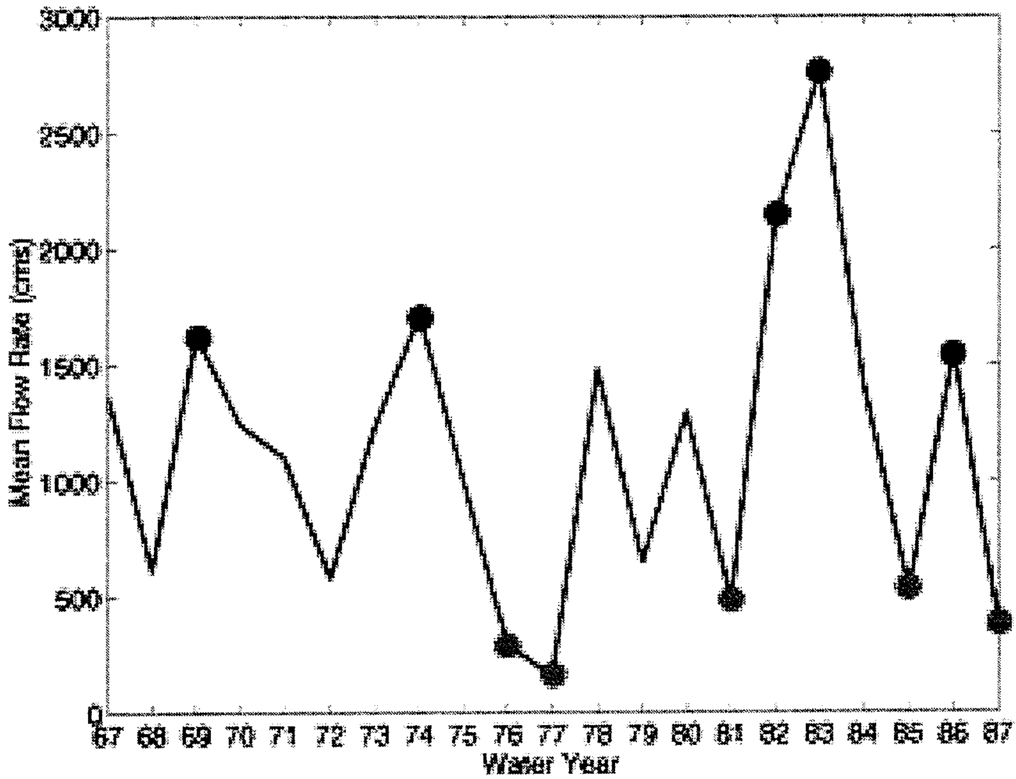

Figure 11 Annual average flow rates, with five wettest and driest years indicated

Note also by comparing Figure 10 and Figure 11 (which shows mean annual inflows) that there is no clear correlation at the annual scale between May management effects and natural variability. Also, May is the time when the second mode, the mode representing human effects not correlated with natural variability, reaches its largest amplitude (see Figure 5). It appears that in May, human effects on Delta flow reach not only their largest level, but also their greatest independence from concurrent natural variability.

Extreme Years

Having examined the long-term average impacts of humans on salinity in the Bay-Delta, it is now interesting to consider the the average effects in particular types of water years. Figure 11 shows the mean annual flow rates for the simulated period. The five wettest and driest years are highlighted; these are used in the following to generate composite mean annual cycles of X2 for the different human impact levels, shown in Figures 12 and 13.

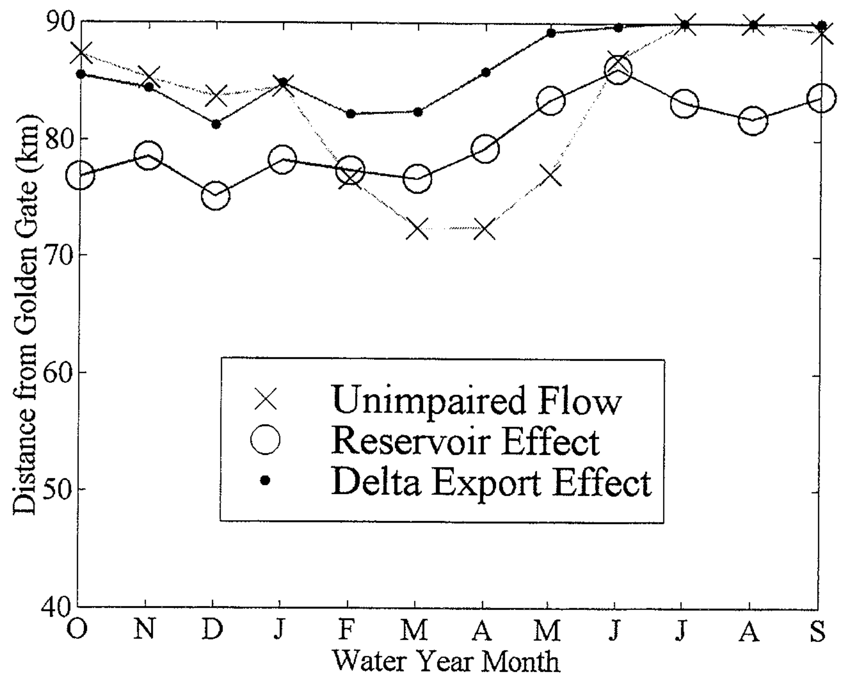

Figure 12 Dry year composite annual cycle of human effects on salinity

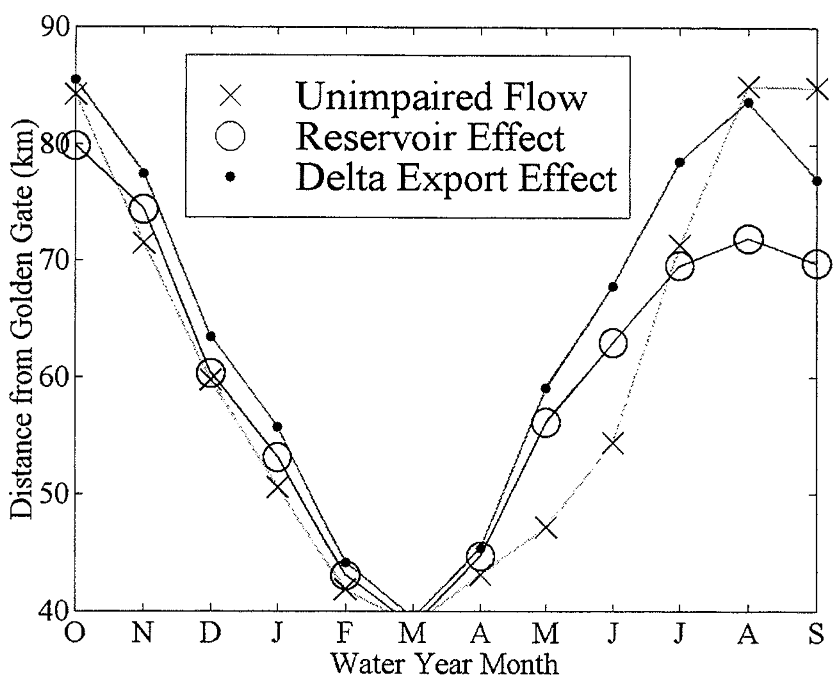

Figure 13 Wet year composite annual cycle of human effects on salinity

Several interesting facts emerge from a comparison of these two figures. First, with the exception of late summer, human effects on X2 are much stronger in dry years. Though this is partially due to the greater proximity of the 2 psu isohaline to the Delta during dry conditions, it is largely a result of increased human effects on flow during such years. Also, though springtime impacts are still the largest, during dry years the maximum human impact comes in April, one month earlier than in the mean annual cycle of Figure 9. Conversely, in wet years this maximum occurs in June. Note also that though it may not be obvious, the maximum human impact on X2 is slightly larger in wet years than in dry years. In both composites, it is still true that reservoir and Delta effects counter one another during the dry season. This is particularly evident during dry years and during August and September of wet years, when releases to provide flood control storage generate a large reservoir effect.

Perhaps the most noteworthy aspect of Figures 12 and 13 is that human effects in the estuary during the wet season are dwarfed by natural differences between the wet and dry composites. Clearly, the overwhelming difference in springtime X2 values between relatively wet and dry years suggests that natural variability will often impact the estuary in ways that are not, and likely can not be, mitigated by upstream freshwater management.

Conclusions

In this study, effects of reservoirs and Delta losses on Bay-Delta salinity were estimated by using reconstructed Delta outflows to drive a numerical salinity model. Both natural and human effects showed significant interannual variability. The long-term mean annual cycles and a modal analysis of Delta flow contributions showed human effects to be strongly related to concurrent natural variability. Reservoir effects were largely anti-correlated with both natural variability and Delta losses. This leads to competing effects from the two human influences on the mean and variance of baywide salinities. Within a water year, the relative effects of Delta losses and reservoirs are, on average, opposite during the wet versus the dry parts of the year. During the wet season, both effects serve to raise salinities, while they tend to curtail one another during the dry season. While some of these results may seem obvious considering the operating procedures of the reservoirs and the Delta pumping stations, understanding the magnitude and timing of these impacts could have important implications for the health of estuarine ecosystems.

Springtime was shown to be the period of largest human impacts in the estuary in terms of X2 position. This is a critical time of year for many species in and around the estuary (Jassby and others 1995), though the implications of particular changes caused by altered flows are still poorly understood. The significance of the springtime management period is enhanced by recent research (Cayan 1999), which suggests that just about every year there is a snowmelt-driven runoff surge that marks the transition from winter to spring. This appears to be a continental-scale phenomenon driven by global-scale atmospheric patterns. The global scale of these patterns suggest that the spring snowmelt surge may be a predictable event, possibly allowing the timing and magnitude of the estuarine impacts to be more accurately forecast.

Creating composite mean annual X2 cycles for wet and dry years revealed several interesting differences in impacts between water year types, such as the fact that maximum human impacts occur around April in dry years and around June in wet years. The most interesting result, however, was that natural variability in the freshwater supply can cause large year-to-year shifts in salinity patterns, which are not significantly altered by human effects. This has important implications for the estuary. For example, these inevitable natural effects must be taken into account when attempting to understand ecosystem health. In the case of several consecutive dry years followed by several wet years, as has occurred since 1987, native and restored estuarine ecosystems must be capable of adapting to the accompanying shift in salinity regimes. Much attention has rightfully been given to the concept that "the volume and timing of freshwater flows to the bay should reflect historical or natural conditions under which the bayland habitats and animals developed" (Goals Project 1999). It is also important to remember the existing large natural variability when thinking about the surviving and restored ecosystems, which are but patches of the original native ecosystem and must be able to adapt to inevitable natural variability.

Future work includes the development and application of a macroscale model of the Bay-Delta watershed's hydrology, including a more explicit accounting of the effects of irrigation, groundwater exchange, and land use change. This will permit more of the subtleties of human impacts in the watershed to be studied, and their implications for the estuary to be better understood.

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Snowpack, ENSO, and Atmospheric Circulation on the Colorado Front Range

Mark V. Losleben

Introduction

Snowpack in the Colorado Front Range mountains, just west of the Denver urban corridor, contributes to at least part of the water supply of many communities (Figure 1). This paper examines the relationships between winter atmospheric conditions and snowpack in the Front Range by posing three questions.

1. What are the atmospheric circulation conditions associated with the deepest and shallowest snowpacks?
2. What are the winter circulation conditions associated with ENSO events in this area?
3. Is there a consistent relationship between ENSO events and snowpack?

Data and Analysis

The period studied was from 1 November through 31 March for 1952 through 1996.

ENSO events are periods that meet the criteria defined by Trenberth (1997) for the full winter period (1 November through 31 March). The year designation is the year of the matching snowpack value. For example, the period from November 1956 through March 1957 is labeled 1957. Also, the cold ENSO event is referred to as La Niña and the warm event as El Niño.

The circulation indices are derived using NCAR gridded pressure height data, 5 x 5 degree spacing, and based on the algorithm developed by Jenkinson and Collison (1977) (Figure 2). Four indices are used to characterize atmospheric circulation: a north-south (S), an east-west (W), a flow strength or vigor (F), and a vorticity or cyclonicity (Z) index. These indices are calculated at four elevations: sea level (one mile below Denver's ground level), 850 mb (about the level of Denver), 700 mb (roughly a mid-mountain height), and 500 mb (well above the highest peaks in this area).

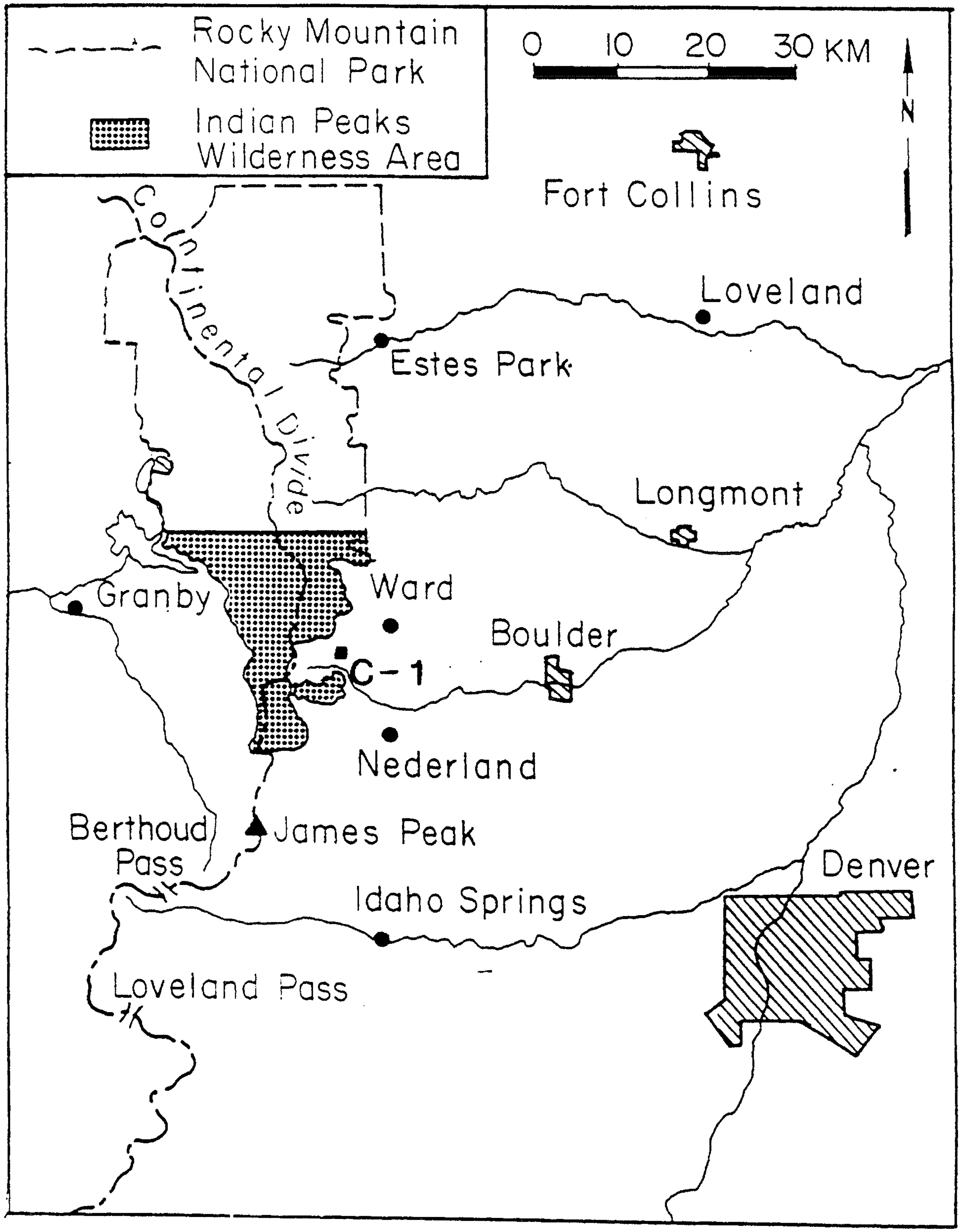
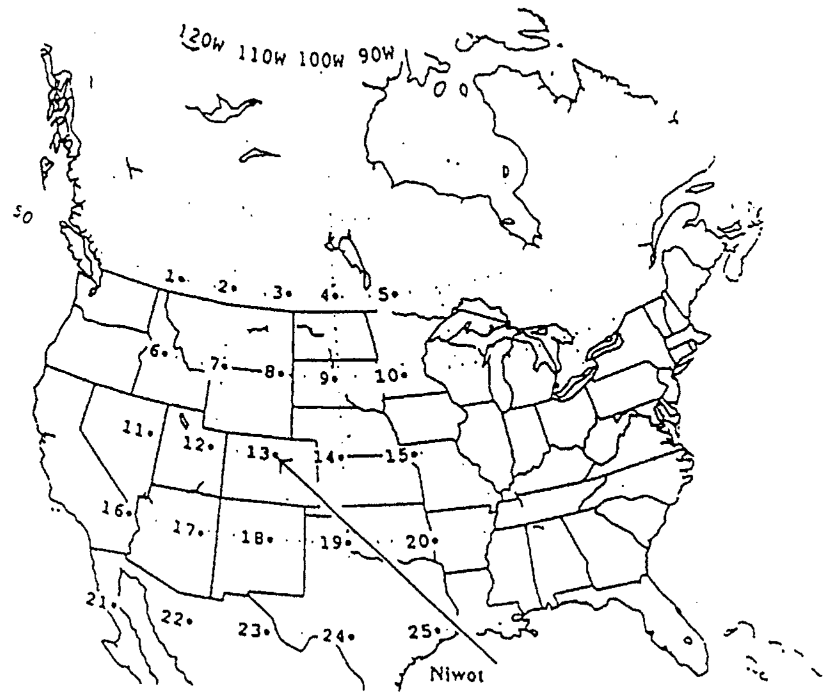


Figure 1 Location map. The sites are just east of the Continental Divide, from Ward south, and north of Nederland.



Circulation Index Algorithms

Southerly (S) and Westerly (W) flow strength indices are obtained using the following algorithms:

$$S = 1.31*(((p_9+(2*p_{14})+p_{19})/4)-((p_7+(2*p_{12})+p_{17})/4$$

$$W = ((p_{17}+(2*p_{18})+p_{19})/4)-((p_7+(2*p_8)+p_9)/4$$

Flow Strength (F) is obtained by:

$$F = (S^2 + W^2)^{0.5}$$

Derive Vorticity (Z), by first calculating southerly vorticity and westerly vorticity separately:

$$Z_S=1.14*(((p_{10}+(2*p_{15})+p_{20})/4)-((p_8+(2*p_{13})+p_{18})/4)- ((p_8+(2*p_{13})+p_{18})/4)+((p_6+(2*p_{11})+p_{16})/4))$$

$$Z_W=(1.07*(((p_{22}+(2*p_{23})+p_{24})/4)-((p_{12}+(2*p_{13})+p_{14})/4)))- (0.95*(((p_{12}+(2*p_{13})+p_{14})/4)-((p_2+(2*p_3)+p_4)/4)))$$

and then summing for Z:

$$Z = Z_W + Z_S$$

Figure 2 Circulation index grid map and algorithms. Point 13 on this 5 x 5 degree grid is the study area. Subscripts in the algorithms denote grid points. Based on Jenkinson and Collison (1997).

Snowpack values are the April 1 measurements, as reported by the Natural Resources Conservation Service, at three sites in the Front Range: University Camp (3,121 m elevation), Boulder Falls (3,030 m), and Ward (2,879 m). The highest and lowest snowpack years are the top and bottom quartiles based on the range of snowpack values and not the number of years in the data set. Snowpack values were used instead of number of years in the data set to more clearly focus on the circulation patterns of those years with the deepest or shallowest snowpack conditions. This approach yielded six years in the top quartile and nine years in the bottom quartile.

"Significant" refers to the statistical level of 0.01% (0.0001) level or better. A *t*-test of means of the circulation indices was used for the appropriate comparisons: high compared to low snowpack, or El Niño events compared to La Niña events.

Background of Weather Patterns of Precipitation

Very generally, the circulation patterns that deliver snowfall to the Front Range belong to one of two airflow categories: zonal or meridional. The zonal pattern is dominated by strong, westerly airflow that comes directly over the Continental Divide, then descends to the cities of the eastern plains (Figure 3A). Snowfall from this pattern is characterized by frequent, light events, "a little bit every day" regime, and tends to deposit snow mainly in the mountains, with little to no accumulation in the cities.

The meridional pattern has a larger southerly and easterly flow component. The easterly flow forces the airmass up the eastern slope of the Front Range (Figure 3B) causing cooling and enhancing precipitation occurrence. Snowfalls associated with this type of flow tend to be heavy, as the airmass often entrains considerable moisture from the Gulf of Mexico before reaching the Front Range and can deposit as much (or more) snow on the cities as in the mountains. Although great snow producers, meridional events are relatively infrequent compared to zonal events.

Thus, in theory, a zonal winter tends to produce frequent snowfall in the mountains, but little at the lower elevations or over the cities. By contrast, a meridional winter tends to produce infrequent, yet heavy, snowfall that blankets the urban and mountain areas.

Results

Snowpack and Circulation

There is a significant difference in circulation characteristics at the 700 mb and 500 mb levels comparing the highest (1952, 1957, 1959, 1965, 1984, 1996) and the lowest (1966, 1969, 1977, 1981, 1983, 1985, 1989, 1991, 1995) snowpack years. The deepest snowpacks are associated with greater westerly (0.0000 at 500 mb, 0.0005 at 700 mb), and northerly (0.0006 at 500 mb, 0.0001 at 700 mb) airflow and increased flow vigor (0.0000 at 500 mb and 700 mb), but there is no significant difference in vorticity compared to the lowest years. There is also no significant difference between high and low snowpack groups at the 850 mb or sea level elevations.

ENSO and Circulation

At the 500 mb level, La Niña events are significantly (0.0000 for both W and F) associated with a stronger westerly flow and with greater flow vigor compared to El Niño events. There are no differences in the north-south or vorticity indices.

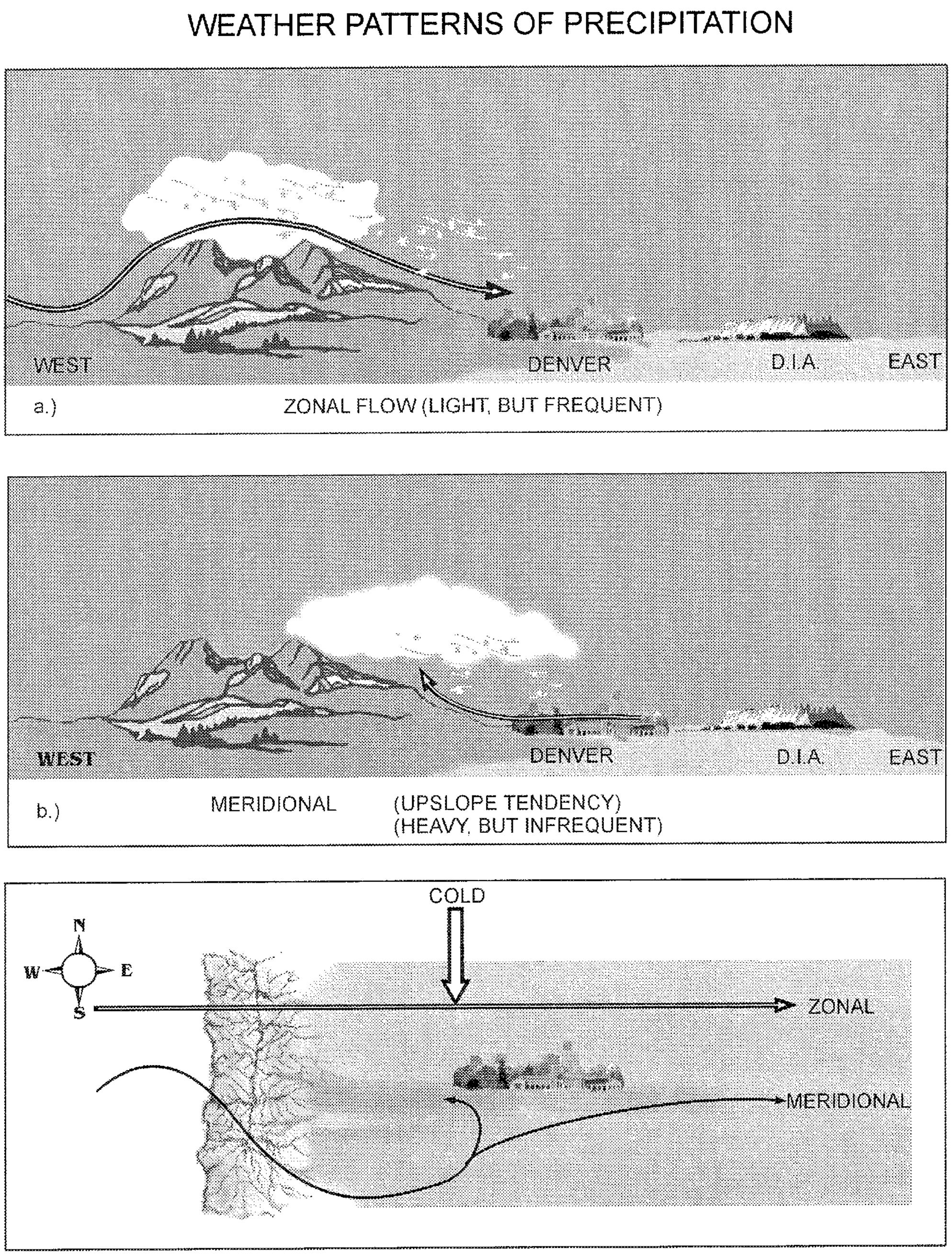


Figure 3 Weather patterns of precipitation on the Front Range. Winter precipitation occurs during either of two circulation patterns, generally speaking. a. zonal flow with air coming over the Continental Divide deposits snow mostly in the high mountains to the west of the urban area. b. meridional flow with weaker air flow coming from the east cools as it rises up the mountains, depositing at least as much snow in the urban area as in the mountains to the west. The two flow patterns are depicted latitudinally in the bottom plate also showing cold air intrusions from the north at the time of snowfall.

There are also no significant differences at sea level, although La Niña events tend to be northerly (0.0008) and have increased flow vigor (0.0005).

Snowpack and ENSO

There is the suggestion that El Nino years are associated with low snowpack, whereas La Nina years are associated with moderate to high snowpack. Only one ENSO event, the 1996 La Nina, is in the top quartile, but seven events, five El Niños and to La Niñas, are in the bottom quartile, with eleven events in the middle quartiles, six La Niñas and four El Niños. The suggestion that La Niñas are associated with higher snowpack is bolstered a bit when looking at the 1950s decade. Between 1952 and 1965 there were only two ENSO events, both La Niñas, 1955 and 1956. Although these were in the middle range of snowpack years, they were bracketed by the top quartile years 1952, 1957, and 1959. Interestingly, no other decade has more than one year in the top quartile, and the 1970s had none. Thus, the 1950s was a decade of high snowpack frequency with the occurrence of two La Niñas and no El Niños. Conversely, the suggestion that El Nino events and lower snowpack go together is borne out by noticing that of the nine El Niños in this record, five are in the lowest quartile, and four are in the middle range, with none in the top quartile.

Statistical analysis shows no relationship ($P > 0.1$) between the ENSO and high or low snowpack years. However, the average of the La Niña-year snowpacks is greater than the average for 1952 through 1996 (12.8 inches compared to 11.9 inches). In contrast, the El Niño-year snowpacks average less than the overall average (10.9 inches compared to 11.9 inches).

Conclusions

The deepest snowpacks in the Front Range are significantly correlated with a zonal airflow plus a northerly component, and the circulation of La Niña events tend to be zonal, while El Niño events are more meridional (Figure 4). Although there is no significant relationship between ENSO events and snowpack, there appears to be a consistent trend associating La Niña events with deeper snowpacks and El Niño events with shallower ones, an association consistent with the circulation-snowpack relationship.

Interestingly, these findings suggest city residents may have the wrong impression of mountain snowpack depth based upon their personal experiences because we found the deepest snowpacks to be associated with the zonal pattern, which delivers the least snowfall to the cities, and the lowest snowpacks to be associated with the meridional pattern, which delivers the most snowfall to the cities. Ironically then, on the average, city residents will tend to get more snowfall in shallow snowpack years and less snowfall in deeper snowpack years.

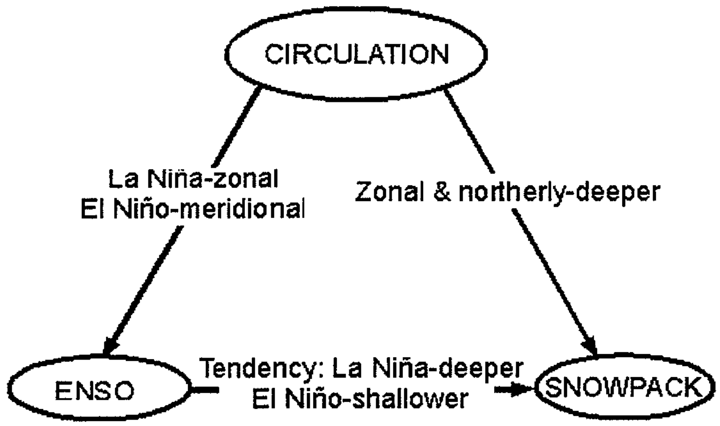


Figure 4 A pictorial summary of the connection between atmospheric circulation patterns, snowpack depth, and the phase of ENSO for the Front Range mountains west of the Denver urban area. A zonal, northerly flow gives deeper mountain snowpacks. La Niña periods tend toward zonal flows and deeper snowpack, whereas El Nino tendencies are for meridional flow and shallower snowpack. This relationship suggests that snowfall in the urban area can be the inverse of that in the mountains immediately to the west.

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The Role of Atmospheric Circulation for Precipitation Quality and Intensity at Two Elevations in the Colorado Front Range

Mark V. Losleben, Nick Pepin, and Sandra Pedrick

Introduction

Atmospheric circulation characteristics are defined for precipitation occurrence, pH, and conductivity at two National Atmospheric Deposition Program (NADP) sites of different elevations: Niwot (CO02 at 3,529 m) and Sugarloaf (CO94 at 2,530 m) in the Colorado Front Range. Niwot is located in the alpine tundra about 3 km east of the Continental Divide. Sugarloaf, 11 km southwest of Niwot, is located the lower montane ponderosa forest, closer to the Denver metropolitan area. The relationships between precipitation events, chemistry, and atmospheric circulation are analyzed by season and year for the 14-year period from 1984 to 1997.

Data

The precipitation pH, conductivity, and dates of precipitation events come from the NADP. The atmospheric circulation indices were derived at four levels: sea level (1,013 millibar [mb]), 850 mb, 700 mb, and 500 mb, using gridded pressure data from the National Center for Atmospheric Research in Boulder, Colorado (Figure 1).

Results and Discussion

Precipitation

Correlation with precipitation occurrence is strongest with circulation indices based on the 700 mb and 500 mb pressure height levels (Figure 2). At Niwot, under conditions of increasing precipitation, circulation becomes more westerly and northerly and shows “increased vigor.” Also, increased cyclonicity at higher atmospheric levels contributes to Niwot precipitation. Much of the precipitation at Niwot is orographic due to the location of the site. On the other hand, heavy precipitation days at Sugarloaf are usually accompanied by more southerly and easterly airflow and decreased vigor. Mid- to surface-level cyclonic storms tend to produce heavy precipitation at Sugarloaf. At both sites, the relative cleanliness of larger amounts of precipitation confirms the common belief that most deposition occurs during the first period of any rainfall event.

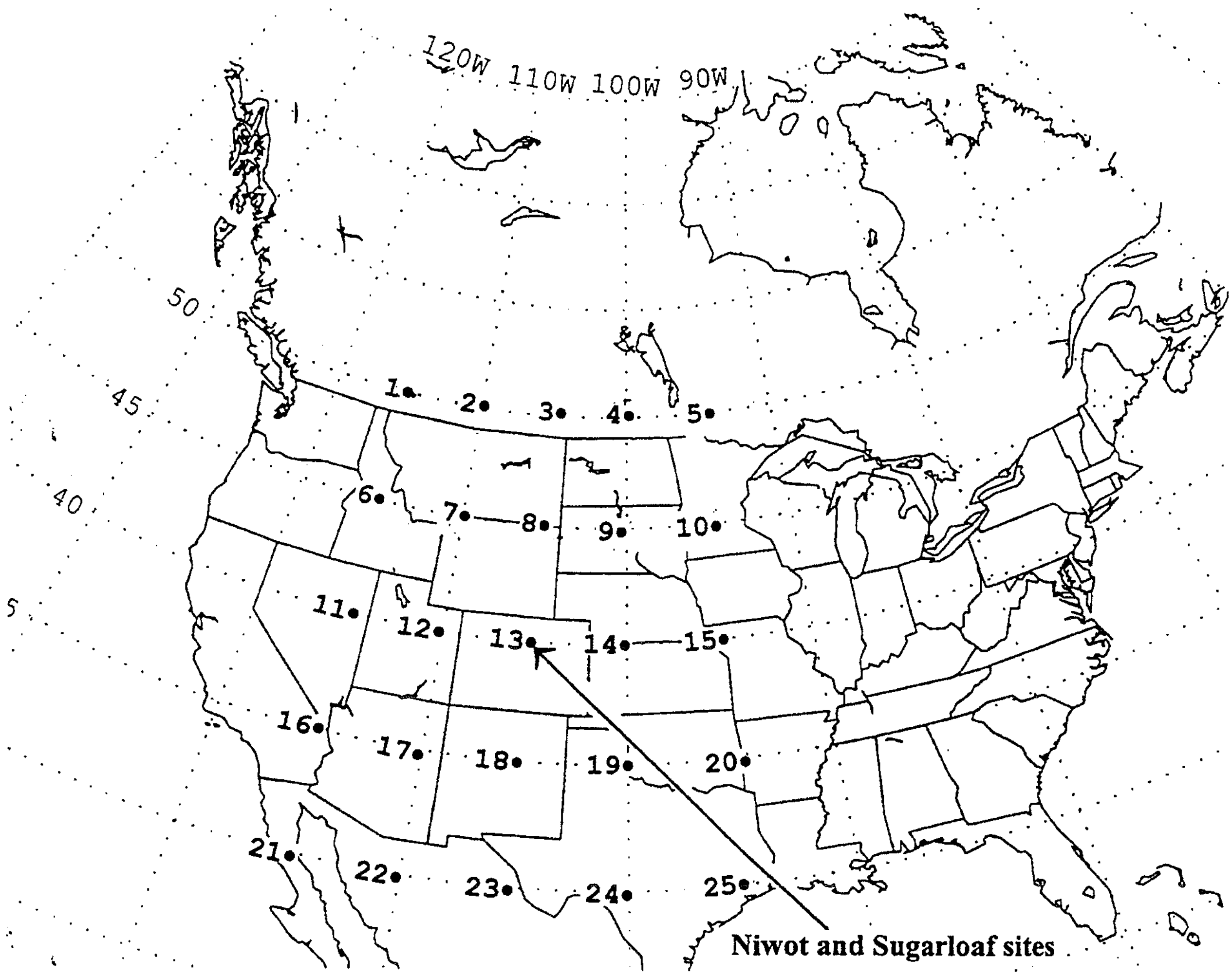

Figure 1 Grid area for which circulation indices are calculated. The grid extends from lat 30°N to 50°N and long 115°W to 95°W. The center of the grid lies near Boulder, Colorado. The location of the two study sites in indicated.

Chemistry

For the sake of simplicity, precipitation conditions of lower acidity (higher pH) and lower conductivity were referred to as "cleaner" and the reverse conditions as "dirtier." We found that Sugarloaf, the lower elevation site, is cleaner than Niwot (Figure 3), even though Sugarloaf is closer and more frequently influenced by the Denver air shed. The pH is less acidic at Sugarloaf for each season and also annually, and the conductivity is lower at Sugarloaf in the spring, summer, and annually. Both sites, however, are getting cleaner with time (statistically significant at Niwot), and Sugarloaf is getting cleaner faster than Niwot (significant only for conductance).

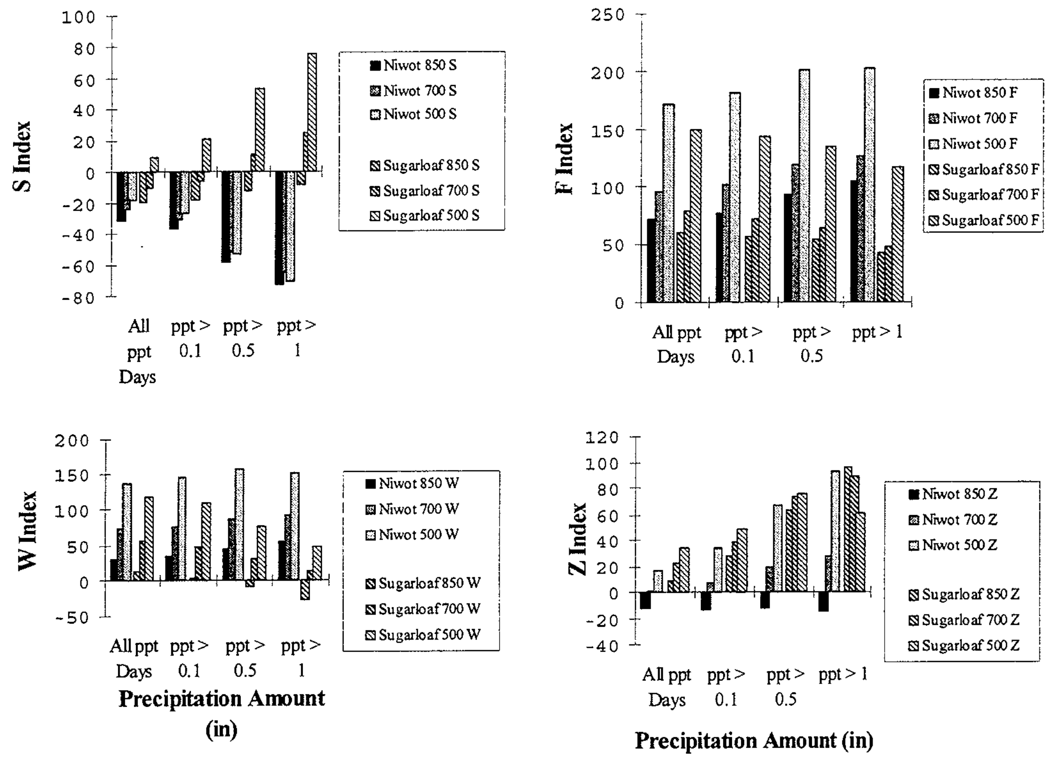

Figure 2 Index values for increasing precipitation amounts at standard millibar levels

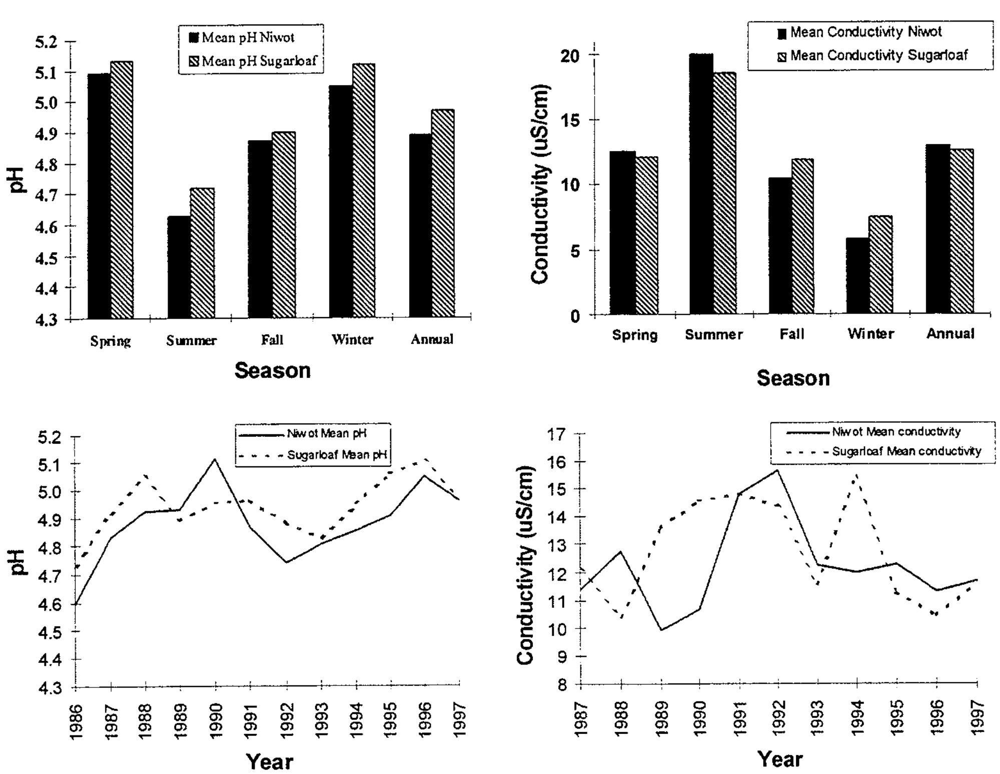

Figure 3 Comparison of Niwot and Sugarloaf pH and conductivity

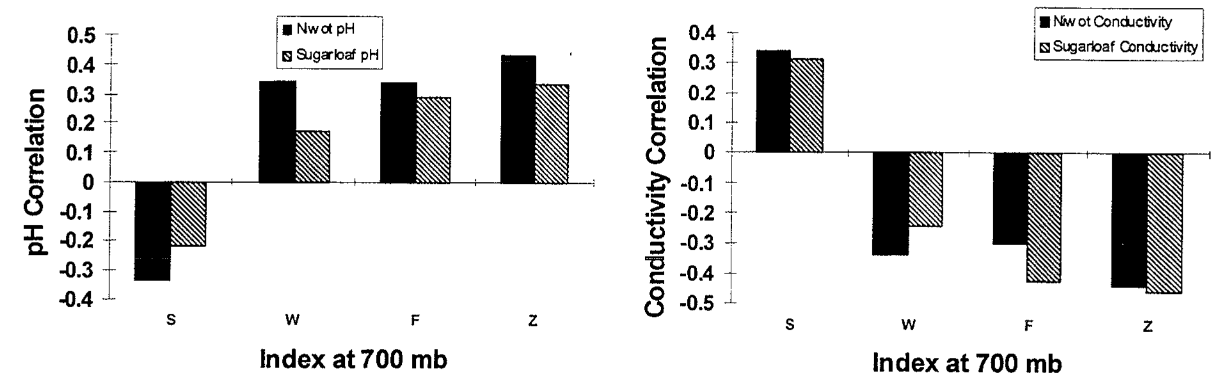

Figure 4 Correlation analysis of indices and pH and conductivity

These results are interesting because they are counter-intuitive, given the relative proximity of the sites to Denver (an assumed pollution source) and compared to the expected cleaner air reflected in the precipitation at Niwot. This suggests chemical inputs from western sources may be higher than assumed. Supporting this possibility, Heuer and others (1998) found that winter chemical loading of the snowpack is greater on the western slope of the Colorado Rockies when compared to the east side.

Atmospheric Circulation

Correlation with airflow indices (see appendix for index derivation) is highly significant, especially at the 700 mb level. Examination of pH shows a positive relationship with the W index at both sites (Figure 4), indicating that air passing over the Divide under situations of strong westerly flow is much cleaner (higher pH) than easterly upslope flow that has passed over the Front Range urban corridor. Also, negative relationships are shown with the S index, suggesting that polar air masses are cleaner than tropical air masses approaching Colorado from the south. The relationships of pH with Z and F are also intuitive with higher pH recorded (cleaner) when both Z and F are high, representative of unsettled windy cyclonic weather. Anticyclones with low flow strength and stagnant circulation lead to much higher precipitation acidity in the little that does fall under such circumstances. Conductivity also shows strong relationships with the circulation indices, in an opposite direction of pH, as higher conductivity indicates greater atmospheric pollution. Similar relationships are shown at 500 mb and at sea level, although the latter are much weaker, indicating that sea level pressure is less relevant in Colorado where sea level is well below the surface of the earth.

Regression of the environmental indicators of pH and conductivity on the four indices shows that between 15% and 36% of the variation in such indicators can be explained by circulation alone. The percentage varies among sites, the atmospheric level, and the indicator chosen. Other potentially important factors not included in this analysis are precipitation amount, intensity, length of the dry period before the precipitation event, the circulation characteristics over the previous few days or weeks (high pollution events are often cumulative, developing over several days), and the behavior of the sources of pollution themselves.

A synoptic scale comparison of extreme pH events reveals clear differences (Figure 5). Low pH extremes (high pollution rainfall events) occur with weak southwesterly airflows associated with a broad trough to the west of Colorado, especially in late summer. High pH extremes (low pollution rainfall events) occur with northwesterly airflow associated with a narrow high pressure ridge over the Pacific Coast of North America.

Conclusions and Future Work

It is somewhat surprising that Sugarloaf is "cleaner" than Niwot, given their relative proximity to the Front Range urban corridor. This fact, coupled with circulation analysis, suggests that precipitation chemistry along the Front Range may be equally influenced by more distant sources to the west (perhaps mostly to the southwest) as it is from the local Denver area. Clearly, more work can be done in this area, since we also found that up to one-third of the variability in field pH and conductivity is due to atmospheric circulation changes. This leaves the remaining two-thirds of the variability unexplained. Changes in source strength and composition; length of time between precipitation events; length, duration, and intensity of each precipitation event; sampling instrumentation artifacts; and the circulation characteristics over the previous few days or weeks, are all factors to be investigated.

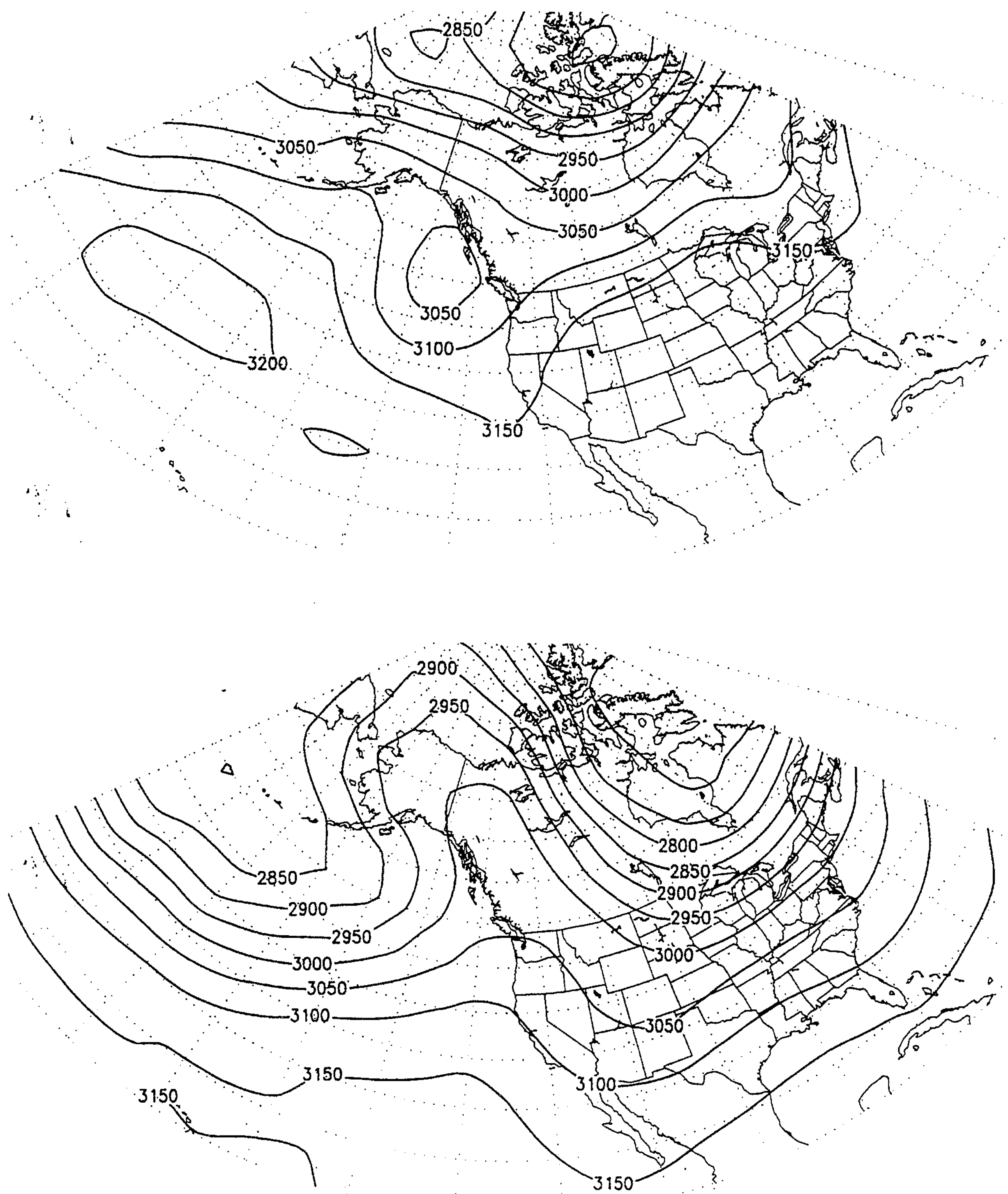

Figure 5 (A) Extremely low pH (high acidity) at Niwot, 700 mb pressure height map (14, 15, 16, and 20 August 1984); (B) Extremely high pH (low acidity) at Surgarloaf and Niwot, 700 mb pressure height map (1–4 April 1984)

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Appendix

Method For Air Flow Classification and Development of Indices

Synoptic climatology attempts to relate surface elements to the larger scale atmospheric circulation pattern. This can be done through classification of airflow patterns using objective or subjective approaches. In this study, indices of circulation characteristics were developed to represent the vigor of the circulation or flow strength (F), the strength of southerly (S) and westerly (W) flow components, and vorticity (Z). The indices are outlined in Figure 6 and are based on those of Jenkinson and Collison (1977) with some modifications. The region of interest ranges from lat 30° N to 50° N and from long 115° W to 95° W (see Figure 1), with the Front Range of Colorado centrally located.

Pressure values are required for the 25 grid points covering the area from lat 50°N to 30°N and from long 115°W to 95°W. Grid points are labeled p_1 to p_{25}. The method is a modified version of Jenkinson and Collison (1977).

Southerly (S) and Westerly (W) flow strength indices are obtained using the following algorithms:

$$S = 1.31[0.25(p_9 + 2p_{14} + p_{19}) - 0.25(p_7 + 2p_{12} + p_{17})]$$

$$W = 0.25(p_{17} + 2p_{18} + p_{19}) - 0.25(p_7 + 2p_8 + p_9)$$

Flow Strength (F) is obtained by:

$$F = \sqrt{(S^2 + W^2)}$$

Derive **Vorticity (Z)** by first calculating southerly vorticity (Z_s) and westerly vorticity (Z_w)separately:

$$Z_s = 1.14 \times [0.25(p_{10}+2p_{15}+p_{20}) - 0.25(p_8+2p_{13}+p_{18}) - 0.25(p_8+2p_{13}+p_{18}) + 0.25(p_6+2p_{11}+p_{16})]$$

$$Z_w = 1.07 \times [0.25(p_{22}+2p_{23}+p_{24}) - 0.25(p_{12}+2p_{13}+p_{14})] - 0.95[0.25(p_{12}+2p_{13}+p_{14}) - 0.25(p_2+2p_3+p_4)]$$

And then summing for Z:

$$Z = Z_w + Z_s$$

Figure 6 Classification mathematics

The flow strength index (F) is strongest when there is a steep pressure gradient across the chosen region and is a measure of the magnitude of ventilation across Colorado.

The airflow can be further broken down into southerly (S) and westerly (W) components. Under a strong outbreak of tropical air the S value will be high, whereas a negative S indicates strongly northerly advection. A high W value means a strong zonal flow from West to East, whereas a negative value indicates a blocked situation with easterly flow. In Colorado's case, this would be upslope flow.

Finally, vorticity (Z) is a measure of anticyclonic or cyclonic spin in the circulation pattern. Negative vorticity is associated with anticyclones and fair, settled weather, whereas positive vorticity is associated with cyclonic storms. In this way Z and F are often related, although they measure different features of the circulation.

Organic Geochemical Analysis of Sediments from the California Continental Margin: Reconstruction of Climate and Oceanographic Conditions During the Last 160 kyr

Kai Mangelsdorf, Ute Güntner, and Jürgen Rullkötter

Abstract

Sediment samples from three ODP holes (Ocean Drilling Program Leg 167) representing a south-north transect along the California coastline were investigated by organic geochemical methods to reconstruct the climatic and oceanographic conditions on the California continental margin during the last 160 kyr. Alkenone-derived paleosea surface temperatures (calculated from the $U_{37}^{K'}$ Index) reveal a clear relationship to global climatic changes during that time. Total organic matter accumulation often coincided with glacial-interglacial variability, indicating a connection between marine bioproductivity and climate. Apparently, atmospheric circulation induced stronger coastal upwelling during interglacial stages and weaker upwelling during glacial stages. Consequently, it is suggested the California Current was weaker during glacial periods and stronger during interglacial periods.

Introduction

The California continental margin is characterized by a complex atmospheric and oceanographic system, which strongly influences sedimentation along the California coastline. The California Current (Figure 1) and the coastal California upwelling are largely driven by the wind pattern prevailing in this area. The local wind pattern depends on the seasonal variation of strength and position of the atmospheric pressure systems of the North Pacific Ocean and the western North American continent, in other words, the North Pacific High and the North American Low, inducing an intra-annual variability in upwelling pattern along the coastline (Huyer 1983). The structure of the California Current and the closely associated coastal upwelling, therefore, are highly sensitive to climatic changes.

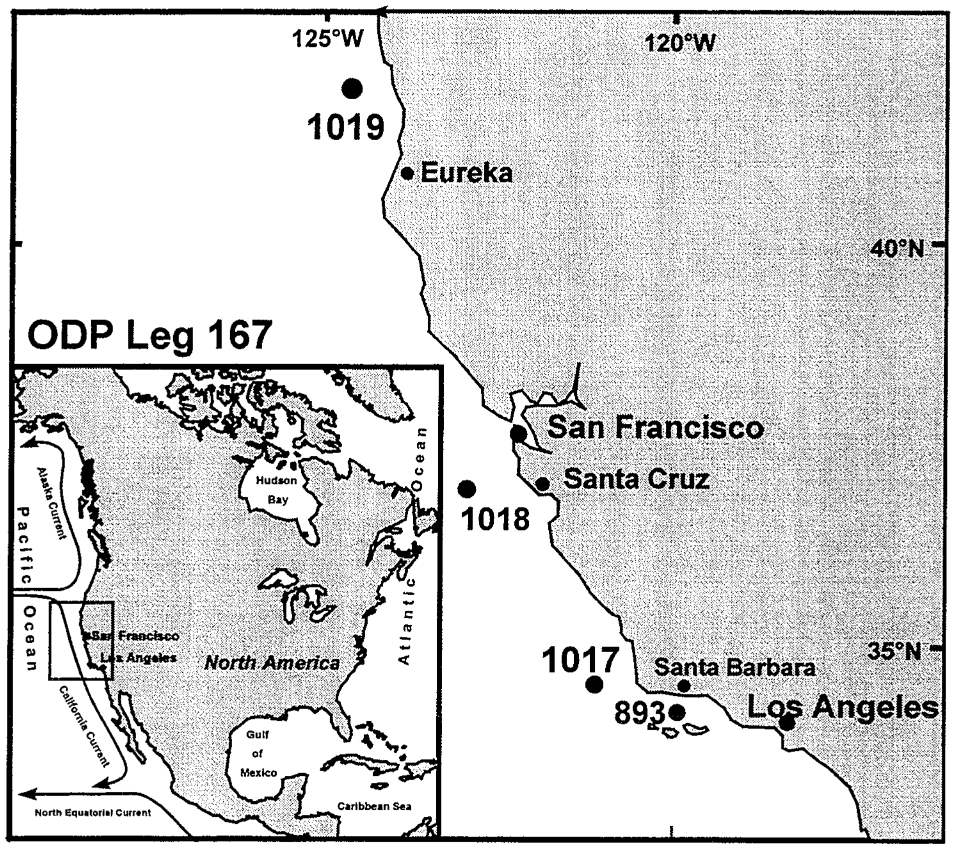

Figure 1 Map of the study area on the western North American continental margin showing the drilling locations 1017, 1018, and 1019 (ODP Leg 167), as well as Site 893 in the Santa Barbara basin (ODP Leg 146)

For the reconstruction of the climatic and oceanographic conditions on the California continental margin during the last 160 kyr, we studied sediments from Ocean Drilling Program (ODP) Holes 1017B, 1018A, and 1019C representing a south-north transect (see Figure 1). Molecular organic geochemical response to climatic variations in this area has already been studied by our group in the Santa Barbara basin (ODP Leg 146, Hole 893A; Hinrichs and others 1997), and the results are used for comparison here.

Analytical Methods

After freeze-drying and grinding, the sediments were analyzed for their carbon and sulfur contents by combustion in a LECO CS 444 instrument. The carbonate contents were determined by a coulometric method using a UIC CO_2 coulometer.

For lipid analysis, the sediment samples were extracted ultrasonically using a mixture of dichloromethane and methanol (99/1, v/v). After addition of internal standards (squalane, erucic acid [n-C_{22}:1], 5α-androstan-17-one), the n-hexaneinsoluble portions ("asphaltenes") were precipitated by addition of a large excess of *n*-hexane. The *n*-hexane-soluble material were separated into fractions of aliphatic hydrocarbons, aromatic hydrocarbons, and polar compounds (NSO fraction) by medium-pressure liquid chromatography (MPLC; Radke and others 1980).

Due to the complexity of the NSO fractions, the carboxylic acids were separated using a liquid chromatography column (120 mm x 10 mm) filled with KOH-impregnated silica gel 100 (63 to 200 µm; a solution of 500 mg KOH in 10 ml isopropanol was added to 4 g silica gel). After elution of the nonacidic compounds with 120 ml dichloromethane, the potassium salts of the acids were converted to the free acids with 50 ml of a solution of formic acid (2% in dichloromethane) and eluted with 80 ml dichloromethane. For molecular analysis, the polar fractions were silylated with N-methyl-N-trimethylsilyltrifluoroacetamide (MSTFA).

Gas chromatography was performed on a Hewlett Packard 5890 series II instrument equipped with a Gerstel temperature-programmed cold injection system and a fused silica capillary column (30 m length, 0.25 mm inner diameter, 0.25 µm film thickness, coated with DB-5 [J&W]). Helium was used as the carrier gas, and the temperature of the oven was programmed from 60 °C (1 min) to 305 °C (50 min) at a rate of 3 °C/min. For compound identification the same gas chromatographic system was used linked with a Finnigan SSQ 710 B mass spectrometer, which was operated in the electron impact mode at a scan rate of 1 scan/s.

Reconstruction of the Paleoclimate on the California Continental Margin

In the past decades, a molecular organic geochemical proxy, the $U^{K'}_{37}$ Index, was established to estimate paleosea surface temperatures (SST; Prahl and Wakeham 1987). Long-chain polyunsaturated methyl and ethyl ketones with 37-39 carbon atoms are known to be constituents of certain phytoplankton genera, such as the coccolithophores *Emiliania huxleyi* and *Gephyrocapsa oceanica*, belonging to the family Haptophyceae (Volkman and others 1995, 1980). The unsaturation ratio of the C_{37} methyl ketones with two to four double bonds ($U^{K'}_{37} = [C_{37:2} - C_{37:4}]/[C_{37:2} + C_{37:3} + C_{37:4}]$) was, therefore, recognized as a temperature-sensitive parameter reflecting environmental growth temperatures (Brassell and others 1986). With rising temperature, the concentration of the diunsaturated ketone ($C_{37:2}$) increases relative to that of the more highly unsaturated isomers. In laboratory culture experiments of *Emiliania huxleyi*, Prahl and Wakeham (1987) found a linear relationship between the simplified $U^{K'}_{37}$ Index ($U^{K'}_{37} = [C_{37:2}]/[C_{37:2} + C_{37:3}]$) and growth temperatures over the range of 8 to 25 °C. They established a calibration equation for paleosea surface temperature assessment, which was slightly modified later by Prahl and others (1988). The modified equation ($U^{K'}_{37} = 0.034 * SST + 0.039$) allows SST estimates with remarkable accuracy throughout much of the world ocean (Müller and others 1998).

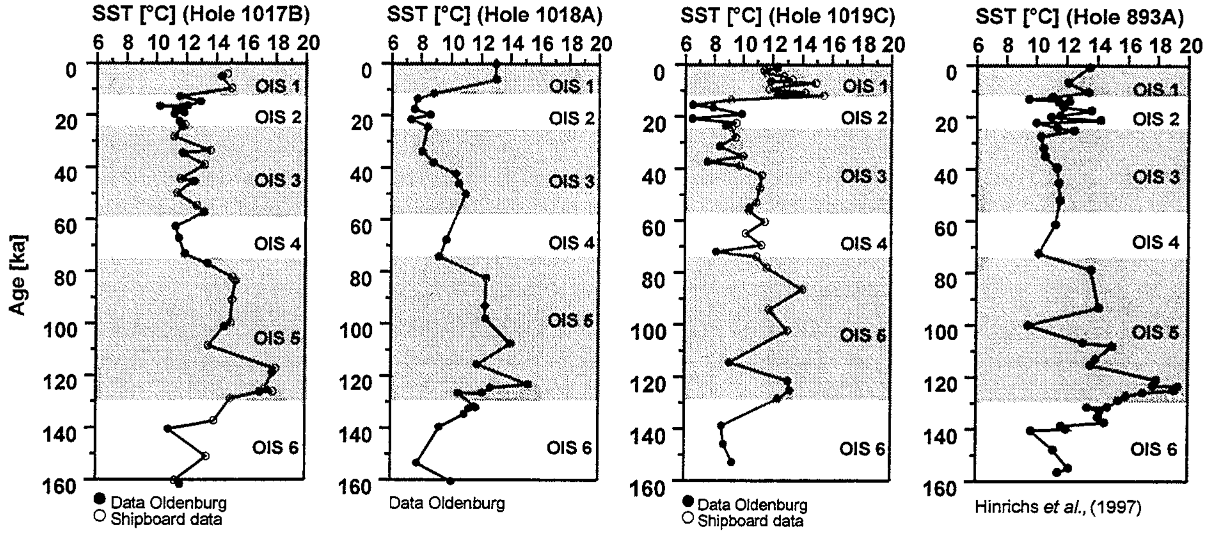

Figure 2 Alkenone-derived paleosea surface temperature (SST) profiles for Holes 1017B, 1018A, 1019C (California continental margin), and 893A (Santa Barbara basin). The sections shaded gray represent warmer periods. OIS = oxygen isotope stage.

The alkenone-derived paleosea surface temperature profiles (calculated from $U^{K'}_{37}$; Prahl and others 1988) of Holes 1017B, 1018A, and 1019C reveal strong temperature changes, which match well the glacial-interglacial cycles during the last 160 kyr (Figure 2). Higher temperatures were observed during the Holocene (Oxygen Isotope Stage 1) and the last interglacial (OIS 5) whereas up to 4 to 6 °C lower temperatures occurred during the last glacial (OIS 2), and stages OIS 4 and 6. OIS 3 is characterized by only moderately increased temperatures. This temperature variability shows how sensitively the California Current, transporting water masses and thereby the temperature signal into this area, reacts to climatic changes.

A comparison of the SST profiles of Holes 1017B and 1018A with the SST data from Hole 893A in the Santa Barbara basin (Hinrichs and others 1997) reveals little coincidence for the last glacial period (OIS 2). During that time, the California Current was probably weaker and diverted further offshore due to the lower sea level. This may have reduced the influence of the California Current on the temperature signal in the sediments of the Santa Barbara basin. At the same time, warmer surface currents from the southeast may have become occasionally more important. In contrast to the differences during the last glacial, uniformly elevated paleosea surface temperatures during the last interglacial (OIS 5) in all holes studied point to a stronger California Current extending closer to the coast and influencing also the water masses of the Santa Barbara basin.

Reconstruction of the Paleoceanographic Conditions

The modern California continental margin is strongly characterized by seasonal upwelling along the entire coastline (Huyer 1983). Taking the present situation as an analogy for the past, we believe that the total organic carbon (TOC) contents in sediments of Holes 1017B and 1018A together with the organic carbon mass accumulation rates (C_{org}MAR) suggest elevated marine bioproductivity during large parts of the interglacials (OIS 1 and 5) and during OIS 3 due to enhanced coastal upwelling. Reduced bioproductivity during the glacials may then have been due to reduced coastal upwelling. As a slight deviation from this general trend, organic carbon accumulation appears to have increased already in the late glacial period at Site 1017.

Off Oregon (Site 1019), TOC contents reveal higher marine productivity for the transition from the last glacial to the Holocene (as already reported by Lyle and others [1992]) and at the beginning of OIS 5 (Figure 3), but not during OIS 3. Additionally, the C_{org}MAR data reveal higher organic carbon accumulation already during the last glacial period. This may indicate that the mechanisms affecting organic carbon accumulation on the Oregon continental margin were not identical to those on the California continental margin.

Contrasting the marine (dinosterol; Volkman 1986; Volkman and others 1998) and the terrestrial (C_{25}-C_{35} *n*-alkanes; Eglinton and Hamilton 1967) biomarker profiles with that of TOC reveals that the latter predominantly reflects the marine organic matter signal. The strong correlation between organic matter accumulation and the glacial-interglacial cycles in the sediments of Holes 1017B and 1018A suggest organic carbon accumulation along the California continental margin is controlled, or at least strongly influenced, by climatic and thereby atmospheric changes.

During the interglacials, the climatic and atmospheric regime appears to have supported enhanced marine productivity by inducing strong coastal upwelling similar to the present-day situation along the California continental margin while there was not such an effect in glacial periods. Such a scenario would be consistent with a climatic model proposed for the Holocene/last glacial transition by Kutzbach (1987). In this model (Figure 4), the summer position of the North Pacific High is located more to the south (about 30°N) and nearer to the North American coast (about 130°W) than today due to glaciation of the North American continent during the last glacial. The coast-parallel winds are replaced by weaker and variable winds coming more from the east than from the north. These winds are less favorable for inducing coastal upwelling at the central California margin and should also reduce the intensity of the California Current.

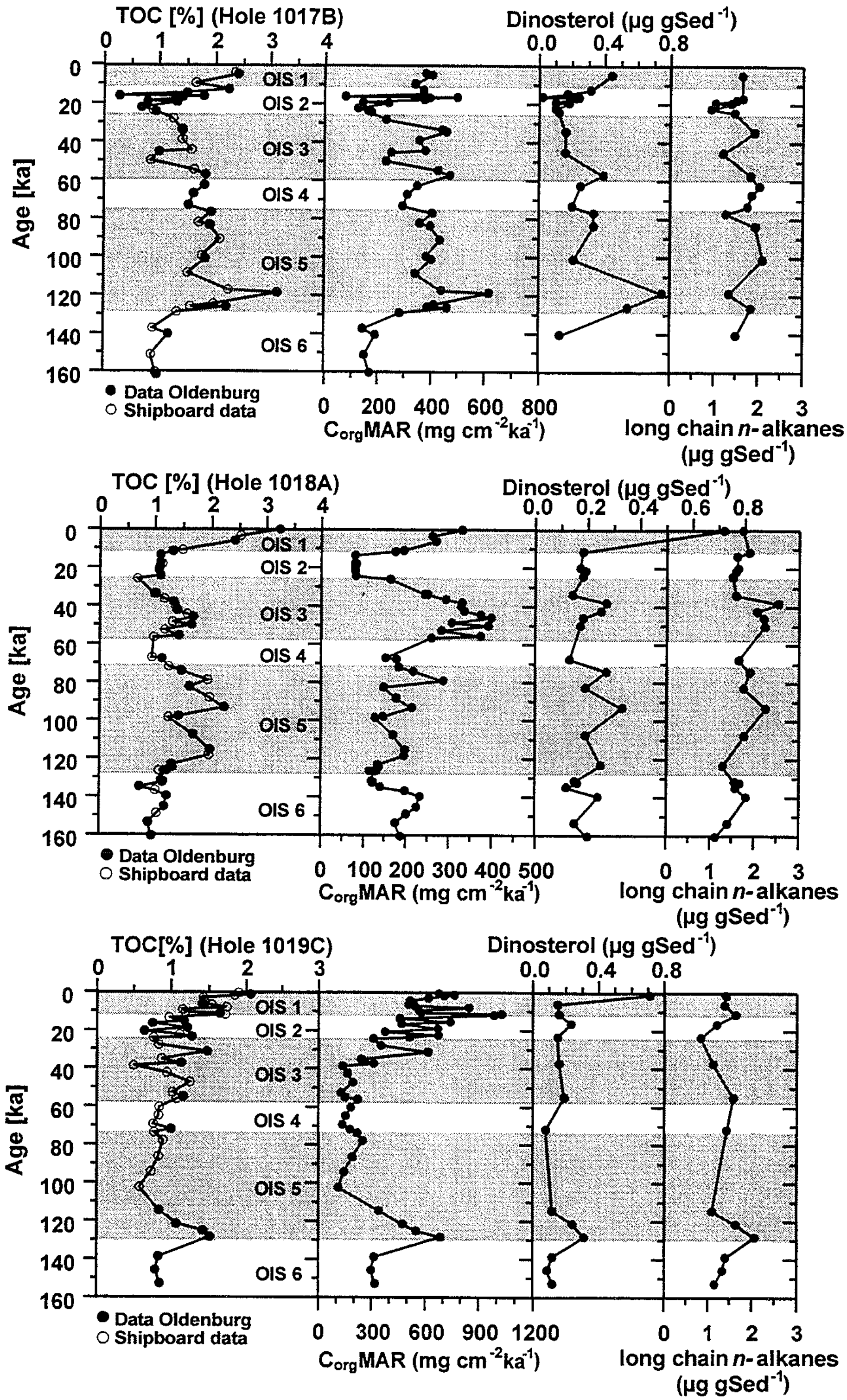

Figure 3 Total organic carbon contents, organic carbon mass accumulation rates (C_{org}MAR), and marine (dinosterol) and terrestrial (C_{25}-C_{35} *n*-alkanes) biomarker records of sediment samples from Holes 1017B, 1018A, and 1019C. The sections shaded gray represent warmer periods. OIS = oxygen isotope stage.

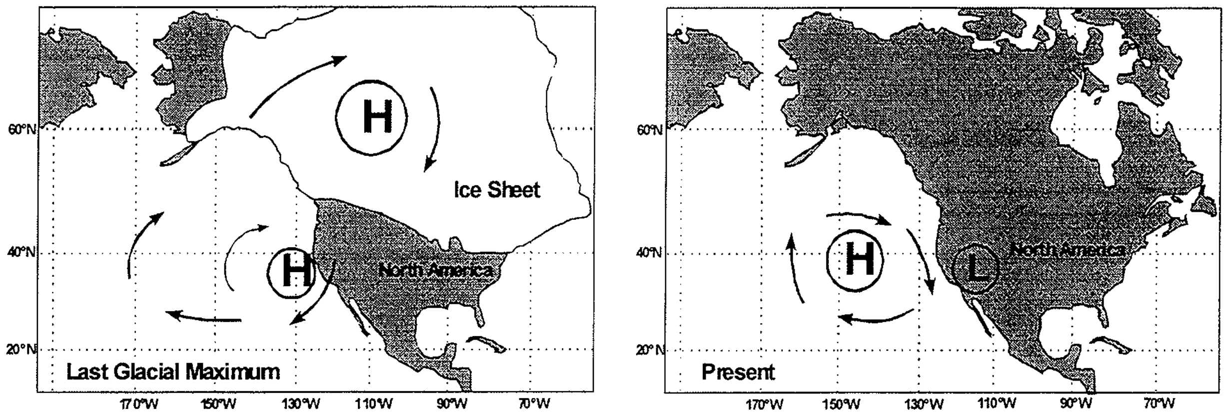

Figure 4 Surface winds and position of the North Pacific High for the 18 ka (last glacial maximum; modeled by Kutzbach [1987]) and the present summer situation. Arrows denote main wind directions.

Conclusions

Climatic and atmospheric conditions similar to those today apparently led to strong coastal upwelling during the interglacials and OIS 3 along the central California coastline and appear to have been less favorable for coastal upwelling during the glacials. The investigation of paleosea surface temperatures and coastal upwelling indicators—and, therefore, of the local wind system—suggests a weaker and further offshore flowing California Current during the glacials and a stronger current intensity closer to the coast during the interglacials.

Acknowledgments

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Pacific Northwest Integrated Assessment of the Impacts of Climate Variability and Change: The Potential Role of Spatial Comparisons and Synthesis

Edward L. Miles, Amy K. Snover, Alan Hamlet, Bridget Callahan, and David L. Fluharty

Abstract

The Pacific Northwest (PNW) regional assessment is an integrated examination of the consequences of natural climate variability and projected future climate change to the natural and human systems in the region. The assessment currently focuses on four sectors: hydrology and water resources, forests and forestry, aquatic ecosystems, and coastal activities. The assessment begins by identifying and elucidating the natural patterns of climate variability in the PNW on interannual to decadal timescales. The pathways through which these variations are manifested and their impacts on the natural and human systems of the region are investigated. Knowledge of these pathways allows an analysis of the potential impacts of future climate change, as defined by Intergovernmental Panel on Climate Change climate change scenarios. In this presentation, the Pacific Northwest region is defined as the Columbia Basin plus the coastal regions of Washington and Oregon. Synthesis is achieved in the following ways. Firstly, by constructing an empirically-derived representation of the climate system of the region and the pattern generated by the flow of impacts within each sector. Secondly, by assessing the nature and magnitude of impacts within each sector. Thirdly, by assessing the interactive effects of impacts across all sectors. Fourthly, by assessing the sensitivity and vulnerability of the region, as represented by the four sectors, to climate variability and climate change.

Introduction

Our procedure for the regional assessment began with seeking to understand seasonal/interannual-decadal/interdecadal climate variability over the instrumental meterological record (about 120 years) and beyond that using surrogate indices in paleoclimate recontructions (for example, tree rings, sediment cores). The emphasis is placed on understanding shifts in the physical climate dynamics of the coupled ocean/atmosphere/terrestrial systems of the Pacific Northwest (PNW).

We proceeded to assess the impacts of climate variability on natural systems within four "sectors" in detail: hydrology and water resources, forests and forestry, and aquatic ecosystems—emphasizing salmonids as the bridge between marine and freshwater environments—and coastal activities, particularly those at the land-water interface. A similar assessment is performed on the socioeconomic and political systems of each sector. In both assessments we try to differentiate between climate-induced and anthropogenic effects as stressors. At this stage, we asked whether the observed climate dynamics generated threshold effects for both natural and social systems. Threshold effects are important because they speed up and amplify rates of change.

We then engaged in a detailed comparison of the impacts of climate change, that is, the projected changes in temperature and precipitation for the region derived from the Intergovernmental panel on Climate Change (IPCC) "best guess" climate change scenarios. For this purpose, we use downscaled versions of four general circulation models (GCMs), three of which are archived by IPCC for this purpose: Max Planck Institute (MPI), United Kingdom Meteorological Office/The Hadley Centre (UKMO), the NOAA Geophysical Fluid Dynamics Laboratory (GFDL). We also use the Canadian Center for Climate Modeling and Analysis (CCC) model. These GCMs are then linked to hydrologic and reservoir operation models to determine the impacts of climate change on the regional hydrology and on regional patterns of reservoir operations. Regional hydrology appears to be the most sensitive terrestrial signal of climate variability and change in the PNW.

The final stage in the assessment is a detailed evaluation of the capacity of existing institutional arrangements to respond effectively to the scope of predicted change. The emphasis at this point is on assessing the region's planning, adaptation, and mitigation capabilities on an aggregated regional basis, as well as a sector-by-sector basis. Alternative options for improving response capacity and reducing vulnerability are also identified and evaluated.

It is somewhat unusual to have a fully-integrated interdisciplinary team that combines the natural sciences, social sciences, and law, and operates as a single organic entity on a problem such as the one we have chosen. But more unusual is that since its inception this team was required to build linkages with the community of state, federal, regional, tribal, non-governmental, and private sector agencies and firms. These organizations may use climate forecasts and would benefit from a greater understanding of how climate variability and change affect the operations and activities in which they were engaged, both now and in the future.

Within the PNW, we have well-developed connections with 31 organizations, of which 15 are considered full partners in this research by contributions in kind (information or staff members or both) or by funding. The full list of our user community connections is presented in Table 1. Although private sector firms are not listed, this is not for lack of trying.

Table 1 Connection to the user community

Partnerships	*Assistance*
• Seattle Public Utility, Water Department	• Seattle City Light
• Portland Water Bureau	• Seattle City Council
• Oregon Department of Land Conservation and Development	• Tacoma Power and Light
• Washington Department of Ecology	• Alaska Department of Fish and Game
• Washington Department of Health	• Washington Department of Transportation
• Washington Department of Fish and Wildlife	• Washington National Guard
• Oregon State University: Coastal Impacts	• Northwest Indian Fisheries Commission
• Northwest Power Planning Council	• Columbia River Intertribal Fisheries Commission
• Columbia Basin Ecosystem Management	• Bonneville Power Administration
• Sustainable Development Research Institute, University of British Columbia	• NOAA River Forecast Center
• National Park Service	• Environmental Protection Agency
• US Bureau of Reclamation	• US Army Corps of Engineers
• National Marine Fisheries Service: Northwest Fisheries Science Center	• USDA Natural Resource Conservation Service
• International Pacific Halibut Commission	• North Pacific Fisheries Management Council
• National Marine Fisheries Service, Office of the Regional Director	• National Marine Fisheries Service: Northwest Fisheries Science Center
	• Bureau of Land Management

Observing Regional Patterns of Climate Variability and Impacts

The results of the conceptual approach adopted by the JISAO/SMA Climate Impacts Group to observing and assessing regional patterns of climate variability is shown in Figure 1. This figure depicts two independent drivers (human intervention or anthropogenic activities and climate variability and change) of impacts in the four sectors (hydrology, forestry, aquatic ecosystems, and coastal activities) chosen for analysis. Within the climate box two specific patterns of climate variability are identified, the El Niño-Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO). Both climate drivers operate independently, but the former is on an interannual timescale and the latter is on a decadal timescale. Important interactions can be observed between the two drivers.

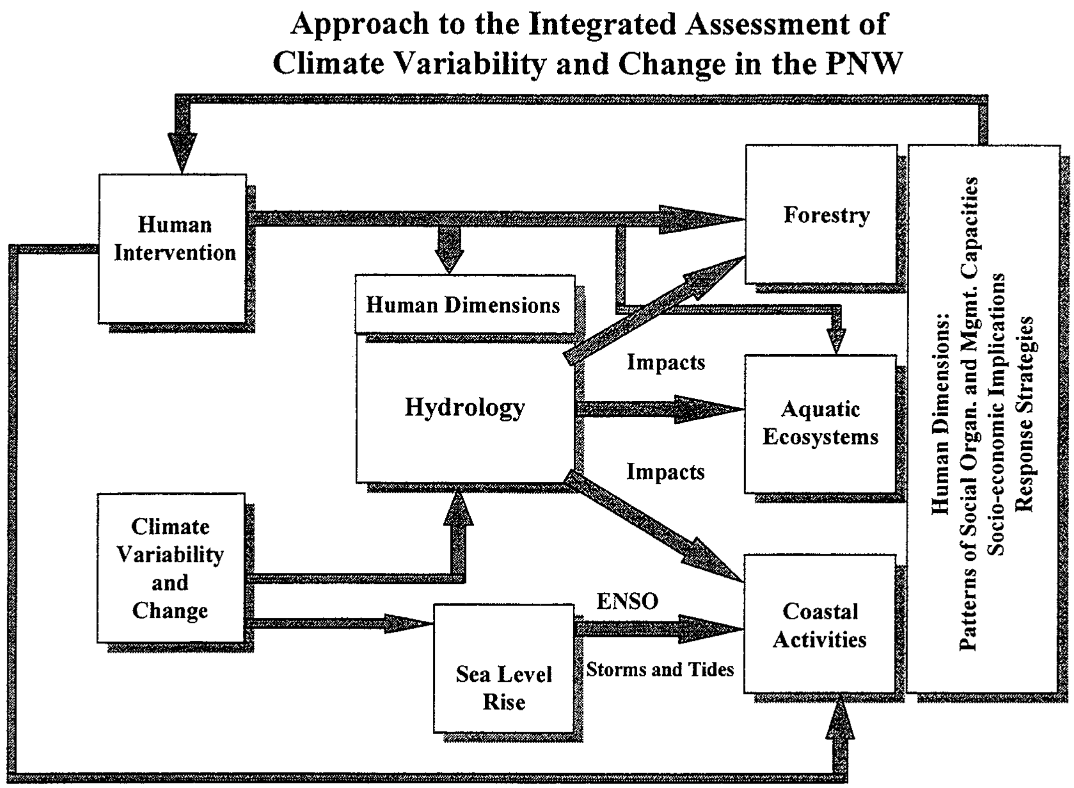

Figure 1 Results of the approach to the integrated assessment of climate variability and change in the PNW

The PNW is highly sensitive to climate variability on seasonal-interannual and decadal-interdecadal time scales. Thus, both ENSO and the PDO generate important impacts on the four sectors, although the PDO tends to have far more pervasive and longer lasting effects. When the two "drivers" are in phase, these effects are amplified.

There is a remarkable degree of coherence to the regional impacts of climate variability since all impacts, except those generated by sea level rise, are mediated through the regional hydrology. The dominant impact pathway for climate impacts on the PNW, on both seasonal-interannual and decadal time scales, is the regional hydrologic response. This pathway is shown in Figure 2. Climate affects natural systems directly, but the impact of climate on natural systems also depends on the characteristics of the human institutions that use and manage those systems. As a consequence, the direct effects of climate variability are modified to a considerable degree by rule curves and priorities defining patters of reservoir operations in managed river systems.

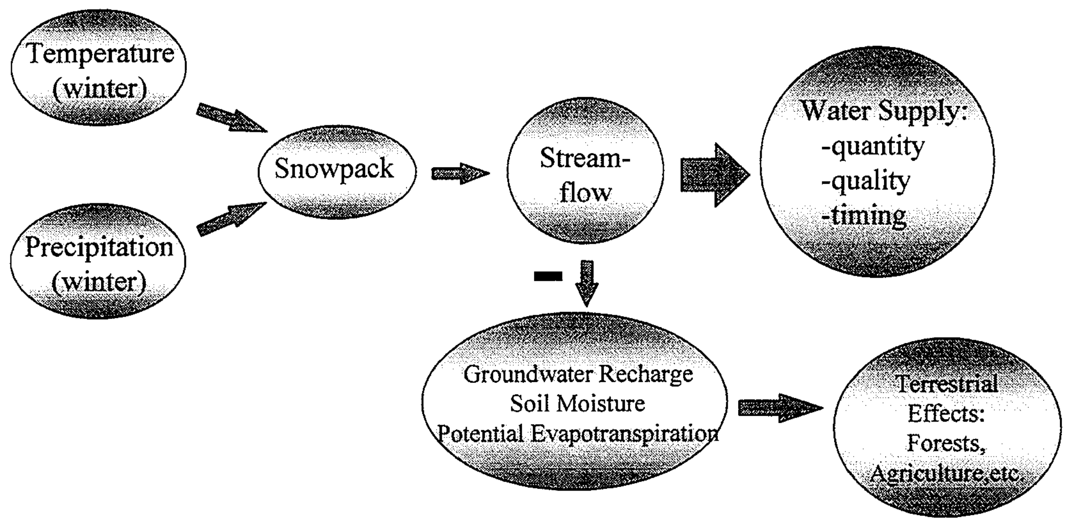

Figure 2 The dominant impact pathway

The region is most vulnerable to precipitation extremes (either floods or drought), but its adaptability is high only with respect to floods in managed rivers. Great technical capacity for adapting to floods exists as a result of advanced infrastructure and high centralization of authority. These conditions do not generally apply in the Columbia Basin with respect to drought, where diverse users stress the water resources system to its limits. Western water law, as represented by the Prior Appropriation Doctrine, severely inhibits society's ability to optimize water use with an emphasis on efficiency. In contrast, both Seattle and Portland, on the western sides of the Cascades, have developed substantial capability to respond to both floods and droughts resulting from current patterns of variability. However, neither the region as a whole, nor Seattle and Portland, possess the storage capacity to respond to prolonged multiyear droughts in the future under conditions of high rates of population growth and significantly declining snowpack as a function of anticipated climate change. Declining capacity to respond to growing demand is aggravated because no single organization effectively speaks for the interests of the region as a whole on a multisectoral basis.

With respect to spatial comparisons, we note that significant differences exist in temperature and precipitation on the westside vs. the eastside of the Cascade Mountain Range. Consequently, significant differences will be experienced in the impacts of climate change on watersheds at different elevations. These differences will contribute to produce significant differences in the capacities of different water resources systems, and therefore in their adaptability. As a result, all analysis in the assessment need to take into account this kind of spatial heterogeneity.

Snow Avalanche Climatic Extremes: Two Examples in the Western United States

Cary J. Mock, Karl W. Birkeland, and Gerald J. Gress

Abstract

The snow avalanche climate of western North America has long been believed to be comprised of three main zones: coastal, intermountain, and continental zones. Examination of daily plots of climate and avalanche variables during a continental extreme at Red Mountain Pass, Colorado, and a coastal extreme at Snowbasin, Utah, demonstrate the importance of understanding snowpack and climatic variations that occur at daily to weekly timescales. These examples indicate the sharp differences in how coastal conditions trigger avalanches in contrast to continental conditions. Avalanches occurring during coastal conditions are related primarily to large snowstorms and recent snowpack accumulations. Conversely, avalanches occurring during continental conditions are related to occasional avalanche events resulting from weak snow layers caused by faceted crystals that persist during most of the winter.

Introduction

Snow avalanches are a severe natural hazard in the mountainous regions of western North America, destroying property, disrupting transportation networks and recreational facilities, and occasionally causing deaths (Voight and others 1990; McClung and Schaerer 1993). Annual numbers of avalanche accidents and fatalities in the United States have increased steadily during the last 50 years. The current average national annual fatality rate was about 25 by the late 1990s, more than five times greater than the average rate in the early 1950s. Economic losses from avalanches are difficult to assess, but conservative estimates indicate they amount to millions of dollars each year when accounting for property damage, snow removal from highways, and avalanche rescues (Voight and others 1990). In recent decades, avalanche hazards are greatest in the Rocky Mountain states due to the increased popularity of skiing and snowmobiling.

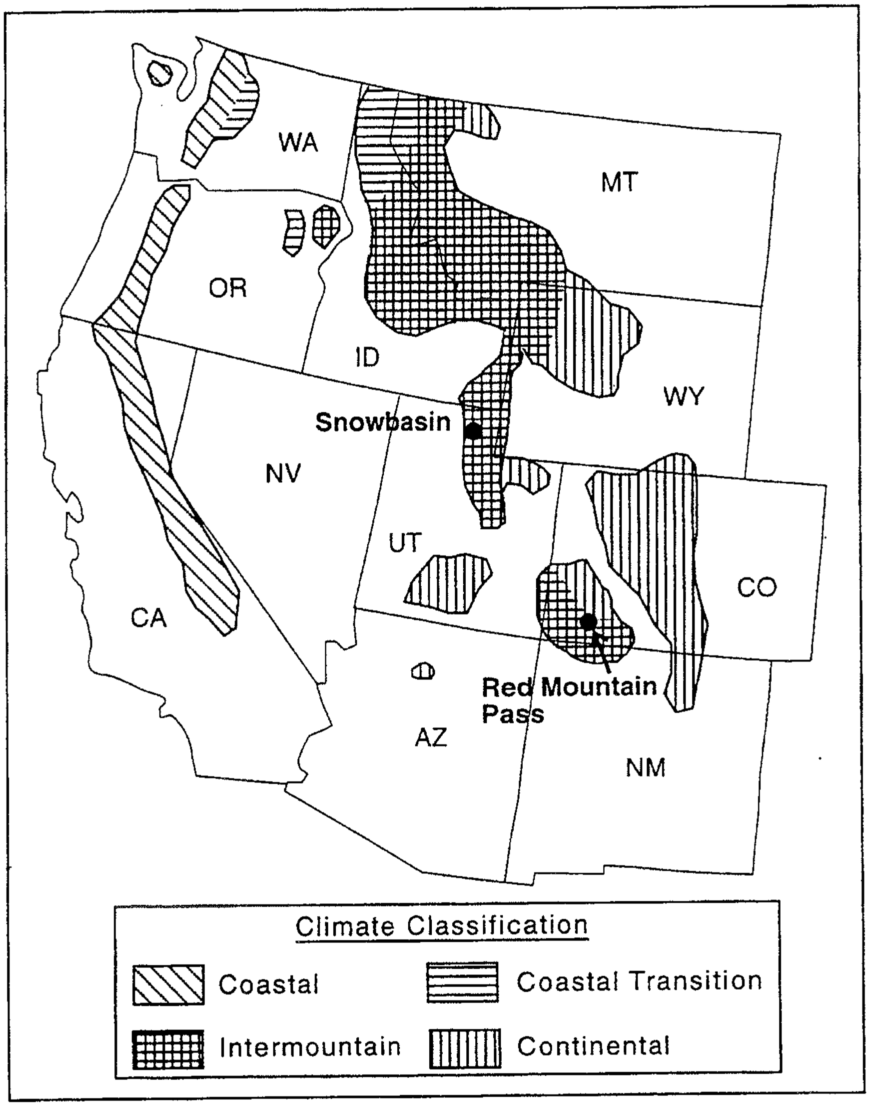

Figure 1 Zonation of avalanche climates in the western United States and selected localities mentioned in the text

The snow avalanche climate of the western United States has long been believed to encompass three major zones following a west-east gradient: coastal, intermountain, and continental (Roch 1949; LaChapelle 1966; Armstrong and Armstrong 1987; Mock 1995; Mock and Birkeland 1999; see also Figure 1). The coastal zone (which includes the coastal transition zone), including the Sierra Nevada and Cascade ranges in the Pacific coast states and extending a bit into northern Idaho, is characterized by mild temperatures, abundant heavy snowfall, a high density snowcover, and a low temperature gradient in the snowpack. Conversely, the continental zone of the Uinta Range in Utah and the Rocky Mountains in Colorado, Wyoming, New Mexico, and parts of Montana, is characterized by cold temperatures, less abundant snowfall, lower density snowcover, and a steeper temperature gradient. The intermountain zone of the northern Rocky

Mountains of Montana, the Wasatch Range of Utah, the Blue Mountains of northeastern Oregon, and the mountains of southwestern Colorado, is intermediate in avalanche climate characteristics between coastal and continental. All of these climatic and snowpack differences are important since they determine the structure of the snowcover and the resultant character of the avalanches that each zone normally experiences.

Examples of Avalanche Responses to Climate

We discuss two examples of how avalanches respond to weather and climate during an extreme continental winter (Red Mountain Pass, Colorado, 1976–1977) and an extreme coastal winter (Snowbasin, Utah, 1985–1986). We developed a daily avalanche hazard index based on the size and frequency of avalanches, with an emphasis on potentially large, damaging avalanches. For further details, refer to Mock and Birkeland (unpublished manuscript). We also constructed daily time series of each entire winter for these two examples: the avalanche hazard index, snowfall, snow water equivalent, snow depth, and maximum and minimum temperature. Such plots allow us to interpret the history of the snowpack for a given season and are routinely used by avalanche forecasters (Fitzharris 1987).

An analysis of the daily data from Snowbasin, Utah, for the 1985–1986 winter shows an example of a coastal year at a predominantly intermountain site (Figure 2). Snowfall starts early, with total snow depth exceeding one meter by 1 December. Such rapid increases in snow depth in the early season are important because this limits temperature gradients within the snowpack, preventing the formation of weak, faceted crystals or depth hoar, which would form an unstable base for subsequent snowfall. The relatively warm (near freezing) and low diurnal ranges of temperatures at Snowbasin during the 1985–1986 winter are common for most coastal sites in the Cascades and Sierras (Ferguson and others 1990), including a rare significant rainstorm which occurred in mid-February that was responsible for an avalanche cycle. Since temperature gradients within the snowpack are minimal, and therefore weak layers of faceted crystals are limited, the snowpack existing before any snowfall is mostly strong. Periods of significant avalanching are evident, but typically occur immediately following large and prolonged storms and usually involve only new snow. Avalanche data for Alta and Snowbird exhibited similar responses during the 1985–1986 winter (Mock and Birkeland, unpublished manuscript).

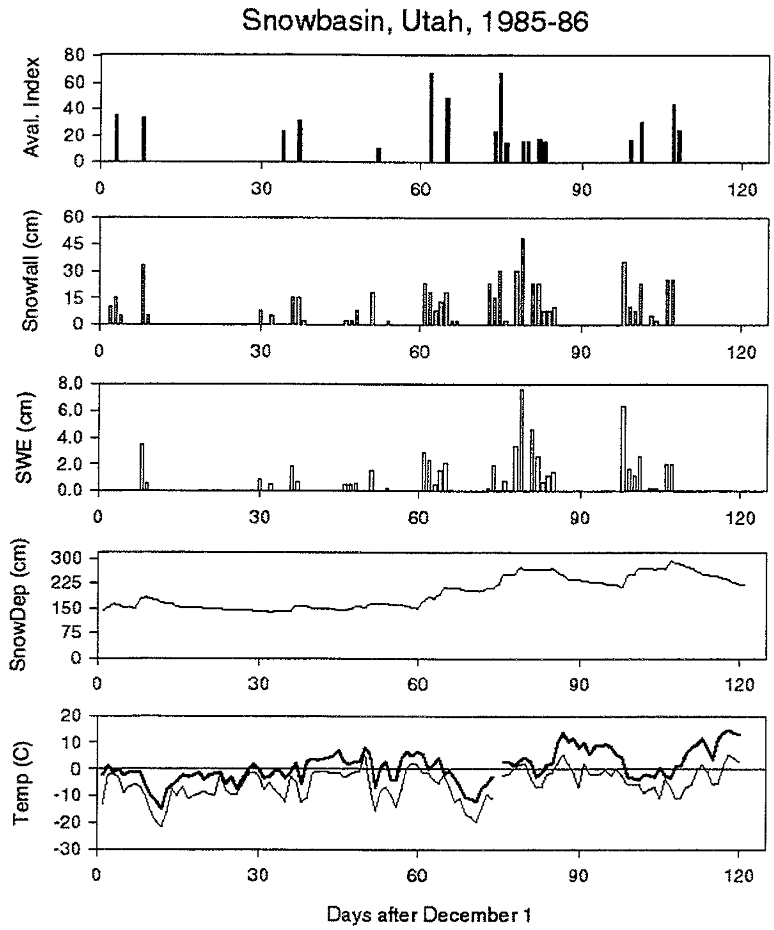

Figure 2 Daily plots of weather and avalanche variables for Snowbasin, Utah, during the 1985–1986 winter

The seasonal plot for Red Mountain Pass, Colorado, during the continental winter of 1976–1977 shows a much different avalanche response than the previous example discussed for Snowbasin (Figure 3). Due to a strong amplified ridge over the western United States (Wagner 1977), the 1976–1977 winter at Red Mountain Pass started out with a thin snowpack of less than 50 cm, mostly subfreezing temperatures (averages are primarily less than –7 °C), and large differences between maximum and minimum temperatures. Assuming a ground temperature of 0 °C, the temperature gradient in the snowpack exceeded 10 °C/m, which is conducive to the formation of weak faceted crystals that form an unstable base for subsequent snowfall (Armstrong and Armstrong 1987). Cold temperatures and a thin snowpack throughout the 1976–1977 winter ensured that weak layers remained prevalent in the snowpack, and even some small storms (less than 25 cm) are associated with relatively high avalanche activity, as measured by the avalanche index. In these cases, only limited, new snowfall is necessary to overload old, weak snow layers of depth hoar, and avalanches releasing often run on the ground and involve the snowpack from the whole season.

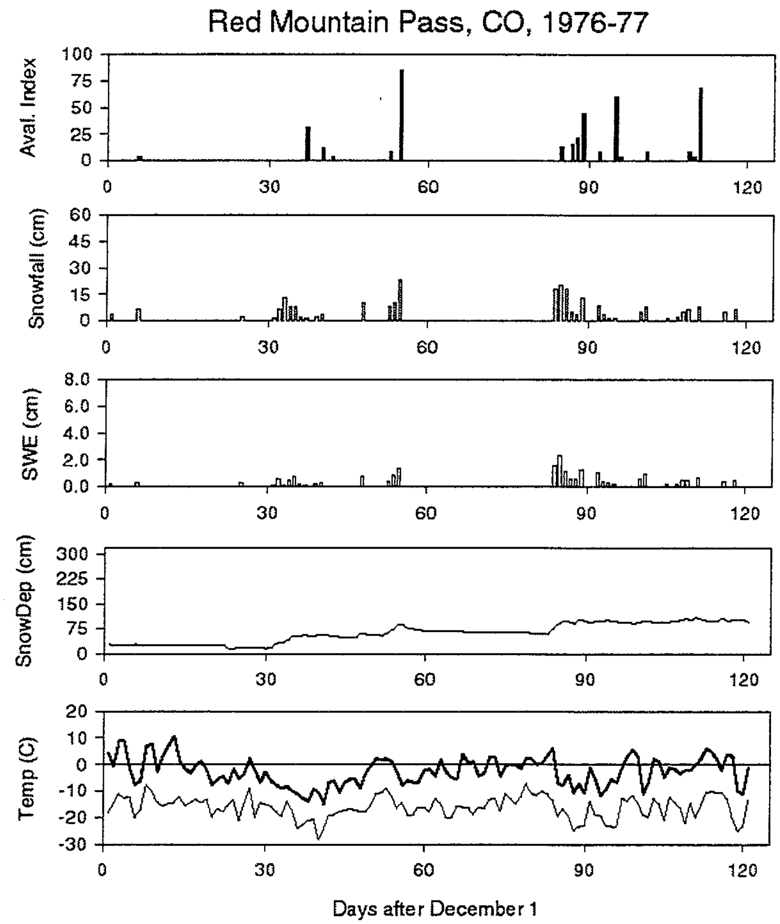

Figure 3 Daily plots of weather and avalanche variables for Red Mountain Pass, Colorado, during the 1976–1977 winter

Summary

Predicting seasonal avalanche characteristics is crucial in areas like Snowbasin, Utah, which is the site of the 2002 Olympic downhill race, and Red Mountain Pass, Colorado, which is the one of the most avalanche-prone roads in the United States. The examples discussed for these two sites indicate the sharp differences in how coastal conditions trigger avalanches in contrast to continental conditions. A thorough knowledge of the type of avalanche climate characteristics that predominate during a given winter provide important supplementary information when examining the relationships between atmospheric circulation, snowpack, and daily weather trends to forecast destructive avalanche cycles. The winters of 1976–1977 and 1985–1986 are well-known avalanche winter extremes (Mock and Kay 1992). Ultimately, accurate forecasting would prove invaluable for avalanche hazard planning and assessment for events such as the 2002 Winter Olympics.

Acknowledgments

We gratefully acknowledge Tom Leonard, Daniel Howlett, and Dan Judd for providing data. This work was supported by NSF Grant #SBR-9807388, from the Geography and Regional Science Program.

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Coping with El Niño-related Droughts in Peasant Agriculture, Northern Costa Rica, 1997–1998

Sarah M. Otterstrom and Benjamin Orlove

Abstract

In northern Costa Rica, the 1997-98 El Niño event was blamed for the severe drought conditions that led to tremendous losses in agriculture. Along the pacific lowlands of northern Costa Rica (Guanacaste), there is a documented strong El Niño drought signal. Nevertheless, for the Caribbean lowlands of northern Costa Rica (Zona Norte) no strong or consistent El Niño signal has been documented. Following the subsidence of drought conditions (July 1998), informal interviews were conducted with small-scale (2 to 15 ha) farmers throughout the Zona Norte and Guanacaste regions. This was done in order to evaluate the methods by which farmers ameliorated the effects of drought and to qualify the cultural perception of El Niño events. Results suggest a strong presence of anticipatory and preventative coping mechanisms in the Guanacaste region. Examples of these coping mechanisms include laying land fallow during dry periods, seeking alternative wage labor during drought, maintaining social and family networks in the city, planting drought resistant forage grasses, selling half of their cattle before dry season begins, and maintaining a network of alternative wells during the dry season. Meanwhile, in the Zone Norte, very few, if any, coping mechanisms were observed. Not surprisingly, losses were most severe for farmers in the Zona Norte. Results suggest a relationship between the presence of cultural coping mechanisms in peasant agriculture and the frequency with which anomalous climate conditions effect them. In the future, policy makers may use this relationship to identify communities that are particularly vulnerable to anomalous conditions—those that do not consistently experience these anomalies—during extreme and unique climate events.

Introduction

In recognition of the importance of climate research to human society, climate scientists have begun broadening their scope to find further applications for their work. The 1999 PACLIM workshop focusing on the relationship between climate and society is evidence for this transition. When discussing climate and society, one must recognize that certain global regions, because of either biophysical or socioeconomic conditions, may be more vulnerable to climate variability than others. Recent publications that focus on such regions have pointed out the potential value of forecasts for predicting agricultural yields (Cane and others 1994). Other research has argued that forecasting agencies must produce accurate forecasts that have a local context to maintain the confidence of local farmers and to be of benefit to them (Finan 1998). The reality is, despite improved forecasting abilities, the institutional weaknesses and economic challenges that these countries face often limit the successful application of forecasts.

In the case of institutional dysfunction or economic incapacitation, the only remaining abilities to cope with extreme events may come from cultural practices already in place. For societies that are completely reliant on the natural environment and its variability, preventative and anticipatory coping actions are often incorporated into subsistence practices in response to previous events.

In recognition of the vulnerability of developing countries to extreme climate events and the likely presence of culturally imposed coping mechanisms to deal with these events, we chose coping mechanisms as our unit of study. Coping mechanisms form part of those culturally shared subsistence practices that are present at the household level. The general objectives of this research were to first observe the role that culture plays in coping with climate anomalies, secondly to explore the ways in which variations in cultural practices differentially affect vulnerability to anomalies, and finally to identify the ways in which variation between the cultural coping mechanisms of two sub-regions correspond to the frequency of a given climate phenomena.

Natural scientists have long recognized that for the distribution and abundance of living organisms it is usually the extremes instead of the averages that matter. Similarly, for human societies, extreme climate and geologic events are often those that are most anticipated and feared, and whose impact bring about the greatest economic and human loss. It is with this parallelism, and with the perception that climate anomalies act as disturbances to human society, that we planted our working hypotheses: the frequency and intensity of climate events will be a determining factor in the presence of household coping mechanisms. We carried out field research in the rural areas of northern Costa Rica, both in the Guanacaste Province (Pacific slope) and the Zona Norte (Caribbean slope, Figure 1).

Costa Rica and El Niño

Although Costa Rica is relatively small geographically, there are significant differences in the effects of inter-annual climate variability across a micro-regional scale. For instance, in Guanacaste, the signal consistent across all El Niño events is drought. By contrast, droughts, in correlation with the El Niño-Southern Oscillation, are apparently rare in the northeastern region of Costa Rica.

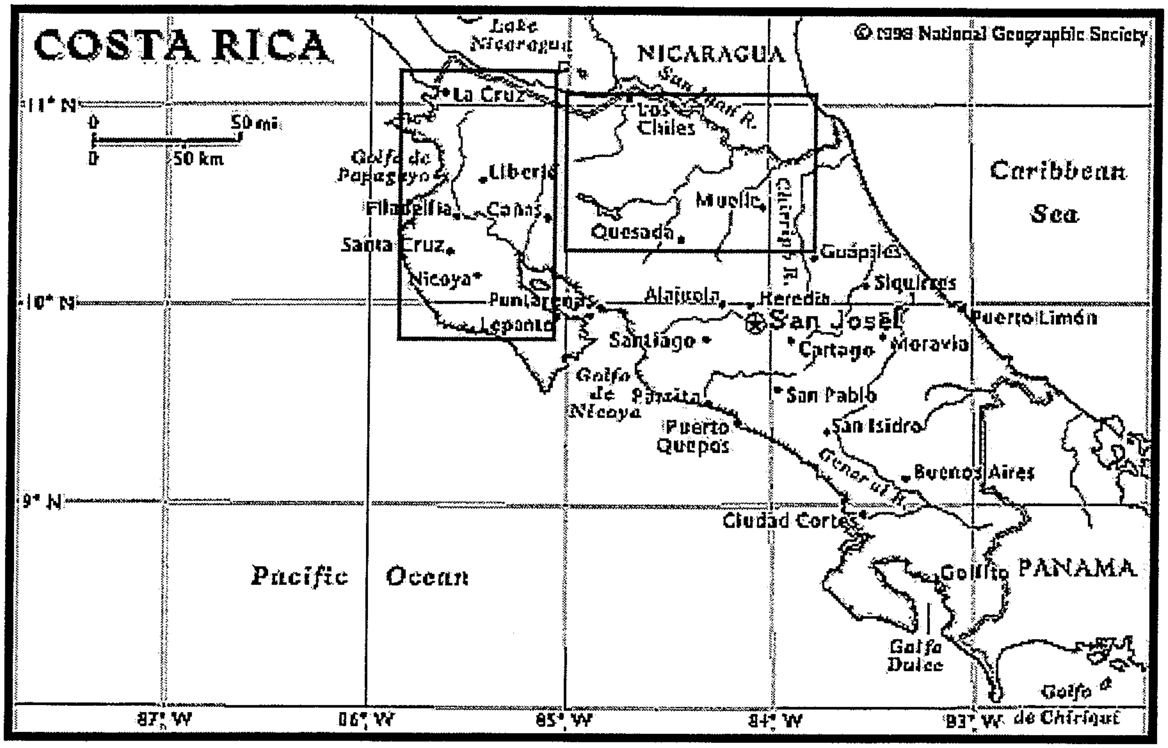

Figure 1 Map of Costa Rica indicating the Guanacaste and Zona Norte study area

For the northwestern province of Costa Rica (Guanacaste), El Niño events are strongly correlated with a decrease in precipitation and an increase in temperature. There is an extenuation of normal, five-month dry season conditions by one or two months (Waylen and others 1994). In contrast, the Zona Norte of northeastern Costa Rica presents a dry season that rarely lasts longer than two months; there is a continual influx of moisture originating in the Caribbean (Matamoros 1990). Furthermore, annual El Niño events in the Zona Norte are generally correlated with an increase in precipitation and flooding. Nevertheless, the 1997–1998 event brought a five-month drought to this region. Relatively short historic records of precipitation do not indicate previous droughts in correlation with ENSO events for the Zona Norte (MAG 1997).

The unexpected drought in the Zona Norte led to heavy economic losses in the agricultural sector. In Guanacaste, although drought related losses in agriculture were severe, they were proportionally less than in the Zona Norte. The rarity of the 1997–1998 drought occurrence in the Zona Norte provided a unique opportunity to study the absence of preventative actions and the presence of reactive ones for coping with the El Niño event.

Given that droughts in the Guanacaste province have occurred repeatedly in the recent history of El Niño events, one would expect the small-scale farming households in this region to have a series of drought-coping mechanisms incorporated into their agricultural practices. One would anticipate that households in the Zona Norte, that had not previously experienced droughts, would lack coping measures.

Coping with Drought

The field component of the research was carried out during July and August 1998 immediately following the subsidence of El Niño related drought conditions. Small-scale farmers were selected from the two regions based on the farm size (farms consisting of less than fifteen hectares). Extension agents from the Costa Rican Ministry of Agriculture assisted in the field by selecting farmers who had been affected by El Niño drought. Informal interviews were conducted with both male and female farmers. Questions were consistent between farms and addressed issues concerning the El Niño drought. For example, farmers were asked about the degree of crop loss, government assistance, farming techniques, preventative measures taken and the general perception of the El Niño phenomena. Thirty interviews were conducted throughout the Zona Norte region and approximately 25 interviews were conducted for the Guanacaste region.

Results of the interviews suggest a strong presence of anticipatory and preventative coping strategies to deal with drought in the Guanacaste region. It was common for farmers to lay their land completely fallow during the dry season, independent of an El Niño event, in order to avoid losses due to potentially extreme dry season conditions. In Guanacasten households, generally, there are family members who have alternative sources of wage labor during the dry season. This source of income serves as a sort of insurance during non-productive droughts. In terms of livestock, the Guanacasten management system is completely adaptive to strongly seasonal conditions. For example, at the onset of the dry season farmers sell half of their cattle to avoid unnecessary losses and lighten the grazing load on their pasture areas. Farmers also plant drought resistant forage grasses and harvest hay, sugar cane, and plantain for cattle food supplements during the dry season. Families often maintain multiple water wells in working condition to guarantee that during rough, dry season conditions a secondary source of water is available for the household and livestock. Finally, there are many cultural holidays in Guanacasten pueblos that are celebrated during the dry season months. These festivities might also be considered a drought coping strategy.

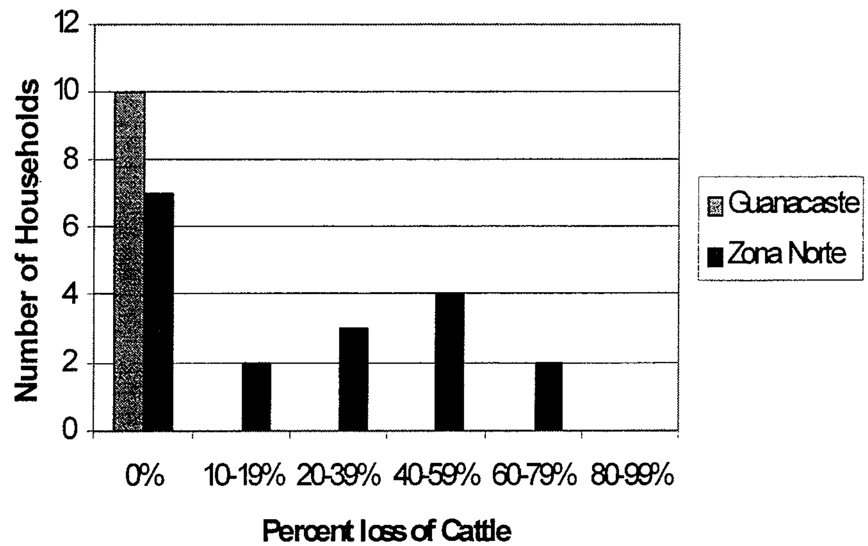

Figure 2 Proportion of cattle lost by region

Meanwhile, in the Zone Norte households, there are few, if any, drought-coping strategies present. Rather, there are some actions that could be considered maladapted to drought. Unlike Guanacaste, the Zona Norte farmers do not have an annual period of fallow for their crops. Drought intolerant crops such as heart of palm, plantain, and root crops were naively planted at the onset of the El Niño drought event. Very few families have alternative sources of wage labor to carry them through periods of low agricultural productivity. With respect to livestock, farmers have drought-intolerant forage grasses in pasture lands and do not plant supplements such as hay and sugar cane. During this particular drought event, farmers did not monitor cattle for dehydration. Not surprisingly, livestock losses were high in the Zona Norte region relative to losses in Guanacaste (Figure 2). Households do not have alternative wells or water sources, a situation that left many families without water during the 1998 drought event.

The majority of household members in both regions had heard that there would be an El Niño event through farm extension workers, radio, and television, yet the belief of the people and the preventative actions taken were distinct between the two regions (Figure 3). Farmers as wells as government agencies in the Zona Norte did not expect drought conditions to occur as a result of El Niño. There was no previous history of their occurrence and drought assistance was not made available to farmers until the final days of the drought. Government agencies and farmers in the Guanacaste region had anticipated a drought during the El Niño event. Although farmers had been forewarned of the drought, because of economic limitations, they took few extraordinary preventative actions beyond what they traditionally do to prepare for the normal dry season. Apparently, the annual dry season conditions in Guanacaste necessitate the implementation of drought mitigation measures every year.

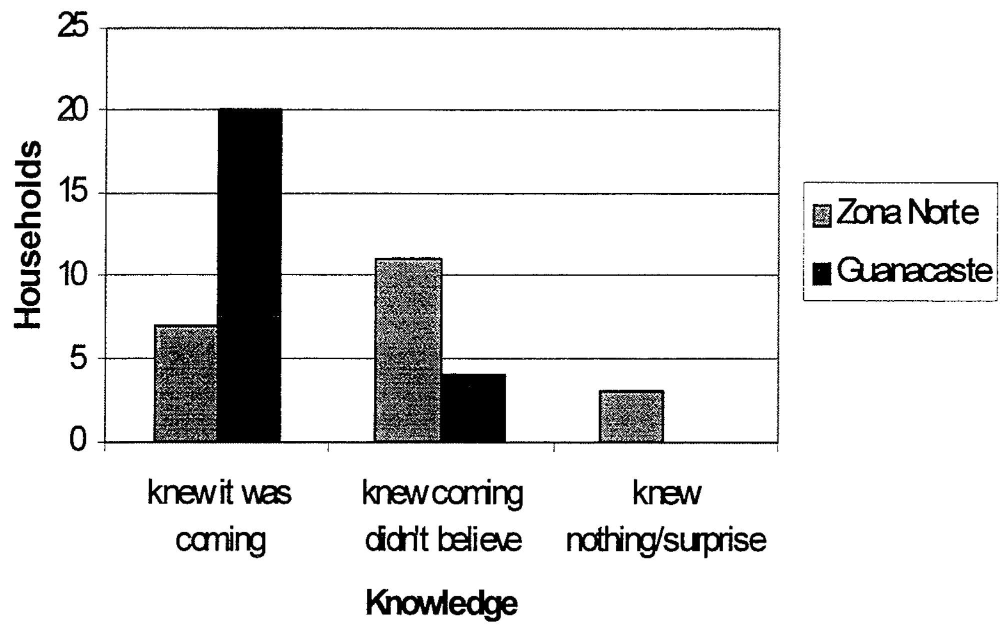

Figure 3 Expecting drought (El Niño)

Policy Implications

Results suggest a relationship between drought frequency and coping strategies to deal with drought in northern Costa Rica. In Guanacaste, where droughts associated with El Niño occur at a decadal scale, farmers have a variety of cultural practices that allow them to cope with drought. Meanwhile, for the Zona Norte, where droughts are rare and the weak El Niño signal is one of increased rainfall, small-scale farmers have almost no cultural mechanisms that allow them to cope with drought. Cultural coping mechanisms track the frequency and intensity at which the anomalous climate event occurs, qualitatively confirming our hypothesis that the frequency of drought events would be a determining factor in the presence of household coping mechanisms.

A more detailed understanding of the relationship between drought frequency and coping mechanisms will help policy makers improve the applicability of forecasts and the implementation of preventative measures. For instance, by recognizing that this relationship exists one can more easily identify vulnerable communities based on how often they have been exposed to a climate "disturbance" (for example, Zona Norte is vulnerable in the case of drought). Predictions can also be made about the types of sociocultural responses to climatic events. Finally, knowing this relationship exists will allow the detection of other factors that limit a groups ability to cope with disturbance (socioeconomic, institutional, biophysical).

The results of our research emphasize the importance of recognizing culture as key in the relationship between society and climate. It is essential that policy makers seeking improved applications for climate research do not discount the value of traditional cultural mechanisms (such as traditional fallow periods) for dealing with climate disturbances.

Some scientists predict an increase in the frequency and intensity of inter-annual climate anomalies in the case of global warming. If this occurs, one would expect new cultural adaptations to the anomalous climate to come forth in regions subject to such events. Nevertheless, if these anomalies become more frequent and intense and occur in opposite directions (drought one year, then extreme flooding) there would be a physical limit to the actions that could be adopted to deal with them. This boundary would be restricted in part by the socioeconomic and educational limitations that these societies often present. The accuracy and lead-time of forecasts would also be a limiting factor in the effectiveness of coping mechanisms. Policy makers and social scientists alike need to recognize that despite the ability of small-scale farming households to respond to climate anomalies, farmers will continue to be limited in their response if improvements are not made to their institutional organizations and socioeconomic conditions.

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A Regression Model for Annual Streamflow in the Upper Mississippi River Basin Based on Solar Irradiance

Charles A. Perry

Abstract

Annual streamflow in the upper Mississippi River Basin demonstrates an apparent connection to annual solar-irradiance variations. The relation is associated with the amount of solar energy available for absorption by the tropical Pacific Ocean and the subsequent effects this stored energy has on mid-latitude atmospheric circulation and precipitation occurrence. The suggested physical mechanism for this relation includes varying solar-energy input that creates ocean-temperature anomalies in the tropical ocean. The temperature anomalies are transported northward by ocean currents to locations where ocean and atmospheric processes can modify jet stream patterns. These patterns affect jet stream location and characteristics downwind over North America, which affect the occurrence of precipitation and, ultimately, the amount of streamflow in the upper Mississippi River Basin. The relation provides an opportunity to estimate the annual streamflow of the upper Mississippi River. A multivariate model using solar-irradiance variations and the previous year's basin precipitation explains nearly one-half of the annual streamflow variability. When data for only La Niña years are considered, the model explains more than two-thirds of the variability since 1950.

Introduction

In the past solar-climate connections have been considered tenuous at best, with apparent significant correlations (Brooks 1926) having phase changes (Clayton 1940) or complete correlation breakdowns (Eddy 1983). Solar-climate correlations that pass significance tests lack physical explanations. At the decadal and interdecadal scales, there is growing evidence that long-term changes in the sun's radiation output do have an effect on global air temperature (Hoyt 1979; Friis-Christensen and Lassen 1991) and on global sea-surface temperatures (White and others 1997), even though the observed change in solar irradiance during the average 11–year solar cycle is small and amounts to only 0.15% variation. However, mean irradiance can differ by 0.25% from month to month and by as much as 0.50% from day to day (Hoyt and Schatten 1997).

Solar irradiance has been measured in space by sensors on several spacecraft including the Nimbus–7 satellite (ERB 1978–1993), the Earth Radiation Budget Satellite (ERBS 1984–1996), two Active Cavity Radiometers (ACRIM 1980–1989) that flew on the Solar Maximum Mission (SMM), and an Active Cavity Radiometer (ACRIMII 1991 to present) that is aboard the Upper Atmospheric Research Satellite (UARS). Currently (1999), these measurements account for more than

20 years of overlapping data. However, the time series of direct irradiance observations is of insufficient length for adequate comparison with climatic data.

Fortunately, several solar-irradiance investigators have developed empirical models for estimating total solar irradiance before 1978 (Foukal and Lean 1990; Hoyt and Schatten 1993, 1997). The Hoyt and Schatten model of solar irradiance (1993, 1997) includes relations between solar irradiance and solar-cycle length, cycle decay rate, mean level of solar activity, solar rotation rate, and fraction of penumbral spots. Using these five solar indices, estimates of total solar irradiance have been made to 1874. Estimates of total solar irradiance also were made from 1700 to 1873 and are based on cycle length, cycle decay rate, and mean level of solar activity.

Solar-Hydroclimate Mechanism

A mechanism proposed for the coupling of global total solar irradiance with short-term regional hydroclimatology was suggested by Perry (1994) and entails four major linkages:

1. Solar-irradiance variations create ocean-temperature anomalies by absorption of solar energy into a deep surface layer.
2. Major currents of the Pacific Ocean transport ocean-temperature anomalies around the Pacific Ocean gyre to temperate regions.
3. Persistent ocean-temperature anomalies affect characteristics of the upper level jet stream.
4. Jet-stream characteristics downwind (troughs and ridges) yield regional climatic factors such as precipitation, temperature, and evaporation that in turn control streamflow throughout North America.

Upper Mississippi River Streamflow Relation to Solar Irradiance

The four major components of the physical connection between solar irradiance and hydroclimatology of the upper Mississippi River Basin are illustrated by the diagrams in Figure 1. A period of increased total solar irradiance heats the Pacific Warm Pool (the western tropical Pacific Ocean) to an anomalously warm temperature forming a warm ocean water (WOW) anomaly (Figure 1A). Two years later the WOW has been transported northward by the ocean currents and is east of Japan (Figure 1B). The atmosphere responds to the warmer ocean surface by moving the jet stream farther north forming a high pressure ridge. This ridge causes the atmosphere to have anticyclonic curvature that results in dynamically sinking air, which inhibits development of precipitation and causes dry conditions to prevail beneath the ridge. Downwind, east of the ridge, the perturbed jet stream must turn back to the left, and a trough is induced.

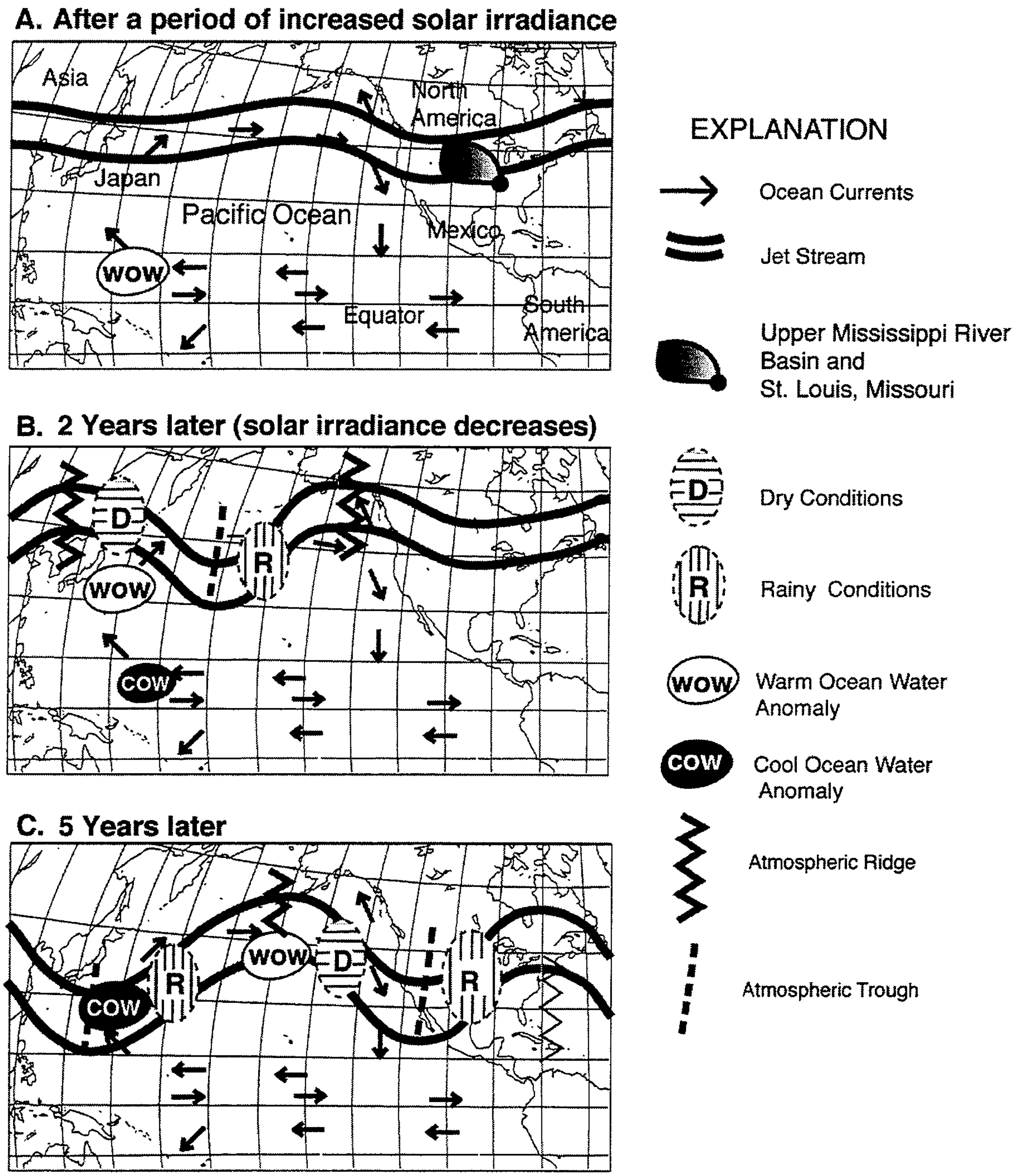

Figure 1 Solar-irradiance and ocean-atmosphere climate mechanism. A. A period of solar-irradiance increase creates a WOW anomaly in the tropics. B. A solar-irradiance decrease creates a COW anomaly. By then, the two-year-old WOW anomaly has moved northward and is causing a ridge and trough to form in the mean jet stream position. The atmospheric dynamics of the jet stream create dry conditions east of the ridge and rainy conditions east of the trough. C. Five years after the initial warming of the western tropical Pacific Ocean, the WOW anomaly and the trailing COW anomaly have resulted in a jet stream pattern that is producing excessive rains and flooding over the Mississippi River Basin. As the ocean anomalies continue to move eastward in the North Pacific Drift Current, drought conditions eventually would move into North America about five years after the COW formation.

To the east of the trough's axis, the atmosphere is dynamically lifted and precipitation occurrence is enhanced. Five years after its formation, the WOW is in the eastern North Pacific Ocean along with its accompanying upper level ridge. A trailing cool ocean water (COW) anomaly, formed during a period of decreased irradiance two to three years after the strong increase, has moved northward and has pulled the jet stream southward forming a trough. These two areas of ocean-temperature anomalies together result in a vigorous jet stream pattern that places a strong persistent trough over western North America. This could have been the case in 1993 when a strong persistent trough over the Rocky Mountains helped to create persistent rains over the upper Mississippi River Basin and historic flooding. This persistent trough may have originated from a very strong increase in solar irradiance that occurred in 1988–1989, followed by a sharp irradiance decrease in 1990.

Hydrologic Data as a Climate Indicator

Climate for a region can be defined as the prevailing or average weather conditions over a period of many years. Short-term climate variations are seasonal to multiyear deviations from the average conditions of precipitation, temperature, and evapotranspiration. The interaction of these meteorological variables and their seasonal and annual fluctuations constitute climate variability. Measuring the variability of climate can be quite challenging as precipitation and temperature data are obtained at specific sites and times and can be subject to various sampling errors. Evapotranspiration at a single site is difficult to measure, and areal observations are virtually nonexistent.

Given these difficulties, streamflow records can be excellent indicators of regional climates, for both the short and long terms. The total volume of water flowing out of a hydrologic basin is the net sum of the water budget for that basin. It is an integration of climatic conditions including precipitation, evapotranspiration, and storage over a continuous area and period of time.

Mean annual streamflow in the upper Mississippi River Basin is the hydrologic variable examined in this paper. The upper Mississippi River Basin occupies about one-fourth of the total area of the contiguous 48 states, and extends roughly from the Rocky Mountains of Montana, Wyoming, and Colorado, eastward almost to Lake Superior and Lake Michigan, and southward to St. Louis, Missouri. The general climatology of the 1,800,000–km^2 basin varies from semiarid in the west to humid in the east. The long-term (1934–1998) mean annual streamflow of the Mississippi River at St. Louis, Missouri, is 5,350 m^3/s. Water storage within the upper Mississippi River Basin includes a vast and complex groundwater component, a riverine component, and an artificial impoundment component.

The integrated effect of these components moderate the short-term variability of streamflow. The variance of the mean annual streamflow is 1,820 m^3/s.

Solar Irradiance, Climatic Factors, and Streamflow

Variations in solar irradiance may yield significant ocean-temperature anomalies that, in turn, affect the regional climate and streamflow of the upper Mississippi River Basin and its outflow. Because it is the relative difference in the temperature between the anomalies in various parts of the ocean that may affect the upper atmospheric patterns, annual changes in total solar irradiance are assumed to be the climatic-forcing mechanism. A slightly varying solar irradiance over several years time would result in ocean-temperature anomalies that are nearly the same temperature, whereas a strongly varying solar irradiance could generate anomalies with contrasting temperatures.

Annual changes in solar irradiance were computed from Hoyt and Schatten's model of solar irradiance (Hoyt and Schatten 1997). The annual differences from 1940 to 1997 are shown in Figure 2. Maximum differences precede slightly or coincide with the solar cycle maxima (which occurred in 1947, 1957, 1968, 1979, and 1989).

Annual mean streamflow for the years 1950–1997 from the Mississippi River at St. Louis, Missouri, is compared with the irradiance variations in Figure 3. Here, the best fit between irradiance variations and streamflow occurs with a lag time of 5 years. The simple linear correlation coefficient between these two data sets is $R = 0.55$. Peaks do not always coincide; the lag times for graphical comparison for different peaks actually range from four to six years, reflecting the variations in ocean-current patterns and velocities. Therefore, a weighted, moving average (1-2-1) of solar irradiance changes lagged five years was used in the correlation with streamflow, and the correlation coefficient increased to $R = 0.63$. Other variables, including the El Niño-Southern Oscillation effects and the Quasi-Biennial Oscillation (QBO) of the tropical stratosphere, may be involved in the delay, early arrival, or dispersal of the solar-irradiance and streamflow relation in the upper Mississippi River Basin.

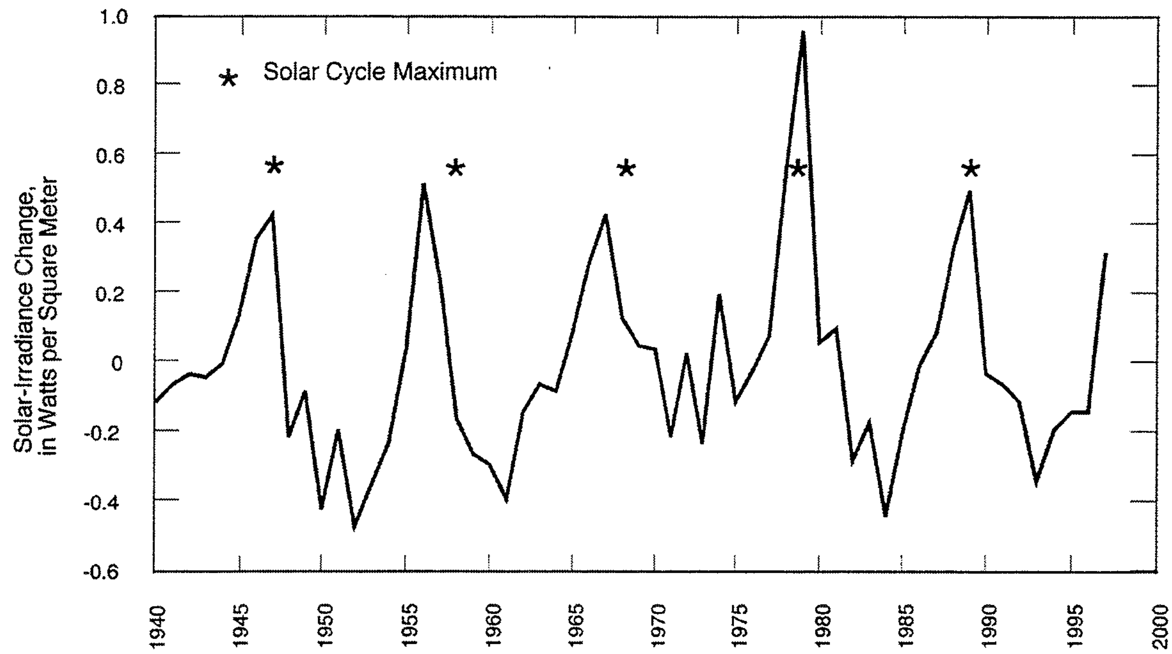

Figure 2 Solar cycle maxima and annual solar-irradiance changes, 1940–1997, computed from Hoyt and Schatten (1997) model

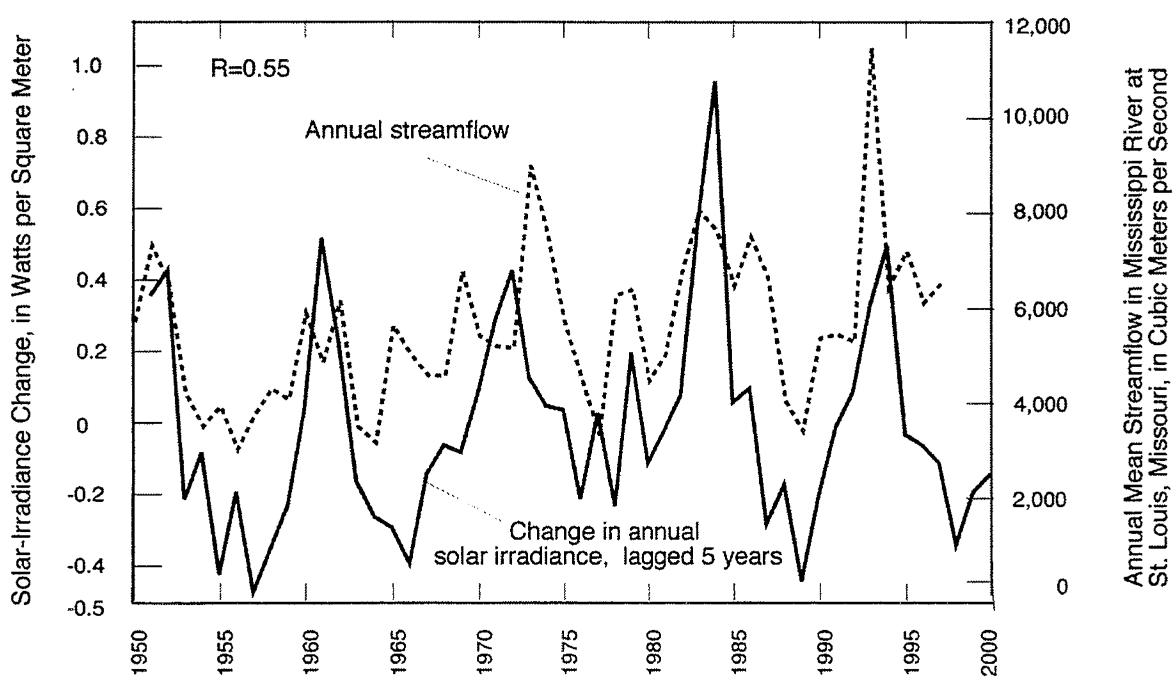

Figure 3 Comparison of annual solar-irradiance changes computed from Hoyt and Schatten (1997) model lagged five years and annual mean streamflow in the Mississippi River at St. Louis, Missouri, 1950–1997

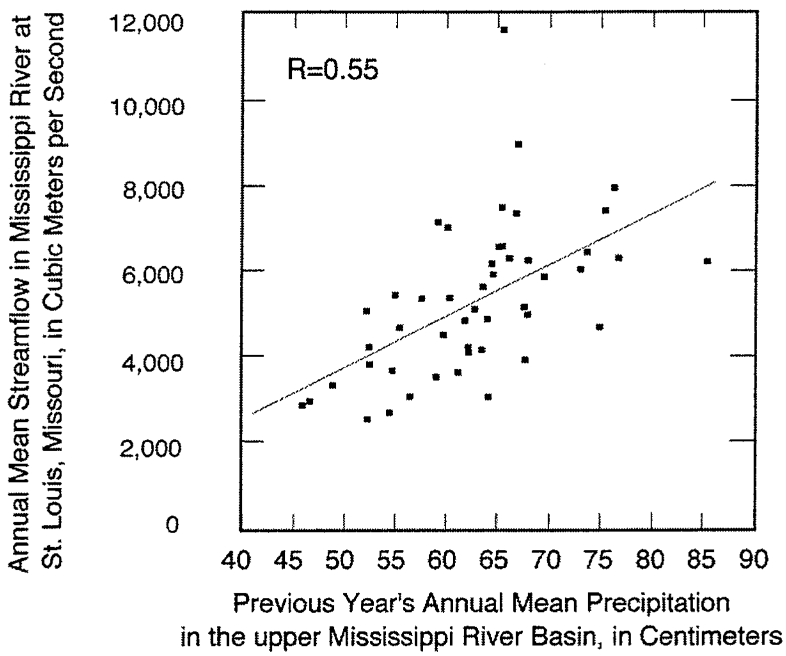

Figure 4 Relation between previous year's mean precipitation in the upper Mississippi River Basin and annual mean streamflow in the Mississippi River at St. Louis, Missouri, 1950–1997

Mississippi River Streamflow Model

The detection of the solar signal in streamflow data allows development of a predictive model for streamflow in the upper Mississippi River Basin. Using only annual solar-irradiance variations, almost 40% of the annual variability of streamflow is explained by the weighted, moving-averaged irradiance lagged five years. However, other atmospheric and climatic variables can be used in conjunction with solar irradiance in developing a multivariate model.

Because storage is an important component of the streamflow from an area as large as the upper Mississippi River Basin, the previous water year's (October to September) mean basin precipitation was included as a variable in the model. Mean basin precipitation was computed by averaging the 75 National Oceanic and Atmospheric Administration (NOAA) meteorological divisions that are in the upper Mississippi River Basin.

The relation between the previous year's mean basin precipitation and streamflow in the Mississippi River at St. Louis, Missouri for 1950–1997 is shown in Figure 4. The correlation coefficient between these data is R = 0.55; the previous year's mean basin precipitation explains slightly more than 30% of the annual variability of streamflow. There is some interdependence between weighted solar-irradiance change and the previous year's precipitation as they are weakly correlated (R = 0.38, which is just significant at the 5% level).

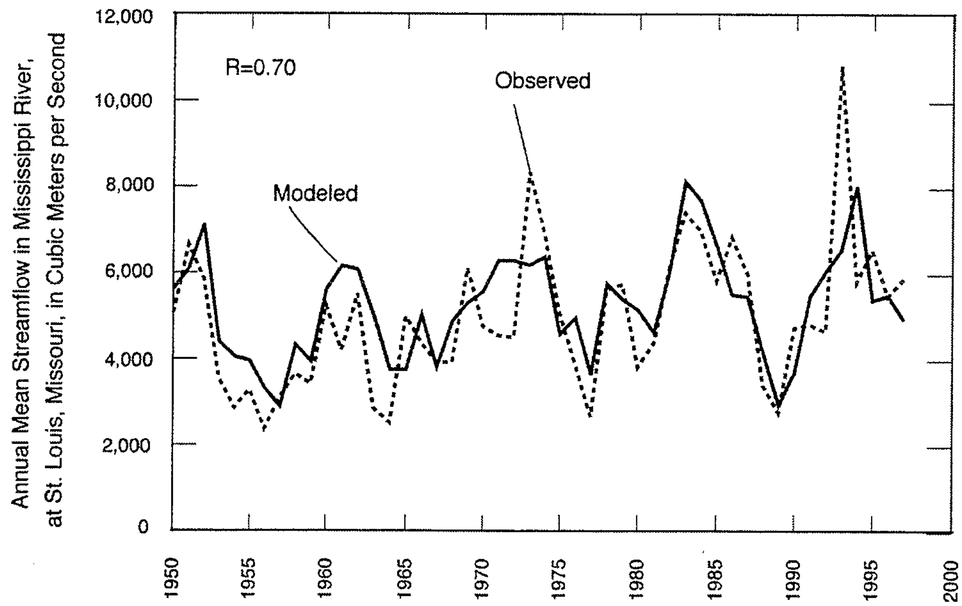

Figure 5 Comparison of observed annual mean streamflow in the Mississippi River at St. Louis, Missouri, and streamflow generated from the multivariate model for 1950–1997

When irradiance change and basin precipitation are included together in a step-wise, multivariate regression analysis, nearly 50% of the streamflow variability is explained. The multivariate model for streamflow in cubic meters per second becomes:

Annual Streamflow = 225(prec-1) + 5,540(Average Irradiance Change) + 2020(1)

where:

- prec-1 = previous year's mean precipitation over the upper Mississippi Basin in centimeters;
- Average Irradiance Change = 0.25(4-yr Irrad) + 0.5(5-yr Irrad) + 0.25(6-yr Irrad) in watts per square meter; and
- 4-yr Irrad = irradiance difference lagged 4 years; 5-yr Irrad = irradiance difference lagged 5 years; and 6-yr Irrad = irradiance difference lagged 6 years.

Figure 5 shows the time series of the observed and modeled annual mean streamflow in the Mississippi River at St. Louis, Missouri. The greatest error of the multivariate model results in underestimating the extreme high streamflows such as those occurring in 1973, 1986, and 1993. These were all warm-phase El Niño years. Years for which the model overestimates the streamflow were 1961 and 1971, which were both cold-phase La Niña years.

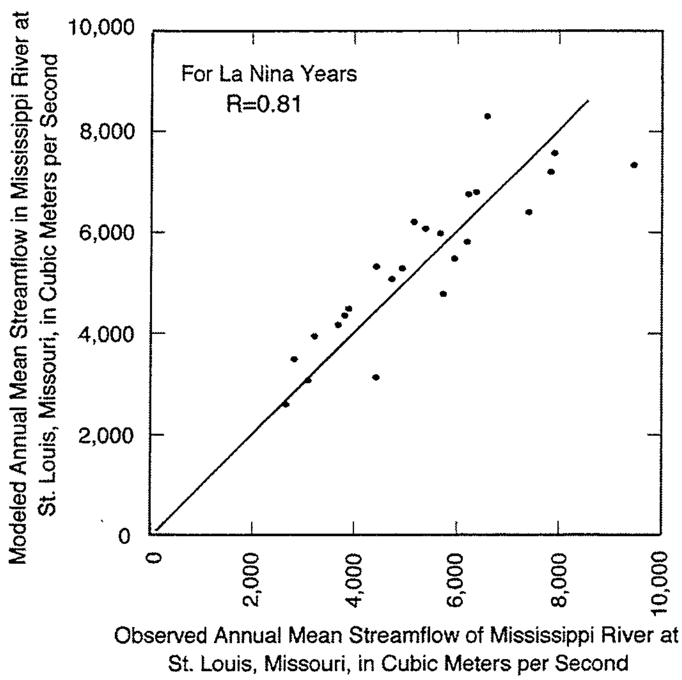

Figure 6 Relation between observed annual mean streamflow in the Mississippi River at St. Louis, Missouri, and streamflow generated from the multivariate model using La Niña years only

When the streamflow data are grouped according to warm or cold phases of the tropical Pacific Ocean, the relation between upper Mississippi River Basin streamflow and solar irradiance change and the previous year's basin precipitation shows some improvement. Warm phase or cold phase years were determined from NOAA's NINO3 index, obtained from the Climate Analysis Center (http://nic.fb4.noaa.gov/data/cddb/cddb/sstoi.indices).

NINO3 is an index computed from the sea surface temperature (SST) anomalies in the eastern tropical Pacific Ocean from lat 5°S to 5°N and long 150°W to 90°W. Figure 6 shows the relation between modeled and observed annual mean streamflow for years when the NINO3 index averaged less than zero for the year (La Niña). Using data for the La Niña years only, two-thirds of the annual streamflow variability is explained (adjusted multiple $R^2 = 0.66$) by solar-irradiance variations and the previous year's precipitation. The multivariate model for streamflow in cubic meters per second with mean basin precipitation in centimeters and irradiance change in watts per square meter becomes:

Annual Streamflow = 355(prec-1) + 4,933(Average Irradiance Change) – 6,388(2).

Comparison of observed and modeled annual mean streamflow for the Mississippi River at St. Louis, Missouri using only La Niña years is shown in Figure 6. There was no improvement in the model using data for only El Niño Years.

Conclusions

Short-term changes in total solar irradiance from the sun may have an effect on the short-term regional climate of North America through global oceanic and atmospheric processes. Annual solar-irradiance variations may create warm and cool ocean water anomalies in the tropical Pacific Ocean, which can affect streamflow in the Mississippi five years later through induced position of ridges and troughs in the jet stream.

The relation between solar irradiance and streamflow in the upper Mississippi River Basin allows the development of a model to predict annual mean streamflow. A stepwise multivariate regression analysis using the previous year's average basin precipitation and changes in weighted solar irradiance lagged five years produces a model that explains nearly one-half of the variability in annual streamflow. When data for only La Niña years (cold phase) are considered, the model explains more than two-thirds of the variability since 1950.

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Climate and Water Management in the Interior West: Critical Water Management Problems and Climate Change

Andrea J. Ray

Abstract

Water allocations in the interior West are relatively inflexible, limiting the potential to change or reallocate uses based in evolving values. Furthermore, conflicts over uses can be exacerbated during times of shortage. The region is also vulnerable to drought hazards, and to the extent that climate change may alter the hydrological cycle and make drought and diminished flow conditions more likely, we are vulnerable to climate change. However, climate implications are not being considered in a number of water management policies surveyed, and the policies to implement ecosystems protection are particularly vulnerable to water shortage. This paper will address how climate information might be better used in an integrated approach to multiple critical water problems, thus reducing our vulnerability to potential impacts of climate change and long-term drought. A case study of the Gunnison Basin in western Colorado is described.

Introduction

Three situations intersect in the management of water resources in the West today. Socially, the institutions for allocating water in the region are relatively inflexible, limiting the potential to change or reallocate uses. Also, society now values water not only for traditional consumptive uses, but also as instream flow to maintain ecosystems, for recreation, and to preserve endangered species (Shupe and others 1989). Physically, climate change may alter the hydrological cycle in the interior West and make drought and diminished flow conditions more likely (Miller 1997). Thus, there is a need to survey current water management policies that might be affected by climate change, and further, to determine how their goals and implementation might be affected by climate.

The interior West is already vulnerable to long-term droughts (Young 1995), and these droughts may have significant environmental effects (Hardy 1995). If diminished flow conditions make droughts more likely (Miller 1997), implementation of water and environmental laws may be compromised. A number of policies surveyed do not consider the risk of decreasing water supplies. This paper addresses how climate information might be better used in an integrated approach to multiple, critical water problems, thus reducing our vulnerability to potential impacts of climate change.

This paper evaluates opportunities to incorporate climate information into existing water management policies in the interior west and investigates how policies put in place for other purposes and goals interact with water management goals in the context of climate change. A case study of policies in place in the Gunnison Basin is described. Ultimately, this paper applies a critical water problems approach to the interior west, which was originally proposed for the Indus Basin (Wescoat 1991). The recent Western Water Policy Review Advisory Commission (WWPRAC) report (WWPRAC 1998) demonstrates that, as in the Indus, there are many other environmental problems that have a higher priority than climate change.

The Climate Setting

In a study for the WWPRAC, Miller (Miller 1997) reviewed the results of a number of studies of climate change in the West. In general, these studies suggest that mountainous river basins such as the Rockies are likely to experience smaller snowpack accumulations and earlier melting and runoff altering the timing of peak flows. Warmer temperatures could experience more rain on snow events, further accelerating runoff and risk of floods. Increased temperatures are also likely to increase evaporation from reservoirs, thereby decreasing storage. In modeling studies using 2- or 4-degree temperature increases, Nash and Gleick (1993) estimate decreases of 10% to 41% in annual runoff: a 2-degree increase in temperature with no change in precipitation would yield nearly a 12% decrease in runoff.

There have been a number of recent studies on climate change and climate variability impacts on water resources (Table 1). In 1987, the US Bureau of Reclamation (USBR) began a multi-year research program, the Global Climate Change Response program (Schuster 1991b), which included development of climate change scenarios of the West, and more specific analyses of particular basins, the Gunnison Basin in western Colorado (Medina 1997) and the Colorado-Big Thompson project area (USBR 1994). In 1991, a national conference was held on climate change and water resources management (Ballentine and Stakiv 1991); a follow-on conference in 1997 added climate variability (Conference on Climate Change, Climate Variability and Water Resources, Colorado Springs, October, 1997). Both conferences attempted to link climate risks to water management.

The Colorado Severe Sustained Drought study researched the probability of droughts not associated with anthropogenic climate change (Young 1995). Even without climate change, the region is at risk for severe, sustained droughts, or a "situation of scarcity relative to 'normal' conditions," as defined by Young (1995). The most severe drought on record in the Upper Colorado River Basin occurred from 1942–1964, with a mean flow of less than 90% of average flow. This region faces the historical likelihood of a 20-year drought of this magnitude occurring every 50 to 100 years based on tree ring data (Tarboton 1995). Because of the massive storage reservoirs in the basin, which hold about four years of flow, it is these longer droughts that are of most concern, and these might be expected to occur every 50 to 100 years. This study demonstrates the current vulnerability to existing climate variability. Long-term variations in Colorado River flow have been considered to be analogous to climate change for the purpose of analyzing institutional and legal responses (Brown 1988).

Water Management Issues and Plans

At the heart of western water law is the prior appropriation doctrine. It establishes that date of appropriation of a water right determines the order in which users have access to water (Getches 1997). This institution was set up to shelter early water rights holders from shortages and droughts, but now constrains water allocations, limiting the potential to change or reallocate water resources for new or different uses. In the interior West, these uses include preserving and maintaining opportunities for future generations, such as the opportunity to pursue ranching or farming cultures, exercise of Indian water rights, and maintaining fish, wildlife, and ecosystems. The Colorado River as a whole is over-allocated, and many new uses compete for water which were not conceived of when the law of the river and the regulating dams and reservoirs were built (Wilkinson 1992). Ironically, policies implementing the Endangered Species Act and federal reserved water rights may create new restrictions for users (in addition to prior appropriations) because these rights may have priority over some other water users (Miller and others 1997).

Table 1 Climate and water resources studies

Title	*Reference*
US Bureau of Reclamation Global Climate Change Response Program 1989–1993	
Gunnison Basin Study	Medina 1997
Colorado-Big Thompson Project Area Study	USBR 1994
National Conference on Climate Change and Water Resources Management and Proceedings	Ballentine and Stakiv 1991
The Colorado River Basin and Climate Change: The Sensitivity of Streamflow and Water Supply to Variations in Temperature and Precipitation	Nash and Gleick 1993
Information Needs for Precipitation Sensitive Systems, Workshop Report	Diaz and Karl 1994
Water Resources Supply and Use in the Colorado River Basin	Morrison and Gleick 1997
Climate Variability, Climate Change, and Western Water	Miller 1998
Colorado Severe Sustained Drought Study	Young 1995

Predictions of climate change suggest the timing of peak flows may be earlier and runoff decreased. Thus, water availability may be altered in the region under an enhanced greenhouse effect (Miller 1997). This prediction has two implications. First, there may not be as much water available as current policies and plans now assume. Second, junior water rights holders, whether for individuals or for environmental purposes, are less likely to get water when the total is decreased. Therefore, it is important to know who the junior rights holders are, and what water uses are represented by those rights. Environmental policies and plans are put at risk if we do not consider the potential climate change. But in spite of a number of studies of climate impacts over the past 15 to 20 years (see Table 1), this risk is generally not being considered in water management policies and plans relating to the interior West. Some of the studies explicitly address the link climate and water management, there is a disconnect between the climate change and variability information that has become available, and the extent to which it is being incorporated, or even acknowledged as an issue in management actions, policy statements, and plans in the region (Table 2).

The report of the WWPRAC (WWPRAC 1998), scarcely mentions climate variability or climate change, nor are these items included among the "major issues" in the Colorado River Basin Study (Pontius 1997). Miller (personal communication, 1 April 1999) says that the WWPRAC had to be convinced that climate change was an issue that should be considered.

Table 2 Policy statements and plans

Title	*Reference*
Western Water Policy Review Advisory Commission Report, 1998 and included Colorado River Basin Study	Pontius 1997; WWPRAC 1998
Colorado Water Conservation Board "Current Issues" List and Water Conservation Plan Guidance, 1999	Available at: http://www.cwcb.co.us via the Internet
Colorado Water Conservation District "Policy Issues" List, 1998	Available at: http://www.crwcd.gov via the Internet
US Bureau of Reclamation Strategic Plan, 1997	Available at: http://www.usbr.gov/gpra via the Internet
Restoring the West's Waters: Opportunities for the USBR for Restoring Functional Ecosystem Integrity	Natural Resources Law Center 1996a

The 1997 US Bureau of Reclamation Strategic Plan does not feature climate change as an issue in spite of their own Global Climate Change Response Program, which funded about $3 million/year in research for five years (Schuster 1991b). A list of current issues published by the Colorado Water Conservation Board includes ecosystem and salinity issues, but not climate (www.dnr.state.co.us/cwcb); a similar list of policy issues provided by the Colorado River Water Conservation District (which includes the upper Colorado River drainage) also does not include climate variability or change as an issue of concern (www.crwcd.gov). A USBR study by the Natural Resources Law Center to determine opportunities for the USBR to aid in restoring ecosystem integrity did not consider potential climate change as a factor in these efforts.

This disconnect is indicative of resistance to using the information to plan and reduce vulnerability. There may be a resistance to act until the scientific information is "perfect." For example, at the Climate Change and Water Resources conference in 1991, the director of the USBR Global Climate Change Response Program specifically stated that adaptive actions will have to wait until models have improved, although he endorsed further study of sensitivities in preparation for planning to address impacts (Schuster 1991a, p II-46). However, even if perfect information were available, it might not be applied due to rigid water institutions and the culture of the water management organizations, or simply the inertia to conduct planning and policy making as been done for decades—without climate information.

Critical Water Problems: An Alternate Approach

Another possible explanation for the lack of attention to climate change risks is that other natural resource problems have a higher priority in management plans and policies. As part of a study of climate change and water management in the Indus River basin of Pakistan, Wescoat (1991) encountered both concerns that climate predictions were uncertain and the reality that there were many other pressing water and environmental problems. As one of four conceptual approaches to climate change, he proposed a critical water problems approach (Table 3).

Table 3 Critical water management problems approach [a]

1. Survey current water problems.
2. Survey current plans and policies for dealing with them.
3. Identify water problems and plans likely to be sensitive to climate change.
4. Refine spatial and temporal scales of assessment.
5. Evaluate the potential effects of climate change on selected problems and plans.
6. Evaluate alternative plans.
7. Draw practical conclusions.

[a] from Wescoat (1991)

This approach was applied to identify critical water problems for the interior West. Unstructured interviews were conducted with water managers in the region from USBR, urban and agricultural water districts, and water conservancy districts. Water problems were also identified in policy documents (see Table 2), the workshop report of the Southwest Regional Climate Change Symposium (Merideth and others 1998), which is part of the National Assessment of Climate Change, and in several books (Brown 1988; Weatherford and Brown 1986). This approach builds on the fact that the water policies and plans discussed earlier outline a number of major issues that managers and policymakers in the region feel need to be addressed.

To determine what issues might be vulnerable to climate, a key criteria is whether the issue involves long-term policies or plans. Recovery of endangered and threatened species is a long-term effort. Another criteria is that any permanent reallocation of water rights should consider how climate change may affect both the right quantified and right holders who become junior to the new right. Furthermore, Hardy (1995) identifies flow dependent facilities (such as fish hatcheries), flow-dependent wildlife refuges, and wetland and riparian habitats as vulnerable to long-term drought. By analogy, these would likely be vulnerable to climate change (Brown 1988).

Water problems found likely to be affected by climate change include ecosystems issues, salinity, equity issues, and allocation among uses. Vulnerability is defined as the potential for negative effects (Meyer and others 1997). A likely negative effect of lower annual average runoff is increased competition for already scarce water; although high runoff years may ameliorate problems temporarily. A likely outcome of changes to the timing of peak flows (earlier is predicted) is that water will not necessarily be available when it is planned for. The implications of climate change for these issues are outlined below.

Ecosystems

Public lands, such as national parks and monuments, have implied rights to water which date to when the park was created (Getches 1997). Many of these rights have not yet been quantified. Older parks and other public lands may have senior water rights, whereas more recently designated areas may have junior rights, which could be affected by a longtime decrease in water availability. Recovery plans for some endangered species depend on water, both in quantity and timing. Diminished flows also may hamper attempts to improve habitat for species, such as the Nebraska sandhill crane and many fish species under the ESA. New designations of water rights for ESA and instream flow rights for ecosystems represent both long-term plans and permanent change in rights.

Equity

As federally reserved water rights are quantified and instream flow designations are made, other users will become junior rights holders to some of these new rights. If flows diminish over the long-term, some junior right holders risk not being able to exercise their right. Is there a way to mitigate or compensate for their loss? Miller and others (1997) suggest that a buffer should be created so that junior rights holders will not suffer if conditions become drier. They further suggest that minimum instream flow levels be determined based on potential climate change effects and be designated as a buffer so that environmentally desirable flow levels will be maintained.

Allocation Among Uses

Water use in the West is shifting from agricultural to urban use. At the same time, there are conflicts between instream "uses" for recreation and ecosystems and either type of consumptive use (Pontius 1997). A corollary is whether people will have the choice to continue their livelihoods and cultures of ranching and farming on the west slope. Out of basin water diversions are another form of shift in use, to use outside the basin.

Salinity

Implementation of the Salinity Control Act has reduced the amount of usable water supply because it must be left in the river for dilution (Wescoat 1986). This is a major focus of agency and water conservation efforts. Ironically, dry years are better for salinity intrusion since less water is irrigated through soils and, therefore, there is less return flow to transport dissolved solids to the river.

Gunnison Case Study

The Gunnison basin in western Colorado is an interesting case study because several of the critical water issues discussed above might be vulnerable to the predicted climate scenario of less runoff. It is similar to many other western Colorado areas where economies are increasingly based on recreation and tourism. Outdoor recreation preserves instream flows for fishing, rafting, and for their amenity to hikers, hunters, and others seeking recreation. As in the West in general, these varied uses are not easily accommodated under existing water law and allocations. About 80% of the Gunnison Basin is federal land, managed by the US Bureau of Reclamation (USBR), the US Forest Service (USFS), and the Bureau of Land Management (Ohman 1998). The USBR operates the Aspinall Unit reservoirs (Blue Mesa, Morrow Point, and Crystal) in the basin for hydropower, storage, and flood control purposes, and provides water to projects and districts for use in several irrigation projects.

Climate change is likely to alter the timing and volume of runoff in the Colorado basin (Nash and Gleick 1993; Dennis 1991). The Gunnison River watershed was studied as part of the USBR Global Climate Change Response Program (Medina 1997). They compared modeled conditions for doubled CO_2 with current conditions and found a 26% decrease in average monthly snow depth for the watershed, based on decreased precipitation and temperature increase of 4 °C. They consider that this result "may imply noticeable repercussions on water resources and environmental planning and management," (p. 37). Medina did estimate runoff, but for the purposes of discussion, an annual average decrease in runoff of 10% seems reasonable (perhaps conservative). The historical severe sustained drought resulted in 10% decrease in flow (Tarboton 1995). How would a 10% decrease in runoff affect management of the river for the multiple goals of ecosystem integrity, irrigation, and hydropower?

Currently there appears to be less than a 10% buffer in the system. The historical annual flows of about 2.2 million acre-feet (maf) are not much more than the net supply provided to several USBR irrigation projects, which is about 1.954 maf (USBR 1992). This is not the only consumptive use of water. Several recent water court cases have denied water rights to out-of-basin diversions arguing that there is not 60,000 acre-feet available (Ohman 1998). The minutes of the April 1999 Aspinall Unit Operation Coordination meeting reflected that there is not much "extra" water in the system. In April, water year 2000 was shaping up to be a very dry year, with most probable inflow to the unit expected to be about 60% of normal (April 1999 minutes, www.usbr.gov/grandjct/hydro/amcurrnt.htm). Blue Mesa Reservoir, the largest in the system, was projected to be 8 to 10 feet short of filling this year (for Aspinall Unit operating status, see www.uc.usbr.gov/wrg/crsp/crsp_cs_aspnl.txt). The minutes of the coordination meeting show that several agencies, including the National Park Service and the state and federal fish and wildlife agencies, were very concerned about how low flows might affect the ecosystem. USBR was carefully planning its water releases to assure water in the river below the dams throughout the summer. Fortunately, storms in April and May resulted in an above-average water year (August meeting minutes, www.usbr.gov/grandjct/hydro/amcurrnt.htm).

Several ecosystem, allocation, and equity issues in the basin could be affected by diminished flows, which are discussed in the following paragraphs.

Ecosystems

Flow needs for four endangered species in the upper Colorado River are expected to be released by the US Fish and Wildlife Service in early 2000. They hope to acquire water rights or water use agreements with other rights holders to achieve the required flows for fish (USFWS 1999a). If these are junior rights, they may be affected by long-term diminished flows. Furthermore, the issue is not just availability of water for fish, but timing of releases and coordination with other user's needs. Water is needed in spring for spawning and for maintaining habitat for fish and in summer and fall for agricultural uses. Hydropower is generated all year, especially in late summer. USBR hydropower managers prefer to release no more water than necessary earlier in the year (Aspinall Unit Coordination Meeting minutes, www.usbr.gov/grandjct/hydro/amcurrnt.htm). In the winter, higher flows from reservoir releases can actually be harmful to fish, which are adapted to low flows at that time. Potential changes in timing of spring runoff obviously become very important, given the careful scheduling of flows in the river to meet various demands. The potential effect of long-term reductions in flows is not discussed in the recovery implementation plan for endangered fish (USFWS 1999a), or in the draft biological opinion that describes flow needs for the reach of the river just upstream of the Gunnison confluence with the Colorado River (USFWS 1999b).

Federal reserved water rights for 300 cubic feet per second are proposed for the Black Canyon of the Gunnison, a level that is not always met currently (see streamflow data, www.dnr.co.us). The US Forest Service also proposes flow rights for several national Forests in the basin (Pontius 1997). Given that these reserved water rights and recovery of the four endangered species are long-term efforts, it seems appropriate to make contingency plans for maintaining flows if climate change decreases the average annual runoff.

Allocation Issues

Currently over 2,500 acre-feet/year are diverted out of the Gunnison basin. The Union Park Project on a tributary of the Upper Gunnison, is proposed now by Arapahoe County near Denver; they plan to sell the water until they need it in about 2020. The proposal has been turned down by the courts on the grounds that there are not enough unappropriated water rights, but water managers and citizens in the region are still concerned (Ohman 1998). There are significant implications of both long-term drought and climate change for this and similar proposals. Because water is already nearly fully allocated, this reservoir would be filled and replenished only in wet years. Thus, the junior rights of the project make it very vulnerable to years of shortage. Out of basin water diversions should consider the potential for 10% less water for multiple years in the decision on whether they should be built.

Equity

If instream flow and federal reserved rights are integrated into the water rights system, a number of users will become more junior. These users have been acting on good faith based on the old system and will want to be compensated. A strategy that might ameliorate conflict is to determine how often these new, more junior rights might be jeopardized based on recent runoff records and a potential 10% decrease in flows. Users whose rights are now essentially dry could be permanently compensated, but perhaps dry year agreements could be made in advance for those whose rights are at risk less frequently.

Discussion and Conclusion

This analysis shows that a number of policies and plans to address society's environmental and water problems are vulnerable to climate change and the risk of climate change should be an integral part of those policies and plans. Society is placing a value on protecting ecosystems, but the policies to implement protection are vulnerable to water shortage. Acquiring water rights for ecosystems may help, but these rights may be vulnerable to shortage.

To understand specifically how to incorporate the potential impacts of climate change into these policies, some very specific research is needed. Key information such as potential ranges of variability of runoff and peak runoff are needed for particular areas or basins, using both climate models and paleoclimate data. Ranges are more practical than exact predictions because water managers already deal with a variable climate, and a "changed" climate is also likely to be variable. Next, vulnerability of flow requirements or water rights (for example, a 300 cubic feet per second year-round right in the Gunnison, or flow requirements for endangered fish) could be determined based on expected new ranges of runoff volume and timing. Finally, based on the water rights seniority for any given right, a risk or probability of not exceeding the minimum flow needed could be evaluated. For example, given various proposed water rights in the Gunnison, it could be determined which water rights are affected by a 10% decrease in flow (or other projected amount). The Colorado Department of Natural Resources has a sophisticated water rights decision support system (cando.dwr.co.gov), which could be used to determine which rights would not receive water under different climate scenarios.

This analysis would yield information on how often there would not be enough water in a given system for these flows to be met. Flow recommendations for endangered fish on the Upper Colorado are in the form of flow volumes to be exceeded in 5, 10, 16, or all years out of 20 (USFWS 1999b); therefore this format would allow comparison. By providing information on how likely a water right will not be met, a policymaker or water manager could more easily understand how the policies they implement or plans they manage would be affected. Perhaps this kind of data would also convince policymakers and managers to implement the "safety margin" that Miller and others (1997) suggest: a minimum instream flow level to buffer climatic variations so that junior appropriated rights do not suffer.

This analysis suggests that this critical water problems approach may be appropriate for water management issues in other regions. Originally developed for the Indus Basin, this approach is appropriate for the interior West. Climate change is an issue that is not being addressed, but might get more attention if it is related to the critical water and environmental issues in the region, and if the case is made that other environmental policies are vulnerable to climate change. In general, very specific (applications-oriented) research needs to be done on how climate interacts with other policies, including how policies and the issues they are designed to address are vulnerable to the anticipated ranges of climate variability.

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Temperature-related Molecular Proxies: Degree of Alkenone Unsaturation and Average Chain Length of *n*-Alkanes

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Abstract

Deep sea sediments recovered during drilling campaigns of the Ocean Drilling Program on the New Jersey continental margin (Leg 150), in the Santa Barbara basin (Leg 146), on the central California margin (Leg 167), and in the eastern Mediterranean Sea (Leg 160) were investigated for molecular organic geochemical indicators of past climatic change. Both the degree of unsaturation of long-chain alkenones from marine microalgae and the chain length of terrigenous *n*-alkanes from epicuticular waxes of higher plant leaves were shown to yield reliable and consistent information of global climatic variations, sometimes modified by regional influence, in different geographical areas and over an extended period of geological time. The alkenone sea surface temperature parameter followed major variations of global sea level back to the Eocene on the New Jersey continental margin. The *n*-alkane para-meter demonstrated land-ocean interaction and was particularly sensitive to humidity changes on the nearby continent.

Introduction

Paleoceanographic studies have taken advantage of the fact that biosynthesis of a major family of organic compounds by certain microalgae depends on the water temperature during growth. The microalgae belong to the family Haptophyceae (often also named Prymnesiophyceae) and notably comprise the marine coccolithophorids *Emiliania huxleyi* and *Gephyrocapsa oceanica*. The whole family of compounds, which are found in marine sediments of Recent to mid-Cretaceous age throughout the world ocean, is a complex assemblage of aliphatic straight-chain ketones and esters with 37 to 39 carbon atoms and two to four double bonds (see Brassell [1993] for an overview and details). But principally, only the C_{37} methylketones with two and three double bonds are used for past sea surface temperature assessment.

It was found from the analysis of laboratory cultures and field samples that the extent of unsaturation (number of double bonds) in these long-chain ketones varies linearly with growth temperature of the algae over a wide temperature range (Brassell and others 1986; Prahl and Wakeham 1987). To describe this, an unsaturation index was suggested, which in its simplified form is defined by the concentration ratio of the two C_{37} ketones: $U^{K'}_{37} = [C_{37:2}]/[C_{37:2} + C_{37:3}]$. Calibration was made with the growth temperatures of laboratory cultures of different haptophyte species and with ocean water temperatures at which plankton samples had been collected. In a major analytical effort, Müller and others (1998) arrived at a uniform calibration for the global ocean from 60°N to 60°S. The resulting relationship, $U^{K'}_{37}$ = 0.033T + 0.044, is identical within error limits with the widely used calibrations, based on *Emiliania huxleyi* cultures, of Prahl and Wakeham (1987), later slightly modified by Prahl and others (1988) to $U^{K'}_{37}$ = 0.034 * SST + 0.039.

Since their first description, alkenones have been found in numerous marine sediments. Their application for estimating paleo-sea surface temperatures (SST) has been demonstrated in many different marine environments and is not restricted to sediments younger than about 268 ka, the first occurrence of *Emiliania huxleyi*, nor to the occurrence of the previously dominant *Gephyrocapsa oceanica*. Other living and extinct members of the family Gephyrocapsaceae apparently have or had the capability of synthesizing alkenones whose degree of unsaturation changes with growth temperature. Nevertheless, most studies published so far are stratigraphically restricted to the last few glacial-interglacial cycles or to sediments ranging back to the Pliocene in a few instances. The alkenone unsaturation index can be determined in sediments lacking planktonic foraminifera for oxygen isotope measurements due to low supply to the sediment or post-depositional dissolution. Furthermore, the unsaturation index seems not to be affected by salinity changes, although this has been debated recently (Rosell-Melé and others, oral presentation at 19th International Meeting on Organic Geochemistry, Istanbul, 6–10 September 1999), and has not to be corrected for eustatic sea level changes like the oxygen isotope record.

Another temperature-sensitive proxy is the average chain length (ACL) of terrestrial *n*-alkanes. In marine sediments, higher-plant organic matter can be an indicator of climate variations both by the total amount indicating enhanced continental runoff during times of low sea level or of humid climate on the continent and by specific marker compounds indicating a change in terrestrial vegetation as a consequence of regional or global climatic variations. Long-chain *n*-alkanes, which are major components of the epicuticular waxes of higher plants, are commonly used as the most stable and significant biological markers of terrigenous organic matter supply (for example, Eglinton and Hamilton 1967).

The carbon number distribution patterns of *n*-alkanes in leaf waxes of higher land plants depend on the climate under which they grow. The distributions show a trend of increasing chain length nearer to the equator, in other words, at lower latitude (Gagosian and others 1987), but they are also influenced by humidity (Hinrichs and others 1998). Poynter (1989) defined the ACL index to describe the chain length variations of *n*-alkanes as $ACL_{27\text{-}31} = (27[C_{27}] + 29[C_{29}] + 31[C_{31}])/–([C_{27}] + [C_{29}] + [C_{31}])$. In this equation $[C_x]$ signifies the concentration of the *n*-alkane with x carbon atoms. Poynter (1989) demonstrated the sensitivity of sedimentary *n*-alkane ACL values to past climatic changes by data from West African continental margin sediments of the last 24 ka.

In this study, we present molecular evidence of paleoclimatic change for three different continental margin areas where deep sea drilling campaigns were performed by the Ocean Drilling Program (ODP):

- Samples from the New Jersey continental slope (ODP Leg 150) clearly support the applicability of the alkenone proxy for sediments back to the Eocene.
- A coupling of the average chain lengths of *n*-alkanes with alkenone temperatures is obvious at the New Jersey continental slope and rise back to the Eocene.
- In late Quaternary sediments from the California continental margin (ODP Site 893, Santa Barbara Basin, and ODP Leg 167) and for Pliocene/Pleistocene Mediterranean sapropels (ODP Leg 160) a correlation between average chain lengths *n*-alkanes and alkenone-derived paleo-sea surface temperatures give valuable information of land-sea paleoclimate interaction.

Analytical Methods

Aliquots of the freeze-dried and ground sediments were used to determine total organic carbon (TOC) contents with a LECO SC-444® instrument. Before TOC determination, the samples were treated with hydrochloric acid to remove carbonates. The remainder of the sediments was ultrasonically extracted three times (15 min each) with dichloromethane (containing 1% methanol). Separation of total extracts into compound classes of different polarities (namely, aliphatic hydrocarbons, aromatic hydrocarbons, and polar hetero (NSO)-components), was performed by medium pressure liquid chromatography (MPLC; Radke and others 1980). Polar extract fractions were derivatized with diazomethane and N-methyl-N-trimethylsilyltrifluoro-acetamide (MSTFA) before analysis.

Gas chromatography (GC) was carried out on a Hewlett-Packard® 5890 series II instrument equipped with a temperature-programmable injector system (Gerstel® KAS 3), a fused silica capillary column (30 m x 0.25 mm i.d., DB-5 film thickness 0.25 µm) and a flame ionization detector (FID). The temperature of the GC oven was programmed from 60 °C (1 min isothermal) to 305 °C (50 min isothermal) at 3 °C/min. The injector temperature was programmed from 60 °C (5 s hold time) to 300 °C (60 s hold time) at 8 °C/s. Relative concentrations of *n*-alkanes and alkenones were determined from peak heights of the FID signals.

Results

New Jersey Continental Margin

ODP Leg 150 was devoted to investigate eustatic (global) sea level changes in Oligocene to Pleistocene sequence boundaries on the New Jersey continental margin. A wide range of organic geochemical parameters was used to detect responses of paleoenvironmental and paleoclimatic changes in the composition of the fossil organic matter (van der Smissen and Rullkötter 1996). Alkenone sea surface temperatures of sediments from Site 903 (upper slope, water depth 445 m, about 130 km offshore) and Site 905 (continental rise; 50 km southeast of Site 903, water depth 2,700 m) are in accordance with climate changes implied in the reconstructed sea level curve of Haq and others (1987) (Figure 1). The degree of unsaturation of long-chain alkenones indicated sea surface temperatures of more than 20°C in the late Eocene, followed by rapid cooling in the late Oligocene. A second cooling event in the middle and late Miocene, as well as a temperature decline in the early Pleistocene, also excellently fit the sea level reconstruction (see Figure 1).

Depth plots of SST and $ACL_{27\text{-}33}$ (carbon number range modified relative to original Poynter [1989] equation) values of sediments from Sites 903 and 905 show a positive correlation of these proxies to each other (see Figure 1; note slightly different age-depth scales). This correlation is more pronounced at the deeper continental rise site, but cooling events are well documented in SST and $ACL_{27\text{-}33}$ data at both locations. ACL values in Eocene to early and middle Miocene sediments are distinctly higher than in younger sediments as a consequence of the general cooling trends toward present-day conditions.

Santa Barbara Basin

Organic matter in late Quaternary sediments from the Santa Barbara Basin (Hole 893A, ODP Leg 146), as well as their texture, exhibit a delicate balance between climatic changes, marine production, and terrigenous supply. These sediments are an excellent archive of paleoenvironmental information about both the marine and the nearby continental environment. Biomarker time series indicate an outstanding climatic situation of the Eemian interglacial with elevated alkenone-derived temperatures about 5.5 °C higher than in the modern system (Hinrichs and others 1997; Figure 2). Strong fluctuations of sea surface temperatures during the last glacial period indicate rapidly changing influence of the cold California Current and the warm southern California Countercurrent on the Santa Barbara basin area; this was recently confirmed by the analysis of deep sea sediments from a location north of the Santa Barbara basin (Mangelsdorf and others this volume).

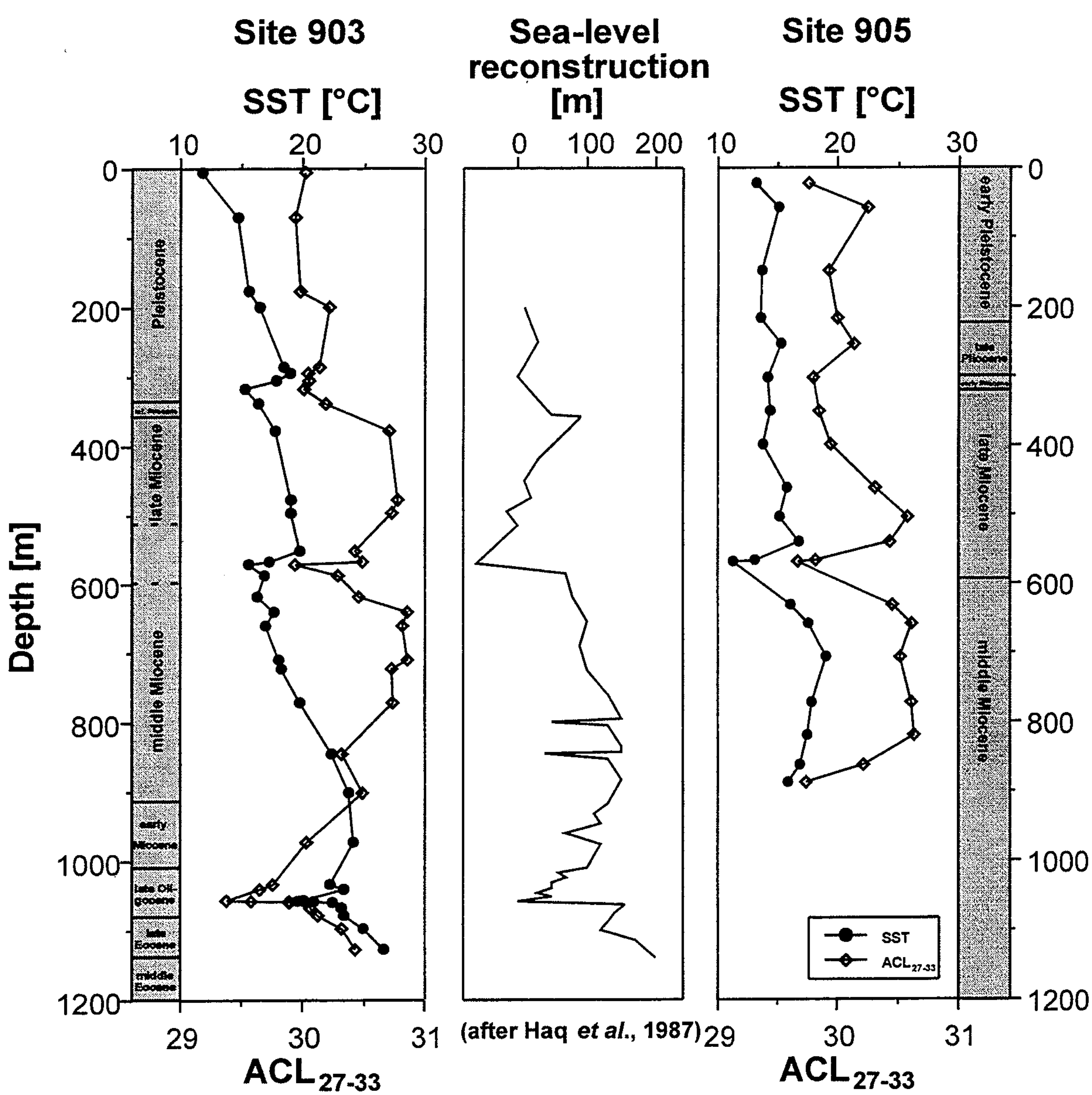

Figure 1 SST and ACL_{27-33} values of sediments from the New Jersey continental margin and sea level reconstruction after Haq and others (1987) for comparison

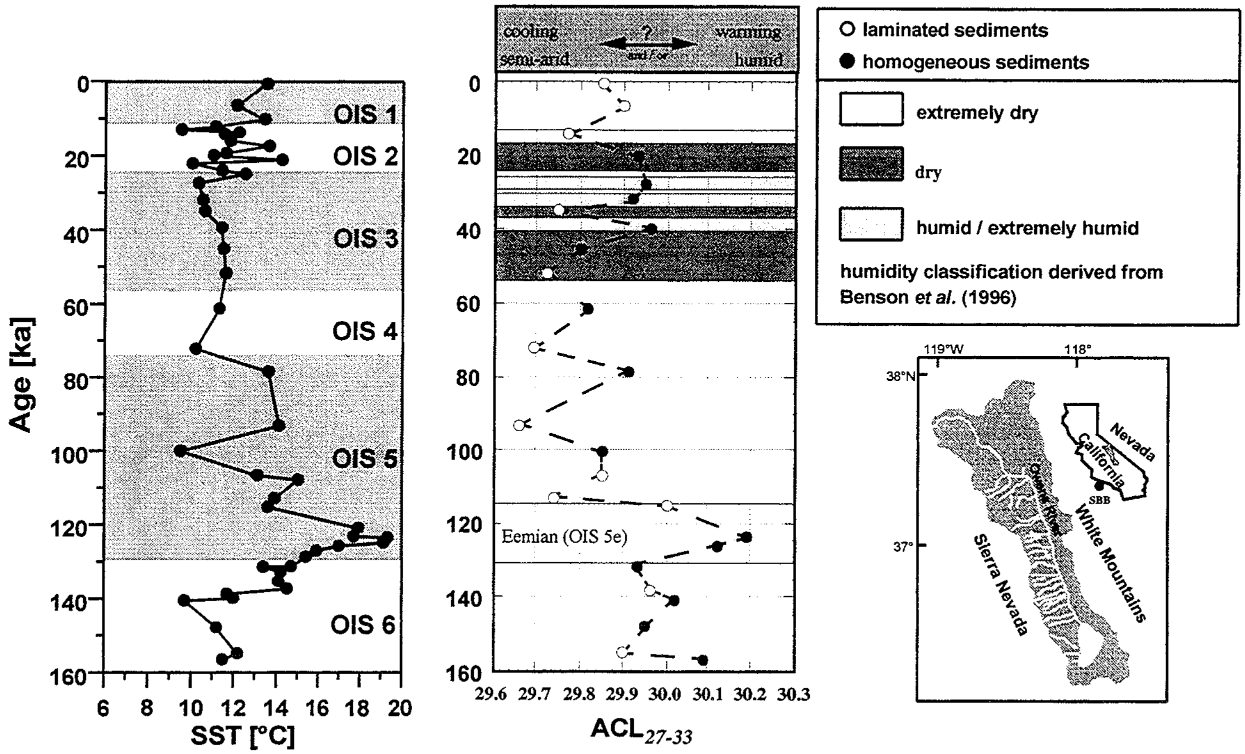

Figure 2 SST and $ACL_{27\text{-}33}$ values of sediments from the Santa Barbara basin covering the last 160 kyr and humidity variation derived from Owens Lake Basin sediments (Benson and others 1996)

Furthermore, the chain-length distributions of terrigenous *n*-alkanes provide evidence that the land climate systematically changed with oceanic variations that affected the redox conditions at the sediment-water interface and led to alternating homogeneous and laminated sediment sections. This conclusion is derived from a comparison with humidity variations deduced from sedimentary variations in the Owens Lake basin (Benson and others 1996; see Figure 2). Apparently, precipitation patterns on land were sensitively influenced by oceanic circulation changes. Most likely, during the formation of laminated sediments a semi-arid to arid climate with seasonal precipitation mainly in winter and spring similar to the present-day situation prevailed in California, whereas periods of deposition of homogeneous sediments occurred at times of higher rates of precipitation (and thus continental runoff), which was also more evenly distributed over the year (for more details see Hinrichs and others 1998).

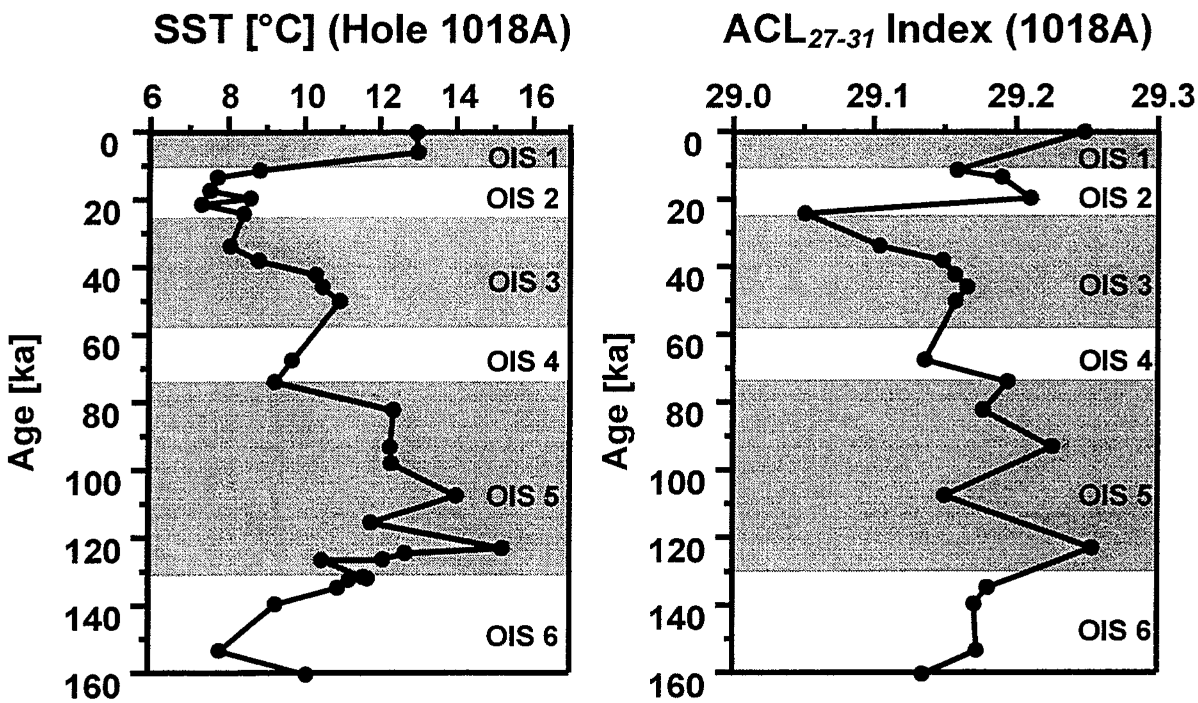

Figure 3 SST and $ACL_{27\text{-}31}$ values of sediments from the central California continental margin covering the last 160 kyr

California Continental Margin

During ODP Leg 167 a series of holes were drilled along the Californian coast and in the southern Californian Bight to investigate the climatic and oceanographic variations in this area and particularly to relate information gained from ODP Hole 893A in the Santa Barbara basin to the entire California Current system. From the organic geochemical analysis of sediments from Hole 1018A on the central California continental margin covering the last 160 yr, the alkenone-derived SST estimates were found to reflect the variations of global climate with warmer temperatures during the interglacials and lower temperatures during glacial times (Figure 3). This shows how sensitive the California current, transporting water masses and thereby temperature signals into this area, reacts to climatic changes. Note that temperature fluctuations in the last interglacial are smaller than at the Santa Barbara basin site. With few exceptions, the $ACL_{27\text{-}31}$ profile reveals a pattern similar to that of the corresponding SST values. This indicates the influence of climatic changes, observed in the paleo-sea surface temperatures, also on the vegetation of the adjacent continent.

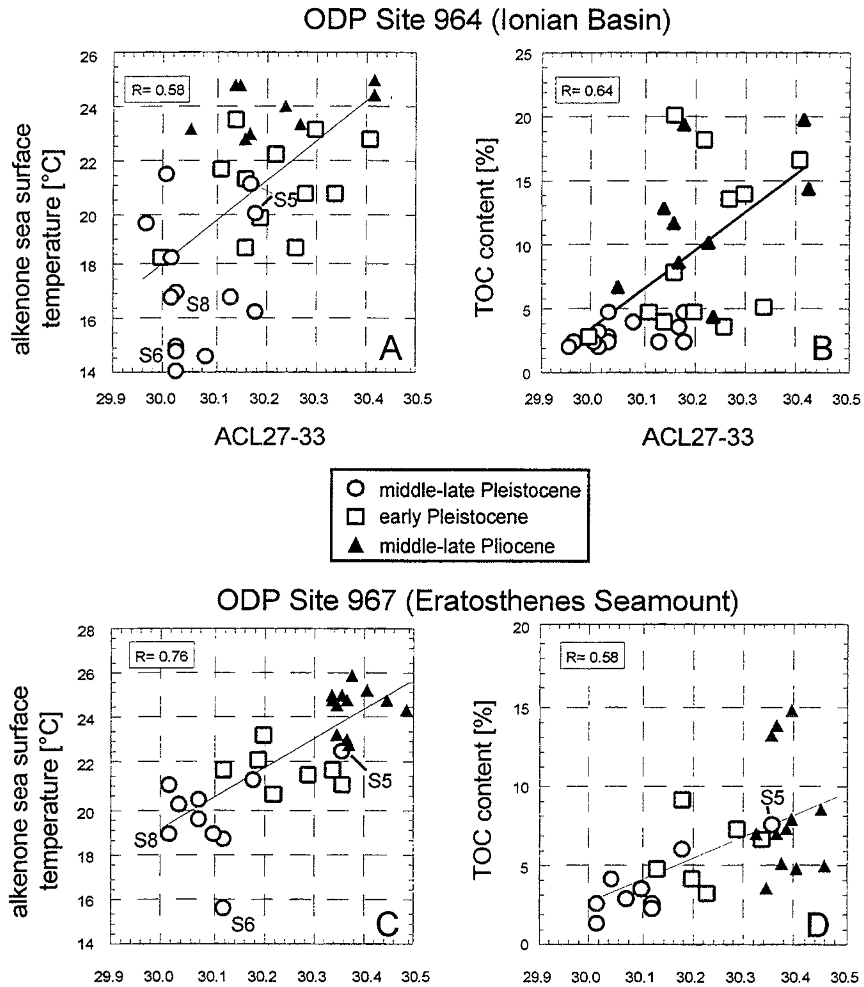

Figure 4 Correlation between $ACL_{27\text{-}33}$ and SST values and TOC contents in sapropels from the Mediterranean Sea.

Eastern Mediterranean Sea

The formation of Pliocene-Pleistocene sapropels in the Mediterranean Sea is controlled by earth orbital parameters, particularly precession cycles and the related monsoon activity. Most of these dark, organic-carbon-rich layers (see Rullkötter and others [1998] and Bouloubassi and others [1999] for more organic geochemical details) were probably deposited under warm and humid (land) conditions, but there are also examples for late Quaternary sapropels, which were formed under a cold and arid climate regime (S6 and S8; for example, Rossignol-Strick 1985). Scatter plots of SST versus $ACL_{27\text{-}33}$ and TOC versus $ACL_{27\text{-}33}$ data (Figure 4) for sapropels from two different locations, ODP Site 964 in the center of the Ionian Basin and Site 967 on the Eratosthenes Seamount close to Cyprus, indicate systematic variations of these parameters. The correlation between SST and $ACL_{27\text{-}33}$ data is less pronounced at the more western Site 964 which may reflect some source area variations of the terrestrial *n*-alkanes, while terrigenous organic matter supply on the Eratosthenes Seamount is assumed to come essentially from the African continent through the Nile. As expected, the sapropels deposited under conditions of cooler climate are characterized by both low SST and ACL values, while sapropel S5, formed during the warm Eemian interglacial, has the highest ACL value of the middle to late Pleistocene sapropels at both sites.

Conclusions

- The application of sea surface temperature proxy derived from the degree of unsaturation of long-chain alkenones biosynthesized by Haptophyceae leads to estimates of temperature variations back to the Eocene that are in reasonable agreement with global paleoclimate indicators like sea level reconstructions. Apparently, marine algae different from but related to those existing in today's world oceans had developed a similar water temperature-related biosynthetic pathway. This does not necessarily imply that the use of the temperature calibration derived from laboratory cultures and measurements in the present ocean provides exact paleotemperature data, but the relative variations are pronounced and appear reliable.
- The average chain length of terrestrial *n*-alkanes is a powerful tool for recognizing land climate variations and land-ocean interactions in different geographical regions and over a wide range of geological times.

Acknowledgments

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A Modesto Age Fossil Plant Record from the Laguna de Santa Rosa, Sonoma County, California: Climatic Implications

G. James West, Jack Meyer, and Eric Wohlgemuth

Abstract

Pollen grains from a 38,000-year-old peat deposit on the Santa Rosa Plain (Llano de Santa Rosa) suggest a significantly different vegetation and climate compared to today. High pollen values of pine (*Pinus*) (51%), TCT (Taxaceae, Cupressaceae, and Taxodiaceae, excluding redwood [*Sequoia sempervirens*]) (26%), and fir (*Abies*) (1.2%) indicate a pine-cedar forest containing a few isolated fir trees. These pollen values are in great contrast to the pollen rain of the Valley Oak Savanna which occurs in the area today. Cooler temperatures, 3 to 5 °C lower than today, are inferred. Comparison with similar-age plant fossil records suggests a coast-to-interior climatic gradient also was present.

Introduction

In cismountane interior California only a small number of late Quaternary alluvial formations containing plant fossil records have been described, and only a few of the alluvial deposits can be adequately correlated to late Pleistocene climatic events. Here we present the results of pollen and seed analysis of a peat contained within Pleistocene alluvium that is equivalent in age to the Modesto Formation. Similar Modesto age sedimentary pollen records from lakes and marine basins and macrobotanical remains from widely disparate locations are comparatively used to reconstruct vegetation and climate.

The Modesto Formation is the youngest of the major Quaternary alluvial units of the eastern side of the San Joaquin Valley. It has been divided into a Lower and an Upper Member (Janda and Croft 1967; Marchand and Allwardt 1981; Shlemon 1972). The Upper Modesto, separated by a soil forming interval from the Lower Modesto, is thought to be correspondent to the Tioga Stage of Sierra Nevadan glaciation. We use the Modesto Formation here for comparative temporal purposes and do not ascribe any genetic relationship with the Laguna de Santa Rosa alluvium.

Location and Description of Sample Locality

The fossil locality is on the Santa Rosa Plain (Llano de Santa Rosa) 50 km north of San Francisco, 20 km east of the Pacific Ocean, and 5 km west of Rohnert Park (lat 38°21' long 122°44'30") (Figure 1). The plain is located at an elevation of 30 to 35 m and was historically covered with a Valley Oak (*Quercus lobata*) Savanna

(Küchler 1977). Drainage is through Laguna de Santa Rosa, a meandering northwesterly-trending stream that transects a series of marshes before eventually connecting to the Russian River. The Sebastopol fault bisects the sample locality and lies parallel to several other faults that also trend in a northwesterly direction. Movement on the Sebastopol fault has undoubtedly lead to the creation of the local marsh conditions and influenced the northwesterly trend of Laguna de Santa Rosa.

The peat was found in fine grained alluvium (silts and clays) (Figure 2) 3.2 m below the surface during excavations for the Laguna de Santa Rosa Water Control Channel, which is about 150 m north of the existing Laguna de Santa Rosa. The peat layer is at least 100 cm thick and was found directly below a distinct bluish-gray clay loam. In places along the exposure, the peat and bluish-gray clay loam are inter-bedded, suggesting contemporaneity. The wood sample came from the location of the sediment profile about 800 m east of the peat.

Methods

Jack Meyer found and collected a large sample of the peat, as well as pieces of wood, from the excavation exposures during a geologic reconnaissance survey. Standard, chemically based, palynological extraction techniques were used to process the sample. A Nikon® Labophot microscope with phase contrast was used to scan the sample. Pollen identifications are based on herbarium specimens obtained from the Jepson Herbarium at the University of California, Berkeley, and the Tucker Herbarium at the University of California, Davis, as well as standard texts. A vial of the remaining sample is stored at the Anthropology Department at the University of California, Davis. For determining pollen percentages, the sums for the aquatic-emergent types are outside of the percentage pollen sum. The radiocarbon sample was cut from the same piece of peat from which the pollen and seed samples were taken. Seeds were collected by flotation and from screening. Seed identification is based on standard texts. Wood identification is based on microanalysis done by the Smithsonian Institution.

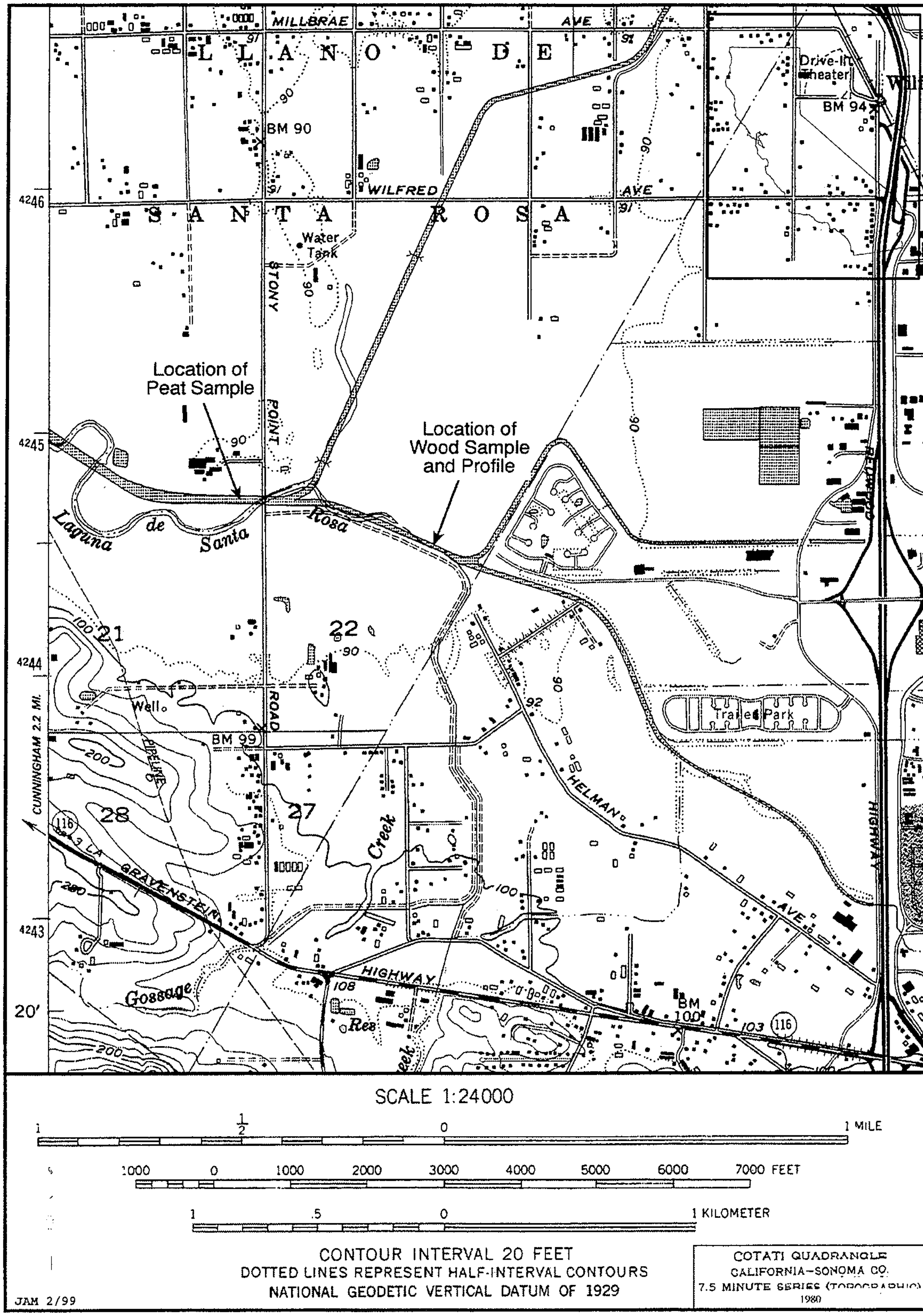

Figure 1 Location of peat and wood sample recovered from Laguna de Santa Rosa sediments

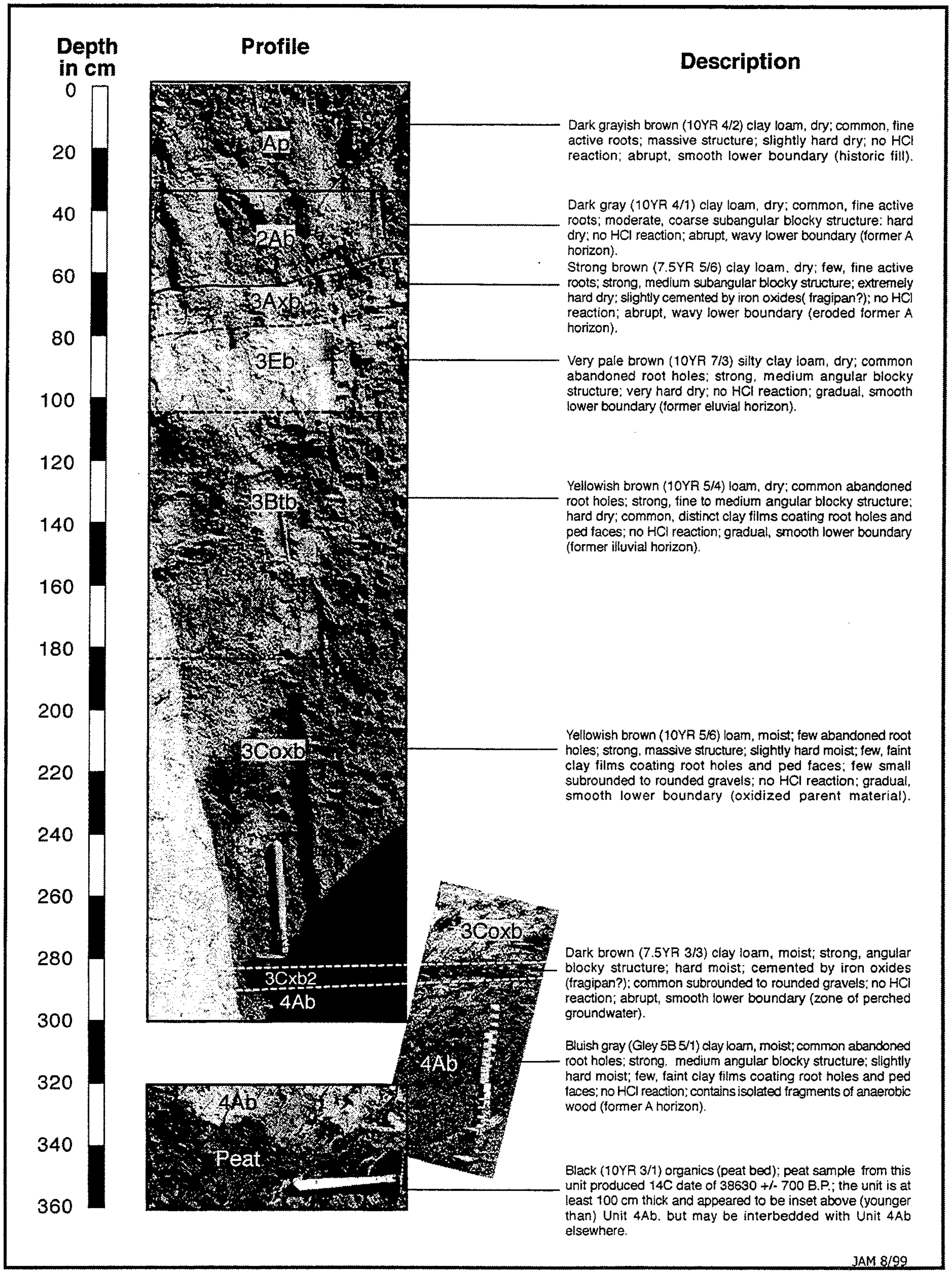

Figure 2 Composite stratigraphic section of Laguna de Santa Rosa sediments and peat layer

Results

Age Determination

A single, conventional, radiocarbon age determination of 38,630 ± 770 BP (Beta-127297) was obtained from the coarse fibrous fraction of the peat that remained after full acid-alkali-acid pretreatment. All carbonates and humic acids (both primary and secondary) were removed by the pretreatment, thus reducing the possibility of secondary contamination.

Pollen

Pollen was well preserved and abundant. A total of 551 pollen grains were counted and 23 pollen types were identified (Table 1). A relatively large number (14%) of unknown pollen grains were encountered. Of these, a large fraction are likely derived from non-arboreal and aquatic-emergent taxa. The most abundant pollen types identified were pine (*Pinus* sp.) (51%) and TCT (Taxaceae, Cupressaceae and Taxodiaceae, excluding *Sequoia* sp.) (25.6%) (Figure 3). Unfortunately, since their pollen morphology is so similar, it is not possible to determine which other member(s) of the TCT group is represented. While pine grains were not differentiated to species a number of grains were quite small, suggesting more than one species is represented. The lack of redwood (*Sequoia* sp.) pollen is significant since redwood is abundant in the region today and is a component of the modern pollen rain (Heusser 1983). Only four other arboreal forms are present in the pollen record—fir (*Abies*), coastal hemlock (*Tsuga heterophylla*), oak (*Quercus* sp.) and Douglas fir (*Pseudotsuga menziesii*). With the exception of fir at 1.2%, all are present at less than 1% of the pollen spectra, suggesting they were not important elements of the region's vegetation. Today, oak and redwood are the important, and in places, the dominant arboreal taxa for the region.

Pollen grains of ten non-arboreal types were identified but none are present in great abundance, suggesting the local upland vegetation was a pine and cedar forest with a few fir trees and a sparse understory. The pollen grains from aquatic-emergent plants are abundant, suggesting ponded areas with water lilies (*Nuphar polysepala*) and marshes with dense stands of sedges (Cyperaceae) and cattails (*Typha latifolia*) along with a few willows (*Salix* sp.). Also of note is the presence of the algae Botyrococcus. Its relative abundance suggests standing bodies of water, such as might be found in an oxbow lake on the flood plain of an ancient Laguna de Santa Rosa.

The spores of dung fungus (Sporormiella) were present. Davis (1987) found dung fungus spores were abundant in Pleistocene and historic age sediments in the Sierra Nevada and equated their abundance to the mega-fauna of the Pleistocene and the introduced livestock of the historic period.

Table 12 Microfossil counts and percentages of peat sample from Laguna de Santa Rosa

	Raw Count	*Percent*
Terrestrial Species		
Pinus sp.	207	51.11
Abies sp.	5	1.23
Tsuga heterophylla	2	0.49
TCT	104	25.68
Quercus sp.	4	0.99
Pseudotsuga sp.	2	0.49
Rhamnaceae	1	0.25
Rosaceae	3	0.74
Asteraceae	6	1.48
Poaceae	5	1.23
Chenopodiaceae	1	1.25
Caryophyllaceae	1	1.25
Polygonaceae	1	1.25
Gilia sp.	1	1.25
Myrica sp.	1	1.25
Brassicaceae	2	0.49
Apiaceae	2	0.49
Unknown	57	14.7
Aquatic Emergent Species		
Cyperaceae	123	30.37
Nuphar sp.	11	2.72
Salix sp.	3	0.74
Typha latifolia	14	3.46
Typha sp. or *Sparganium* sp.	3	0.74
Algal Species		
Botyroccus sp.	64	15.8

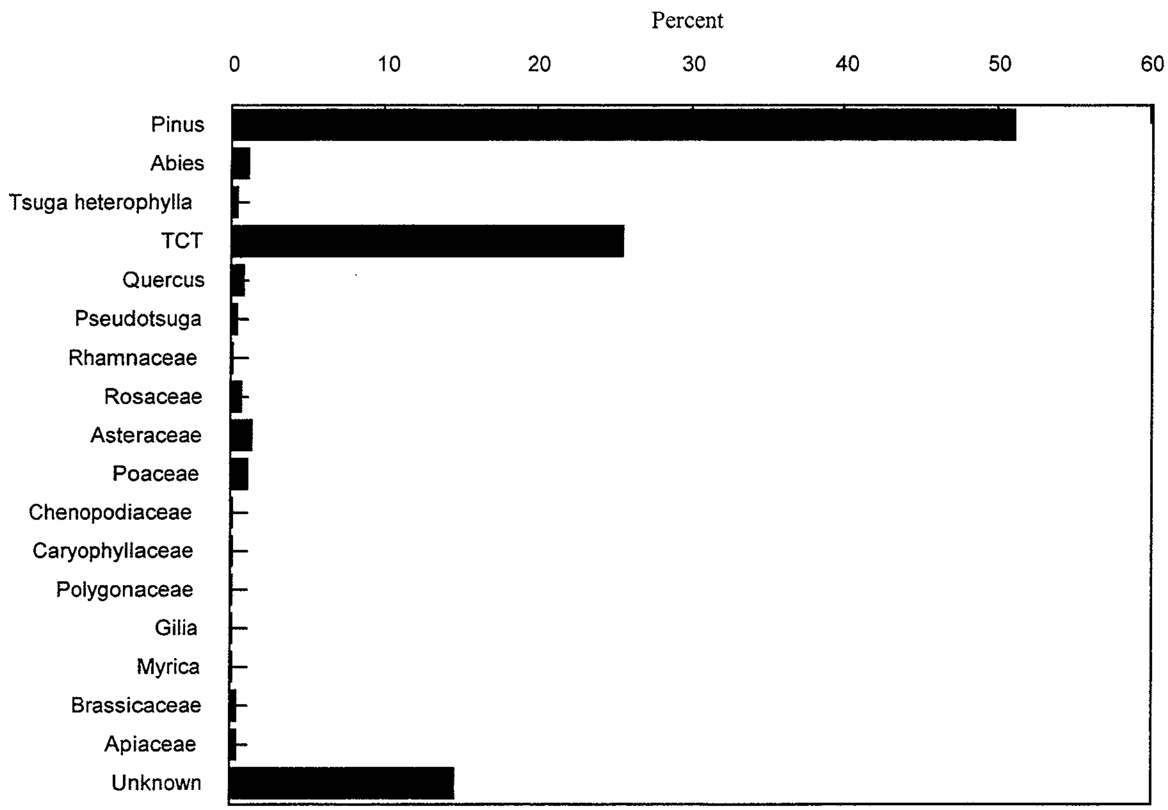

Figure 3 Relative pollen values of peat sample from Laguna de Santa Rosa

Seeds

While seeds are abundant in the peat, their identification is uncertain. One group may be from the Euphorbiaceae but this has not been confirmed. The seeds of pondweed (*Potamogeton* sp.) and *Claytònia* (*Montia* sp.) are rare components of the seed assemblage.

In addition to seeds, the oospores of Characeae, a green algae, are abundant. Most Characeae are submerged taxa that live in freshwater with either sandy or muddy substrates (Hutchinson 1975).

Wood

The single sample was very compressed and degraded. None of the sections observed showed any birefringence under crossed polars, indicating that the cellulose and lignin of the cell walls had been degraded. Further microanalysis revealed uniseriate rays, salicoid ray-vessel pitting, and heterocellular rays. The combination of uniseriate rays and salicoid ray-vessel pitting indicates the sample is in the Salicaceae (willow family). The presence of heterocellular rays indicates that the sample is willow (*Salix* sp.).

Discussion

The radiocarbon age of the peat falls near the ascribed temporal boundary between the Upper and Lower Modesto. The age is at the lower temporal boundary of the Upper Member and the end of the soil forming interval. The Modesto soil forming interval has been correlated to the Promontory and Churchill Soils described for Lake Bonneville and Lake Lahonton in the Great Basin (Morrison and Frye 1965).

The microfossils of aquatic-emergent plants, as well as the macrofosils (oospores, seeds, and wood), all indicate a marsh-like environment. The pollen spectrum indicates that at the time of peat deposition the upland vegetation was a pine and "cedar," (member(s) of the TCT group) forest containing a few fir trees, a vegetation pattern radically different from today's upland potential vegetation (Valley Oak Savanna). While oaks and Douglas fir were present, they were a very minor component of the arboreal community. The two grains of coast hemlock pollen were probably derived from coastal areas by way of prevailing westerlies and not from the local upland forest. The presence of dung fungus spores is consistent with Davis' (1987) findings in the Sierra. The lack of redwood pollen grains suggest that its range was significantly different than today, probably the result of cooler temperatures and greater seasonality due to lower sea levels, which reduced the moderating coastal maritime effect on the Laguna de Santa Rosa area.

The climate indicated from the vegetation suggests a cooler, more Continental climate than today. Temperatures, estimated from the Clear Lake pollen record (Adam and West 1983), were probably 3 to 5 °C cooler than today.

The nearest comparative age pollen spectra are from Clear Lake (Adam 1988). Clear Lake is 80 km north of Laguna de Santa Rosa and 50 km farther inland at an elevation of 404 meters. Clear Lake sediments correlated to the Modesto contain pollen spectra with high pine (40% to 50%) and TCT (50% to 60%) values as well as sagebrush (*Artemisia*) (2%).

In equivalent age sediments from the Santa Barbara Basin Heusser (1995: Figure 9) found a pollen assemblage dominated by TCT (40% to 50%) and pine (20% to 40%) that also contains significant amounts of *Artemisia* (6% to 7%).

The slightly higher pine values and lack of *Artemisia* in the peat sample suggest a slightly more mesic environment than Clear Lake or the Santa Barbara Basin. The *Artemisia* pollen in the Santa Barbara Basin sediments may be from Coastal sage communities, whereas the Clear Lake *Artemisia* grains are likely derived from inland and upland species.

Independently dated, Modesto-age, macrobotanical remains have been reported from several locations in coastal California. Spruce (*Picea*) remains from the Millerton formation near Point Reyes have been dated to 29,000 years BP and cypress (*Cupressus goveniana*) at Carpinteria to >38,000 years BP (Axelrod 1983; Warter 1976). From Rancho La Brea five radiocarbon dates ranging from 40,000 to 25,000 provide time constraints for a closed-cone pine forest that contained two species of cypress (*Cupressus goveniana, C. macrocarpa*), two species of pine (*Pinus muricata, P. radiata*) and coast live oak (*Quercus agrifolia*) (Warter 1976). A Modesto age cool maritime climate can be inferred at these localities, suggesting >300 km latitudinal climatic shift southward from today's conditions.

Conclusions

The following conclusions have been reached:

1. The age of the peat is of equivalent age to the Modesto Formation found on the east side of the Central Valley.

2. The fossil pollen data imply an upland pine-cedar forest containing isolated fir trees with a sparse understory. The plant remains from aquatic-emergent types indicate a freshwater pond and marsh. The climate to support the interpreted upland vegetation would have been cooler by 3 to 5 °C and more Continental than today.

3. The preponderance of pine and TCT pollen is similar to that observed for other sediments of similar age within lowland cismountane California. The lack of *Artemisia* pollen suggests that, like today, a climatic gradient was present during Modesto times. The presence of macroplant remains indicating maritime climates along the coast, is consistent with this interpretation.

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Abstracts

Oral Presentations

Western Climate Events Since PACLIM 1998—First El Niño, Then La Niña, Now What?

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The attention spotlight shifted and dimmed as the major El Niño of 1998–1998 rapidly gave way to its La Niña counterpart. The winter of 1998–1999 brought a classic La Niña pattern to the West—for precipitation, but not temperature. The Southwest experienced one of its driest winters ever, and the Pacific Northwest experienced one of its wettest winters ever. In between, the central Sierra Nevada experienced an unprecedented fifth consecutive very wet winter. Hydrological drought became a significant issue in the Southwest, although precipitation at the start and end of the winter season did help. In the Northwest, near record snowpacks accumulated, especially in the Cascades. The temperature pattern showed warmth both north and south, uncharacteristic for La Niña. The usual La Niño cool pattern in the northern Rockies appears to have been masked this time by a trend in recent years toward warmth. The West Coast experienced a cool winter, and for the past year the coolest temperatures in the U.S. relative to average have been in the Central Valley of California. Parts of Hawaii recovered from the major El Niño dry spell, but other parts remained extremely dry. Another feature of the winter that attracted considerable attention was the number of windstorms.

Water Year 1999—A Classic La Niña Pattern

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Water year 1998–1999 seemed to embody a classic La Niña pattern. It was dry in the American Southwest (which extended into southern California) and wet in the Pacific Northwest. Northern California is in between and can go either wet or dry. But this year the north Pacific storm track was vigorous and the wetness extended almost to central California, especially in the mountains. The exception was a month-long dry spell centered around New Year's Day. This dry period included a temperature extreme, with a severe freeze in the week before Christmas. Many storms seemed to run out of energy between Stockton and Fresno leaving the southern Sierra rather dry.

The drop-off in precipitation to the south showed up in the April 1 snowpack. The snow water content from the Tuolumne River watershed (Yosemite Park) north was above average, whereas from the Merced River south amounts were progressively less than average. The range was from about 150% of average in the North Coast region, near 130% on the American River in the middle, and to only around 50% on the Kern River. The statewide average snowpack was about 110 percent. Spring snowmelt runoff varied accordingly with the statewide runoff forecasted on April 1 to be 110%.

For the Sacramento River system (the four rivers), the forecasted runoff is nearly 22 million acre-feet, or about 120% of average. This marks the fifth consecutive wet year. That long a run has not occurred before this century, and probably not since some early rainfall records began in 1850. Longest previous wet runs were four years in succession, which occurred twice since 1900. The tree ring reconstruction of Sacramento River system runoff back to year 1560 reveals three other runs of five years or longer: 1601–1606 (six years), 1801–1806 (six years), and 1808–1812 (five years). Just a decade ago we were in the throes of a six-year drought.

Reservoir storage has been excellent all season with good carryover from a wet 1998. Amounts during the winter at major reservoirs were limited by flood control requirements, with considerable excess water being released during winter months. Statewide storage on April 1 stood at 115% of average for the date, nearly the same as one year ago. With a good snowpack in most mountain areas, water supplies should be average or better for most areas. Some deficiencies are expected in Central Valley Project service areas on the west side of the San Joaquin Valley and in areas of the southern half of the State which lack storage but are dependent on local runoff.

There were some periods of high water on Central Valley rivers this winter but no large floods. For a change, water year 1998–1999 was fairly benign. The only unusually high stages were on November 21 on the Smith River of northwestern California which saw the highest water level since 1990.

Water, Earth, and Sky—The Colorado River Basin

Mike Collier
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Through photographs taken from a Cessna and discussions of the natural history of the region, we will view the Colorado River basin as if it were a grand banquet spread before us.

The Colorado and Columbia River Systems: Climate, Water, and Human Interactions: Introduction—Comparing the Basins

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Kelly T. Redmond, Western Regional Climate Center, Desert Research Institute, Reno, Nevada

The purpose of this session is to introduce a method for undertaking a comparative appraisal of climate effects and water resources management in paired river basins. The approach is to compare and contrast different systems of water supply and quality management. Two closely separated and relatively small watersheds in the Sierra Nevada, Tahoe, and Walker basins, will illustrate the method. Then, the stage will enlarge to encompass two much bigger and historically significant river basins of western North America, the Columbia and the Colorado. Similarities and differences will be highlighted. The goal is to explore whether lessons learned in one basin or region, in the context of human adaptation to climate variability and change, can be transferred to the other.

Impacts of Climate Variability on Monitoring Restoration Efforts in Two Sierra Watersheds

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Throughout the western United States, environmental restoration efforts are being undertaken for a great many watersheds. These range from large scale, multi-state efforts such as the Snake River Basin and Colorado River Basin restoration projects, to smaller scale, localized efforts, such as the restoration programs at Lake Tahoe and Walker Lake. The hydrographic setting, sociopolitical environment, and ultimate goals of each restoration effort tend to be quite unique from one watershed to the next. However, a problem that appears to be common to many watersheds is how to most effectively monitor the progress of the restoration effort. The most direct method of monitoring restoration progress is to develop a set of monitoring variables that directly indicate whether conditions are improving or degrading within the watershed. However, such monitoring data tends to be highly influenced by climatic conditions, making it difficult to determine if restoration activities are having the desired effects on conditions within the watershed. Two such watersheds facing this problem are the Walker Lake (a terminal desert lake in western Nevada) and Lake Tahoe (a high alpine lake on the Nevada California border). Both lakes are fed primarily by snowmelt from High Sierra watersheds that are within 100 km of each other. A comparative study between the two watersheds illustrates the similarities and significant differences of the restoration efforts for each watershed, and how climate variability influences decisions related to restoration efforts within the recent past. Of particular interest is the period from 1985 through 1997, which starts with a significantly wet year, moves through an extended drought, and then returns to an extended wet period. Restoration monitoring and climate statistics are presented for both watersheds, along with simple statistical analysis techniques that could be used to distinguish between effects of climate variability and restoration activities on the progress of restoration efforts within each watershed.

El Niño and La Niña Effects on Snowpack Evolution in the Columbia and Colorado River Basins

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We use monthly Snow Water Equivalent (SWE) data measured at several hundred sites in the western United States to examine the historic effects of El Niño and La Niña events on the seasonal evolution of snowpack in the major sub-basins in the Columbia and Colorado River systems. Results are used to predict April 1 SWE, which represents the peak SWE in most basins. In the Columbia River Basin, there is a general tendency for decreased SWE during El Niño years and increased SWE in La Niña years. However, the changes in SWE in El Niño years are much less pronounced. This occurs in part because the mid-latitude circulation anomalies in El Niño years are located 30° east of the respective anomalies in La Niña years. This eastward shift in circulation anomalies in El Niño years is most evident in mid-winter and is associated with mid-winter increases in SWE in coastal regions of the Columbia River basin. In the Colorado River Basin, mean changes in SWE during El Niño years depict a transition between drier than average conditions in the north, and wetter than average conditions in the southwest. Signals during La Niña years are generally opposite of those during El Niño years. Anomalies in SWE tend to be more pronounced in spring in the Lower Colorado River basin when the El Niño and

La Niña events have the strongest influence on modulating regional precipitation. Our predictions of April 1 SWE reveal there is reasonable skill for scenarios using only persistence (based on February 1 SWE) and for scenarios using only historic El Niño and La Niña information. Combining knowledge of the seasonal evolution of the snowpack for El Niño and La Niña events with information on mid-winter snowpack conditions improves predictions in most instances.

Climate Extremes and Adaptive Management on the Colorado River

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Extreme event research and applications are expected to assume greater immediacy with foci including effects in urban areas, the public sector, scheduling, operations, performance of various private sector activities, and assessment of users. This paper focuses on the last three issues in relation to climatic risks in a multi-actor setting, the Colorado River Basin at Glen and Grand Canyons. Emphasis is placed on actions taken during the El Niño–Southern Oscillation (ENSO) event of 1997–1998.

The Colorado River system, exhibits the characteristics of a closing water system where management of interdependence becomes a public function, development of mechanisms to get resource users to acknowledge interdependence and to engage in negotiations and binding agreements become necessary, and implementation of such mechanisms does not appear to be viable without focusing events. This paper describes the response of natural resource managers and operations on the Colorado River at Glen Canyon Dam to unanticipated spring runoff and flood-flow events of 1983, 1984, 1995, in the context of management objectives based on periods of drought (such as the 1930s, 1950s, 1977, and 1987–1992). It shows ways in which different lessons were used from these events to prepare for likely effects related to the 1997–1998 ENSO. It also describes how new management approaches in the Colorado River Basin facilitated responses while still meeting seasonal and long-term ecosystem, cultural, inter-basin water resources, and hydropower needs.

American Indian Cultural Adaptations and Climate Change in the Colorado and columbia River Basins

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This paper presents examples of American Indian cultural adaptations to riverine ecosystems that are both responses to and protection from climatic change. The paper compares cultural adaptations in the Colorado and Columbia River basins, but emphasizes the former where climatic changes seemingly have greater potential for disrupting human society. Examples include social changes in Mesa Verde, Colorado, at the end of the 12th century; the integration of beaver into irrigated agriculture in the Virgin River, Utah, watershed during the protohistoric period; and post-Pleistocene continuities in ceremonial use of a power-landmark in southern Nevada despite radical climatic change. The paper concludes with an essay on the power of cultural systems to mediate climatic change and some recommendations for future studies.

Environment and the Anasazi of the Colorado Plateau

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During the last 2000 years, the southern Colorado Plateau was occupied by societies, collectively called Anasazi, that practiced an agricultural lifeway focused on maize, squash, and beans. Because much of this vast and varied region is marginal for farming, modern scholars believe environmental variability to have been a major causal factor in Anasazi population movements and sociocultural change. A case in point is the long-standing idea that the Great Drought of 1276–1299 was the principal cause of the Anasazi abandonment of the San Juan drainage at the end of the 13th century. Recent paleoenvironmental research—involving alluvial chronostratigraphy, packrat midden analysis, palynology, and dendroclimatology—provides integrated reconstructions of past environmental variability that, in combination with archaeological data on human behavior and demography, indicates the degree to which Anasazi subsistence systems may have been affected by environmental variation and change. Although high potential subsistence stress commonly coincides with recognizable behavioral adaptations, contrary instances suggest the relationship is not simple and complex combinations of factors determine the outcome of any particular episode. In the case of the 13th century abandonment, for example, environmental deterioration in the Four Corners area provided an impetus to move, while better natural conditions and tantalizing social development attracted migrants to other areas.

Climate Assessment in the Southwest—The Centrality of Stakeholders

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Considerable interest exists in unraveling the knotty problems of making innovations and findings of climate research more accessible to the public. Integrated assessments that combine theoretical and methodological approaches from both social and natural science provide avenues not only for identifying what sorts of climate information people need but also for uncovering important sensitivities and vulnerabilities to climate variability within the region. The Climate Assessment Project for the Southwest (CLIMAS) has received seed funding from NOAA to improve the flow of climate information so as to enhance the capability of the region to more effectively cope with climate variability. One of the pivotal features of CLIMAS is that it places integration of stakeholders unequivocally at the center of its research and outreach mission. In pursuit of this mission, CLIMAS has undertaken a series of projects aimed at identifying what sorts of climate information people in the region use, what sorts of information they need, and how these needs may be addressed through regional climate research and outreach. Surveys and other stakeholder interactions conducted over the past year provide insights valuable for designing effective research and outreach activities.

Coping with El Niño-related Droughts in Peasant Agriculture, Northern Costa Rica, 1997–1998

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Interviews were conducted with small-scale farmers (2–15 ha) in two regions of Costa Rica in July 1998, following the subsidence of the drought associated with the 1997–1998 El Niño event. One of these regions, Guanacaste Province in the Pacific lowlands, has a documented strong El Niño drought signal. The other, the Zona Norte in the northern Caribbean lowlands, has no documented strong or consistent El Niño signal. Differences were noted between the two regions in (1) the number of the anticipatory and preventative coping mechanisms of the farmers, (2) the effectiveness of these mechanisms, and (3) reported psychological states in relation to the drought. Coping mechanisms found in the Guanacaste region include laying land fallow during dry period, seeking alternative wage labor during drought, maintaining social and family network in the city, planting drought resistant forage grasses, selling off cattle before dry season begins, and maintaining a network of alternative wells during the dry season. Few, if any, coping mechanisms were observed in the Zona Norte. Losses were most severe for farmers in the Zona Norte than in Guanacaste. In addition, farmers in the Guanacaste region did not express alarm concerning the El Niño droughts, often stating that decadal droughts were the "norm." In contrast, households in the Zona Norte related feelings of anxiety and uncertainty regarding the drought event and the possibility of future events. These results suggest a relationship between the presence of cultural coping mechanisms in peasant agriculture and the frequency with which anomalous climate conditions affect them. In the future, policy makers may use this relationship to identify communities that are particularly vulnerable to anomalous conditions (those that do not consistently experience these anomalies) during infrequent climate events, such as those experienced during the extreme 1997–1998 ENSO event.

A Possible Connection Between the 1878 Yellow Fever Epidemic in the Southern United States and the 1877–1878 El Niño Episode

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One of the most severe outbreaks of yellow fever, a viral disease transmitted by the *Aedes aegypti* mosquito, affected the southern United States in the summer of 1878. The economic and human toll was enormous and the city of Memphis, Tennessee, was one of the most affected. The authors suggest that as a consequence of one of the strongest El Niño episodes on record, which occurred in 1877–1878, exceptional climate anomalies occurred in the United States (as well as in many other parts of the world), which may have been partly responsible for the widespread nature and severity of the 1878 yellow fever outbreak.

This study documents some of the extreme climate anomalies that were recorded to 1877 and 1878 in parts of the eastern United States, with particular emphasis on highlighting the evolution of these anomalies, as they might have contributed to the epidemic. Other years with major outbreaks of yellow fever in the 18th and 19th centuries also occurred during the course of El Niño episodes, a fact that appears not to have been noted before in the literature.

Role of Climate Change and Historic Ecosystem Analysis in Land Management Planning

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The study of past conditions of forest ecosystems has important applications in ecosystem management. Foremost is the ability to characterize the natural variability of ecosystems and their response to disturbance and climate change over various time scales to assess recent human-induced changes and to anticipate possible future states. Many historic studies, however, focus on a static pre-settlement period, which ignores the effects of climate change, particularly during the transition between the Little Ice Age and modern climate around the turn of the century. Thus, erroneous management decisions can be made about restoring degraded ecosystems to historic conditions. We illustrate these concerns by first reviewing climate variability over the past 1000 years and its effects on the environment in the western United States. We then compare a recent Forest Service landscape analysis conducted in the eastern Sierra Nevada, California, with results from our historic reconstruction within the analysis area in the Glass Creek watershed. The meadow and surrounding forests in the watershed were apparently affected by a volcanic eruption about 600 years ago which triggered a widespread high intensity fire. Subsequently, forest composition was influenced by successive climate changes and associated fire regimes. There was no evidence that fire suppression contributed to lack of fires in the last century. Nor was there evidence for surface fires of moderate or low intensity at regular, short-return intervals as had been interpreted by the Forest Service landscape analysis. Pollen analysis indicated no significant changes in meadow floristics during the last 150 years, countering inferences that present meadow conditions are the result of livestock grazing.

Climate Forecasts and Pacific Northwest Public Agencies—Is Anyone Listening?

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Did public resource management agencies benefit from climate predictions issued during the major El Niño event of 1997–1998? Since 1996, the Climate Impacts Group at the University of Washington has been investigating how Pacific Northwest natural resource managers use climate information in their decision making processes. Responses to surveys conducted in 1996, 1997, and 1998 indicate that interest in and use of climate information by some Northwest resource managers has increased sharply in the past few years. On the other hand, many agencies face major institutional constraints that severely limit the flexibility necessary for using seasonal to interannual climate predictions.

Generally speaking, the agencies with the greatest technical capacities and those facing the greatest perceived threats are most attuned to climate forecasts. Major obstacles to the current use of (ENSO-related) climate forecasts include concerns over forecast accuracy, a lack of interpretation, a misunderstanding of probabilistic forecasts, and institutional constraints arising from legal, managerial, and other conflicts.

Only a few public agencies made major changes to their operations in response to climate information related to the El Niño for 1997–1998. However, regional inter-

est in the 1997–1998 El Niño was intense as evidenced by numerous requests for El Niño briefings by regional, state, and local agencies, and private sector interest groups.

Climate and Water Management in the Interior West

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Water allocations in the interior West are relatively inflexible, limiting the potential to change or reallocate use based on evolving values; this condition can be exacerbated during times of shortage. The region is also vulnerable to drought hazards and, to the extent that climate change may alter the hydrological cycle and make drought and diminished flow conditions more likely, we are vulnerable to climate change. However, climate implications are not being considered in a number of water management policies surveyed, and the policies to implement ecosystems protection are particularly vulnerable to water shortage. This paper will address how climate information might be better used in an integrated approach to multiple critical water problems, thus reducing our vulnerability to potential effects of climate change and long term drought. Several policy alternatives are evaluated and a case study of policies in place in the Gunnison Basin are described.

EL Niño and One Hundred Years of Storm Surges in the Northeast Pacific

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This paper analyzes daily mean sea-level height measurements for one hundred years from four National Oceanographic and Atmospheric Administration (NOAA) tide stations in the Northeast Pacific, and finds some evidence for an increase in the frequency of large winter storms as proxied by storm surges in the sea-level record since the beginning of this century. The long-term pattern of large winter storm events over the four stations is compatible with an intensification of the El Niño–Southern Oscillation (ENSO). The data are filtered to remove tide cycles, an increasing trend, and fluctuations in sea level associated with ENSO and other climate events. Linear regression models and the Mantel–Haenszel chi-square statistic are used to test for increases in annual frequencies of large winter storm surges. The hypergeometric distribution is used to test for changes in maximum storm intensity. Four climate scenarios are projected onto forecast mean sea levels for 2001–2025 to generate possible future extreme sea-level events for San Francisco.

Changes in Magnitude and Timing of Annual Maximum Floods

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We investigate the variations in the historical record of the annual maximum floods for Blacksmith Fork River in Utah. Changes in the timing and magnitude of annual maximum floods are assessed in the context of low-frequency climate variations and their potential role in modulating surface hydrologic response over the western U.S. Interesting associations between the flood response and the phase of the key interannual and interdecadal modes of large-scale climate variability are found. Analysis of precipitation (P) and temperature (T) records evinces (a) the role of snowmelt as the principal in-basin dynamical process in engendering extreme

response, and (b) the variations in P and T (associated with the low-frequency modes) may significantly delay/advance the snowmelt process. Further, "temporal variations" in the shape of the empirical flood distribution are examined for possible signatures of systematic climatic forcing. Finally, we discuss a simplified framework for assessing and predicting flood response based on the slowly varying oscillatory modes of climate.

Solar Irradiance Variations and Annual Streamflow in the Upper Mississippi River Basin

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Annual solar-irradiance variations demonstrate an apparent connection with annual streamflow in the upper Mississippi River Basin. The connection is related to the amount of solar energy available for absorption by the tropical Pacific Ocean and the subsequent effects this stored energy has on the mid-latitude atmospheric circulation. The physical mechanisms for this connection is presented and examined in a stepwise manner. The steps include a varying solar energy input that creates ocean-temperature anomalies in the tropical ocean. The temperature anomalies are transported northward by ocean currents to locations where ocean and atmospheric processes can modify atmospheric vorticity patterns at jet-stream levels. Atmospheric vorticity patterns over North America affect the formation of precipitation and, ultimately, the amount of streamflow from the upper Mississippi River Basin. At each step the connection with solar-irradiance variations is supported by sea-surface temperature, vorticity, precipitation, and streamflow data. This connection provides an opportunity to model and predict the annual streamflow of the Mississippi River. A simple model using solar-irradiance variation and the previous year's basin precipitation explains one-half of the annual streamflow variability. When only La Niña years are considered, the model explains more than two-thirds of the variability.

Evaluating Local Climate Model Results—Validation and Confidence Building

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A Local Climate Model developed in our lab has been used to calculate estimates of mean monthly temperature (TMAX) and precipitation (PREC) for three scenarios: modern (control), glacial, and doubled CO_2. Boundary conditions are derived from the GFDL GCM. We have tested the solutions of TMAX and PREC by comparisons to observational data of two instrumental records in the study domain. The model produces solutions that generally lie well within the natural variability of climate observed at these two stations. We also compare the glacial scenario to paleoclimate records and reconstructions. The scenarios presented are internally consistent and are consistent with many measures of behavior of the system during the time of modern observations and for the period reconstructed from paleoclimatic information for the last glaciation. The spatial patterns of the variables reflect the strong topographic control that is known for this area. Seasonal cycles represent the pattern of change through the months that corresponds to intuition built on observation. There is considerable evidence that the scenario for the control run is a valid representation of the modern climate. Similarly, there is considerable evidence that the glacial scenario is a valid representation of the paleoclimate of that

time. Because the model appears capable of useful solutions of climate and hydrology for both of these periods, times that are extremely different in climate and hydrology, the doubled CO_2 scenario may be a useful representation of climate to be anticipated in a greenhouse warming.

High-resolution Solutions of Climate Mean and Variance for a Doubled CO_2 Scenario in the Western U.S.

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Model solutions of the Kent State University Local Climate Model for the region of the upper Salt River tributary to Roosevelt Lake in Arizona and for the upper San Joaquin River at Millerton Lake are reported for three scenarios: control (modern), glacial and doubled CO_2. Boundary conditions for these calculations are specified with output from the GFDL GCM. All variables are computed on a grid with a spacing of one square kilometer.

In the Salt River basin, the doubled CO_2 scenario is 2.5 °C warmer on average than the control scenario. That difference changes importantly throughout the year, being larger in cool months and smaller in the summer months. The greatest difference is about 5.6C° in October and the least (no change) occurs in July. The lower elevations in the doubled CO_2 scenario are, on average, 2 °C warmer than the same areas in the control whereas the higher elevations are 3 °C warmer. In contrast to the change from the control seen in the doubled CO2 scenario, the variability of the means across the twelve months is larger than in the control. In this case the increase is much greater (about 2.5 °C) than the decrease to the doubled CO_2 scenario. The doubled CO_2 scenario has only 86% of the control total annual precipitation. On average the months experience about 6 mm less precipitation with the greatest decrease in the summer months. The variability of precipitation is larger in the doubled CO_2 scenario than in the control. In the doubled CO_2 scenario some months are wetter than the control and some dryer.

In the solution for the upper San Joaquin, the doubled CO_2 scenario is 2.4 °C warmer on average than the control scenario. That difference is relatively constant throughout the year, unlike the case for the Salt River. The doubled CO_2 scenario has 92% of the control total annual precipitation. Overall our results suggest that climate in the Sierra would change less than in central Arizona under conditions of doubled CO_2.

The Interaction Between Topography and Regional Rainfall Patterns in the San Francisco Bay Region

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Rainfall in the San Francisco Bay region derives almost entirely from winter frontal systems moving eastward across the North Pacific. As these storms make landfall, they encounter long ridges rising steeply from the coastline, roughly normal to the storm tracks. Although moderate (relief < 1200 meters), the topography strongly influences the long-term rainfall patterns, with upland stations reporting up to 50 inches of mean annual precipitation (MAP), compared to 20 inches at coastal sta-

tions. Some stations in the lee of the ridges, conversely, report reduced rainfall frequencies—65 rain days/year compared to 86 days/year at the coast. Such orographic rainfall patterns have long been known and empirical methods exist for mapping MAP on statewide scales (e.g. PRISM), but reliable, quantitative methods have been lacking for mapping the full rainfall distribution spectrum on regional scales (resolution < 1 km).

Developing such a model requires a reliable statistical representation of the size distribution of rainfall amounts, as well as long-term rainfall data from a network of gauges. As reported at PACLIM 1996, analysis of rain-gauge data from the Pacific coast (Calif., Ore., Wash.) indicates that the square root of the daily rainfall closely approximates a normal distribution function, although the underlying physical mechanisms remain unknown. Using this model to analyze long-term (about 50 years) rainfall data from the network of gauges in the San Francisco Bay region, a clearer picture of the orographic rainfall pattern begins to emerge. On the windward slopes leading from the coastline to the first ridge-top, orographic lifting of the air mass produces a consistent, proportional, increase in the amount of rainfall, but no change in storm frequency. In the lee of the ridge, a rain shadow produces a constant decrement in storm rainfall amounts, with a consequent decrease in storm frequency as the smaller storms fail to make it over the ridge line. From the ridge crest down the lee slopes, however, the interaction is more complex, with very steep gradients in both annual rainfall totals and rainfall frequency.

Amplification of Climate Signals Through Fluvial Sediment Transport

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River flows in four major river systems of the Pacific Coast of North America (the Fraser, Columbia, Willamette, and Sacramento) are strongly correlated with interannual and decadal scale climate fluctuations. All systems respond similarly to the Pacific Decadal Oscillation (PDO), but interannual and seasonal flow variability are smaller to the north. The Columbia and Willamette rivers display the most predictable El Niño Southern Oscillation (ENSO) response. North-south variations in ENSO response are conditioned by the California Pressure Anomaly and PDO. Such climate-induced flow variations are amplified in fluvial suspended particulate matter (SPM) transport, and again further downstream by estuarine physical and biological processes. Initial amplification of SPM transport fluctuations relative to river (QR) occurs because (a) SPM transport increases more than linearly with flow (i.e., SPM transport is QRn, n 1.6 to 2.5 in these systems) and (b) flow standard deviation increases with increasing flow. Thus, variations in annual average Columbia River Flow are 22% between strong El Niño and La Niña years, while SPM transport varies (for 1 2.6) by 250%. Finally, climate effects of occur along a north-to-south gradient in human intervention—the Fraser, the least modified of the systems considered, is climatically the most stable; whereas the largest human demands are made on the more variable Sacramento. These climate and human-induced fluctuations in fluvial SPM supply may play a substantial role in changes in Pacific salmon populations over the last century.

Trends in the Timing of Streamflow in the Conterminous United States Since the 1940s

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Year-to-year variations of streamflow timing have important water-resource and ecosystem effects, and long-term variations are of particular concern. Recent trends in streamflow timing in the United States are identified in reconstructed annual components of daily streamflow series from 650 rivers. Since 1945, about 30% of the series include significant trends in streamflow timing, and 70% of those trends have been toward earlier peak flows. About 30% of the series include significant trends in annual-component amplitudes; these trends tend to be toward lower peaks in the northern half of the country and toward higher peaks in the south. The predominance of trends toward earlier streamflow peaks across so much of the conterminous United States is unlikely to have a single hydroclimatic cause, and a cluster analysis identifies regions in which timing variations are shared. Correlations between timing variations in the clusters and nearby precipitation and temperatures indicate that flow-timing trends in several of the clusters (at least) may be related to simple hydroclimatic-forcing changes in the last 50 years.

Climate Effects on Seasonal Variability of Streamflow and Suspended Sediment Transport in West Coast Rivers

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Suspended particulate matter (SPM) transport fluctuations in major river systems of the North American West Coast (the Fraser, Columbia, Willamette, and Sacramento) are amplified relative to river flow (QR) variations primarily because SPM transport increases more than linearly with flow, i.e., SPM transport is QRn, n 1.6 to 2.5. This amplification of streamflow fluctuations by fluvial SPM transport exhibits strong seasonal variations that are related to river basin geology, vegetation, instream processes, and human alteration. In all four systems, three seasons suffice to describe the annual cycle of SPM transport processes, but the definition of the seasons varies from north to south. In most cases, the primary freshet season exhibits the largest n and the lowest-flow season the lowest n. The Fraser River, for example, has its strongest SPM transport during the summer freshet with $n > 2.5$, while the Willamette has its weakest SPM transport during the late summer dry season with $N < 1$. All systems show climate effects on the timing of the annual flow cycle. These are strongest in the Sacramento, where there is a marked difference in the seasonality of streamflow between the years with high negative and positive California Pressure Anomaly (CPA). The Columbia is exceptional in two respects: (a) it has the highest seasonal SPM transport variability with the n varying between 1.5 and 3.5, and (b) the highest n occurs during winter freshets rather than during the larger spring freshets. These very high winter SPM transports that occur primarily in La Niña years are apparently related to low elevation snowmelt on normally arid lands.

Environmental Variability and Prerecruit Survival of Pelagic Fish Off California—GIS Mapping and Hypothesis Formulation

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Our goal is to identify and characterize the survivor's habitat or areas of high, larval survivorship of pelagic fish off California. We focus on three commercially important fish species: Pacific sardine (*Sardinops sagax*), Northern anchovy (*Engraulis mordax*), and Pacific hake (*Merlucciius productus*). Our research is motivated by the idea that the effects of environmental variability on prerecruit survival are largely responsible for the lack of relationship between stock and recruitment, an important and difficult problem in fisheries management. To identify the survivor's habitat, we calculated spatially-explicit estimates of daily production of late larvae (20-mm length). The 48-year data set of the California Cooperative Oceanic Fisheries Investigations (CalCOFI) was our source for abundance and size-distribution of larval sardine, anchovy, and hake. We also had access to various sources of physical and biological oceanographic data. Our GIS visualizations of the larval and environmental data allowed us to formulate hypotheses about general relationships between environmental characteristics and prerecruit survival. We also examined the potential for specific physical oceanographic features (such as offshore mesoscale eddies) to generate recruitment variability in California fishes. Our aim is that, in the future, our GIS maps could be used to design field studies of the mechanisms linking environmental climate variability and variability in precrecruit survival of pelagic fish such as sardine, anchovy, and hake.

Snowpack, ENSO, and Atmospheric Circulation in Colorado Front Range

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The importance of snowpack conditions along the populous Front Range of Colorado lie in not only its value as a water resource for the ever increasing population along this corridor, but also for its role in basic hydrological processes and its influence on the weather and climatology of the area. This study quantifies the atmospheric circulation of the area that includes the Front Range, its cites and towns, and evaluates the relationship between the developed circulation indices and snowpack conditions. The circulation indices are evaluated for differences between years of highest (top quartile) and lowest (bottom quartile) snowpack amounts for the period 1952 through 1996. Snowpack levels and circulation are also examined for tendencies in winters dominated by El Niño or La Niña events.

The results are interesting because they are not particularly intuitive. During ENSO event winters, no statistically significant bias toward greater or lesser snowpack was evident, however, there is a consistent tendency toward slightly greater snowpack during La Niña events. The atmospheric circulation, however, is more westerly and has a more vigorous flow in La Niña compared to El Niño winters. As for circulation and heavy or light spring snowpack, at 500 mb and 700 mb the heavy snowpack years are characterized by stronger northerly and westerly flow, and increased flow vigor, but not by any increase in vorticity (cyclonicity) compared to the lowest snowpack years. At 850 mb, there are no differences in any of the circulation indices between high and low snowpack, suggesting that the weather in the Denver–Boulder metropolitan area is a poor indicator of the snowpack conditions immediately to their west.

Spatial and Temporal Variability of Snow Avalanche Climate of Western U.S.

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The snow avalanche climate of western North America has long been suspected to comprise of three main climate zones: the coastal, intermountain, and continental. The coastal zone of the Pacific mountain ranges is characterized by abundant snowfall, higher snow densities, and higher temperatures. The continental zone of Colorado and New Mexico is characterized by lower temperatures, lower snowfall, lower snow densities, and extensive faceted crystal growth resulting from high temperature gradients in the snowpack. Relatively low numbers of avalanches occur in the continental zone, but this zone has a higher avalanche hazard potential. The intermountain zone of Utah, Montana, and Idaho is intermediate between the other two zones. We conducted a quantitative analysis of snow avalanche climate of the West, based on 46 sites from the Westwide Avalanche Network from 1969–1995. Results from a binary seasonal snow avalanche classification, based on well-known thresholds and ranges of snowpack and climatic variables, quantitatively confirm the existence of the three major climate zones following a west-east gradient. The classification also illustrates some heterogeneous patterns due to the modification of large-scale atmospheric circulation by smaller-scale topographic features. Widespread spatial shifts towards more coastal conditions occurred during 1985–1986 and 1991–1992, and shifts towards more continental conditions occurred during 1976–1977 and 1987–1988. Five hundred-millibar height anomalies explain many of these spatial changes, but examination of daily plots of climate and avalanches variables during seasonal extremes for sites in northern Utah also illustrate the importance of understanding snowpack and climatic variations that occur at daily-to-weekly timescales. Examination of data for Alta, Utah back to the mid-1940s suggest that fewer extreme continental events occurred before 1969, illustrating the importance of studying long term climate records and applying them to avalanche-hazard assessment.

Neural Networks as a Data Extraction Tool for California's Long-range Precipitation Prediction

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Activity by the El Niño–Southern Oscillation (ENSO) in the east Pacific and the 700 mb height anomaly over the northern hemisphere is known to be related to various phenomena in specific regions of California. These large-scale climatological parameters represent the global atmospheric circulation that, in a sense, brings weather to a region. By determining how these parameters interact over time, we can determine the general weather conditions that will arrive in a region. Because of the large amount of data, the short time span that the data is available for, the unknown type of relationships involved, and the possibly extraneous data, common statistical methods are not easily applied. Artificial neural networks (ANNs) are powerful and useful tools, especially in cases where the complex relationship between the inputs and outputs cannot easily be determined by common modeling methods. For each of California's seven climate zones, ANNs were trained on a calendar year's worth of parameters to predict the following water year's total precipi-

tation (i.e., trained with January to December 1990 data to predict October 1990 to September 1991 total precipitation). Then, these artificial brains were interrogated by two different methods to reveal their secrets. This produced a reduced set of important parameters that were used in a simple linear regression model with good results. The ANN methods proved their ability to see the important relations in the data and have provided a new tool for data extraction.

Late Holocene Paleoenvironments of Los Penasquitos Lagoon

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The late Holocene and recent environments of the Torrey Pines State Reserve were reconstructed using fossil pollen, charcoal, and chemical stratigraphy of a 3600-year-old sediment core of the estuarine sediments from Los Penasquitos Lagoon. The stratigraphic levels were aged using radiocarbon dating and by correlating sediment geochemistry and pollen of exotic species with historical records. Increasing pollen and spores of moisture-dependent species suggest a somewhat cooler and/or wetter climate developed after 2500 yr BP. These changes, happening between 2500 and 2200 yr BP are similar to changes recorded in another century 280 km to the northwest at 3250 yr BP. This implies that these late Holocene climate changes could have been time-transgressive from north to south. Pre-settlement sediment deposition shows a slow rise in the surface of the estuary, probably maintaining an equilibrium with the gradually-rising sea level of the late Holocene Landscape disturbances during the settlement and recent eras then increased the apparent sedimentation rate ten-fold, choking the estuary with excess sediments and disturbing its tidal dynamics.

A Reconstructed Record of marine Productivity Variability Within the California Current (AD 1500–1995)

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Sediment records from silled basins along the eastern margin of the North Pacific margin reveal a transition from laminated to bioturbated sedimentation in the mid-1970s. This transition interrupted a spread of laminated sedimentation that began three centuries ago. We have used $\delta^{13}C$ of benthic foraminifera to reconstruct a 300-year history of ventilation and carbon oxidation in one of these basins to decipher which factors may have been responsible for the transition. In Santa Monica basin the $\delta^{13}C$ of epibenthic foraminifera living at 860-m water depth is sensitive to changes in the isotopic composition of water entering the basin over the sill. At 908 m foraminiferal $\delta^{13}C$ is more strongly influenced by the flux of $\delta^{13}C$-depleted CO_2 from basin sediments because waters have a much longer residence time at this depth. A 300-year record of $\delta^{13}C$ at these two depths reveals there has not been any systematic change in the $\delta^{13}C$ of water entering the basin, but there have been changes in the $\delta^{13}C$ offset between the two depths that indicates there have been changes in carbon oxidation rates within the basin. The onset of laminations at 908 m 375 years ago marked a significant increase in carbon oxidation rates within the basin relative to ventilation rate. We infer from this that either productivity increased at that time or there was a significant change in the way carbon was exported to the sea floor. During the past two centuries laminated sediments spread outward from the center of the basin to encompass all of the basin floor. This observation, in conjunction with the $\delta^{13}C$ results, suggest there has been a progressive increase in carbon oxidation rates within the basin that resulted in the spread of anoxia and laminated sediments. The return of bioturbated sedimentation in the mid-1970s marked a return to lower carbon oxidation rates and appears to be coupled to lower productivity throughout the California Current system. The sedimentation patterns in these low oxygen environments appears to be a very sensitive recorder of ocean/climate change and therefore provides an extensive temporal framework against which to assess temporal patterns of variability within the California Current system.

Lake Level and Climate Changes in Mono Basin, California, During the Last Millennium—High-resolution Stable Isotope Records

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Mono Lake is a closed-basin lake located at the eastern base of the Californian Sierra Nevada. Fluctuations in its lake level and volume serve to indicate changes in the moisture budget associated with climatic change. We have conducted ^{18}O and ^{13}C analyses on 311 sediment samples in two cores from the lake: 7/87 from a water depth of 15 m and 5/86 from the 1986 shoreline. The sedimentary features of the two cores have been described by Mark Newton (1991, Ph.D. thesis at University of Southern California). In the 65-cm long core 7/87, yellow-striped calcareous mud occurs from 0 to 18 cm, laminated algal ooze from 18 to 32 cm, laminated diatomite ooze from 32 to 57 cm, and tufa/tephra sand and gravel from 57 to 65 cm. The 1.2-m long stovepipe core 5/86 contains laminated diatomite ooze in the interval of 1 to 13 cm which overlies deposits of tufa/tephra sand, aragonite-flake mud, and three Mono Craters ash layers (MC1, MC2, and MC3). Our study shows that the deposition of aragonite-flake mud usually occurs in shallow water environments of <10 m (Newton 1991) of high temperature, pH, salinity, and productivity. On the other hand, the deposition of laminated sediments requires that Mono Lake has a water depth >16 m to preserve the laminations under a reduced deep water environment. The sedimentation rates of cores 7/87 and 5/86 for the last 500 yr, determined by varve counting, average 1.36 mm/yr and 0.94 mm/yr, respectively. The ^{14}C date of 610 yr BP for MC1, present at the bottom of 7/87 and at 14 to 20 cm in 5/86, indicates that the laminated diatomite ooze began deposition about 500 years ago. Assuming constant sedimentation at the two core sites since then, we estimate that the laminated diatomite ooze in core 7/87 represents a continuous sedimentary record spanning from 110 to 600 yr BP, and that core 5/86 represents a record from 400 to 500 yr BP. No excess ^{210}Pb has been detected in both cores, suggesting the core tops are older than 100 years. The ^{18}O and ^{13}C values in the 1- to 13-cm interval of core 5/86, measured at 1-mm (about 1-yr) resolution, range from –10.43‰ to –1.66‰ (PDB) and from –5.17‰ to 3.18‰ (PDB), respectively. The ^{18}O and ^{13}C values in core 7/87, measured at a resolution of 0.3 to 1 cm (1 to 10 yrs) vary from –8.72‰ to 1.41‰, and from –2.88‰ to 8.7‰, respectively. Although the isotopic values in core 5/86 are lighter than those in core 7/87 because carbonates in core 5/86 precipitated in a shallower environment, the general trends of the isotope records in both cores are consistent in the same period.

For closed-basin lakes, ^{18}O and ^{13}C reflect lake salinity, alkalinity and productivity. For instance, a transgression of the lake level will lead to a decrease in the lake's isotopic composition. A covariance of ^{13}C–^{18}O will result from a relatively rapid increase or decrease of lake volume. When the lake level is stabilized, vapor exchange between the lake water and the atmosphere drives the lake ^{18}O toward a steady-state value. A poor ^{13}C–^{18}O covariance will result if such a lake is under hyper-alkaline conditions. The isotopic records and sedimentary features of Mono Lake sediments lead to the following reconstruction for lake-level and climate changes in the Mono Basin.

1. From about 2,000 to 550 yr BP, Mono Lake was very shallow due to dry and warm climate, as shown by the deposition of aragonite-flake mud and heavy ^{18}O and ^{13}C in the shoreline core 5/86. The elevation of the Mono Lake surface during this period was around 1956 m, similar to the level just before the 1941 artificial diversion of stream inflow to Los Angeles.

2. Around the beginning the Little Ice Age 550 yr ago, the climatic conditions turned cold and wet. Rapid increases in lake level occurred as indicated by the large depletion in lake ^{18}O and ^{13}C as well as by the deposition of laminated sediments. Mono Lake level rose at least 16 m between 550 to 500 yr BP. This very wet climate lasted until 460 yr BP.

3. Between 460 and 340 yr BP, Mono Lake was moderately large and deep under the cool and wet climate conditions during the Little Ice Age.

4. A Lake-level drop occurred from 340 to 300 yr BP and then stabilized between 300 and 240 yr BP. Lake salinity, alkalinity and productivity increased during this relatively dry period of the later part of the Little Ice Age. Deposition of laminated sediments during the period indicated a deeper lake than the present one.

5. A distinctly wet event causing the lake level to rebound occurred about 230 yr BP. Stine (1989) has placed this high stand of the lake level around 210 yr BP.

6. Between 200 and 110 yr BP, dry climate prevailed in the Mono Basin. Mono Lake level dropped and the lake became hyper-alkaline, as reflected by the absence of covariance in ^{13}C–^{18}O and the deposition of non-laminated, high aragonite sediments. The climatic history outlined above for the Mono Basin during the last 1000 years is representative of the regional climate changes in the Owens Valley, California.

Poster Presentations

Climate Variability in the Southwest for an Integrated Assessment

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As part of a multidisciplinary study of climate and its societal impact, instrumental meteorological records and natural archive paleoclimate records are reviewed and synthesized into a white paper and web-supported database. The purpose of the white paper is to summarize understanding of climate variability in this region on seasonal to multi-decadal time scales in a form accessible to the science-literate non-climatologist. Existing regional research documents upper level synoptic patterns, atmospheric controls on the North American monsoon, paleoclimatic variability, and Pacific Ocean sea surface temperature anomalies. This study builds upon existing climate variability research and will ultimately be integrated with other regional assessment information for the Southwest Climate Assessment Project.

Lake System Dynamics and Paleoclimate Interpretations

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A theoretical approach* to examine interpretations of lake levels leads to a classification of lakes into one of five types and recognition of at least three stable (or quasi-stable) levels for lakes. Some lakes exist in positive balance and increase in depth to a natural outlet where overflow balances the surplus. Some lakes exist in negative balance and continue to decline in level until completely desiccated. The levels of these two types of lakes are not indicators of climatic equilibrium. Only lakes that lie within closed basins and that maintain positive depth are in climatic equilibrium. The equilibrium level may lie above or below the outlet and above or below the basin bottom. With external input, changes in lake depth produce a negative feedback of surface area that leads to stability. Without external input, changes in lake depth produce positive feedback and catastrophic instability with two stable attractors. In that case the equilibrium level is a bifurcation point. Any lake system has at least one equilibrium depth and at least two stable attractors that are controlled by topography. Certain geometries we have explored appear to produce multiple stable attractors and at least two bifurcations. Non-linear geometries (a more realistic assumption) would produce more complex dynamical systems.

These findings, and the implications of lake status within the classification, offer alternative explanations of lake level variations other than climate change. Interclass transitions and lags produced by internal dynamics as equilibrium levels switch position relative to stable attractors may explain features of the paleoclimate record that long have puzzled researchers. For example, climatic states that would maintain an overflowing lake if the lake were already overflowing may be unable to overcome the negative balance if the initial condition were the lower stable attractor and so will not leave an accordant climatic record. In this case, paleohydrologic indicators may mislead the interpretation of paleoclimate.

* As an example we assume a basin shape as a frustrum of a right circular cone, basal diameter of 20 km, top diameter of 100 km, height of base of 0 m, height of top of 4 km and angle of basal sides of 0.05 radians. Surface area above the lake surface decreases inversely as the square of distance. Precipitation rate varies linearly with elevation from 0.2 mm/day at the base to 32 mm/day at the highest point. Evapotranspiration varies linearly from 300 cm/month at the base to 10 cm/month at the top.

Global Characteristics of Streamflow Seasonality and Variability

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Monthly streamflow series from around the world are used to characterize some of the basic spatio-temporal patterns of streamflow variability. The series were compiled from many (mostly) public-domain sources, were prioritized to achieve the broadest geographic and longest historical coverages, and then were edited to remove major discrepancies and human influences. Series from 1350 sites with average series lengths of about 30 years were analyzed. Together the streamflow series provide a global perspective on streamflow seasonality and variability.

Streamflow seasonality varies regionally, depending on the timing of maximum precipitation, evapotranspiration, and contributions from snow and ice. Lags between peaks of precipitation and streamflow vary smoothly from long delays in high-latitude and mountainous regions to short delays in warmest sectors. In the coolest regions, timing of streamflow becomes effectively disconnected from precipitation timing and depends on the timing of summer warming, so that lags between precipitation and flow peaks of up to 11 months are observed.

Streamflow is most variable from year to year in dry regions of the American Southwest, Sahel and southern continents, and varies more (relatively) than precipitation in the same regions. Tropical rivers have steadiest flows. Correlations between annual streamflow totals and climatic indices such as the Southern Oscillation Index (SOI) and North Atlantic Oscillation (NAO) illustrate interannual streamflow teleconnections. Seasonal SOIs are shown to correlate significantly with streamflow variations throughout the Americas, Europe, and Australia. Because SOI and, in many areas, streamflows are slowly evolving indices, long predictive leads are provided by SOI in most of the same regions (with SOI of preceding summers correlating significantly with streamflows for the following year). North Pacific sea-surface temperatures (which are themselves related to tropical Pacific conditions) are correlated significantly with annual streamflows throughout much of North America as well as Europe and the tropics. Seasonal NAOs are reflected in streamflows in the eastern United States, Europe, and tropical South America and Africa.

Documented Validation of Extreme Precipitation Events Reconstructed for Northwest Mexico (1860–1997)

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The relations between climatic changes and human lifestyle are very close in the societies that depend greatly upon agriculture. The history of drought in Mexico shows that the effects of climatic changes are broadcast to the whole society as scarcities, hunger, epidemics, death, social explosions, and politic conflicts. Northwest Mexico is an arid zone with very variable precipitation and severe droughts. The instrumental records though only started in a large way around the 1950s. Rainfall is modulated by ENSOs in this region, increasing winter precipitation. Dendrochronologic techniques let us reconstruct winter precipitation from the region and identify drought periods from 1860 to 1997. These periods were related with documentary evidence to validate them. Northern Mexico was very important in the origin of the Mexican Revolution, the greatest social movement of this century. Previous to the Revolution, it was a drought that increased the discontent of the population.

This severe drought period has been documented in different parts of the region. Some heavy precipitation is documented by a great runoff of the Rio Fuerte in Sinaloa causing disasters at the beginning of this century. However, because of social development and its preventive actions, vulnerability of the population decreased since 1949. The last two decades have been characterized with abundant rainfall associated with more frequent ENSO events.

Public Policy Changes: Land Use, CO_2, and the "Tom Sawyer" Effect

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The International Panel of Climate Change has identified conservation strategies as "among the most cost-effective options for slowing the atmospheric build-up of CO_2." This poster session illustrates some possibilities for using the "Tom Sawyer" effect to reverse destructive land use practices. The Tom Sawyer effect is named after fictional character Tom Sawyer's fence-painting methodology in which Tom only allows others to enjoy the benefit of fence-painting after they have paid for the privilege. We see the Tom Sawyer effect in good citizen land use programs that encourage maintaining or enhancing land cover where participants pay for the privilege of participation. This poster investigates three such programs: the U.S. Sierra Club, the British Trust for Conservation Volunteers, and the worldwide Volunteers for Peace. All three organizations sponsor programs where paying volunteers work on erosion control, habitat enhancement, and tree planting. Typically each program is one week to one month in duration. During that time, teams, usually from different locales, take on specific environmental tasks. Teams generally include biologists and land management specialists who supervise the work and teach participants necessary skills. Individual projects are labor intensive and allow participants to see the positive effects of their effort. Through this participatory program, individuals from many places and many walks of life are introduced to the need for land conservation and restoration. The collective results of these projects on international land management policies and CO_2 build-up have yet to be gauged.

Millennial-scale Fluctuations in Vegetation and Climate During the Last Glacial Period in Western Oregon

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A high-resolution pollen record from Little Lake, central Coast Range, reveals a series of millennial-scale changes in vegetation and climate during the last glacial period. Between 41,000 and 27,000 cal yr BP, periods of abundant pollen of cold- or dry-adapted species alternate with peaks of warm- and wet-adapted species and total organic carbon about every 1000 to 2000 years. A close examination of the response of certain species to specific climate changes suggests variability in the degree of climate change. During the full glacial period (ca. 27,000 to 16,000 cal yr BP) fluctuations between the pollen of cold/wet and cold/dry taxa occurred about every 2000 to 3000 years. An increase in herbaceous taxa between 20,5000 and 17,5000 cal yr BP indicates the coldest and driest interval (last glacial maximum). Brief warm and/or wet intervals at Little Lake during the last glacial period suggest periodic, northward shifts in the position of the jet stream. Warm and/or wet periods at Little Lake correspond with interstadials 2 to 4 in the North Atlantic and the Santa Barbara Basin and imply that fluctuations in the size of the Laurentide Ice Sheet or northern hemisphere temperatures may have influenced the position of the jet stream. Before 30,000 cal yr BP the global correlation of millennial-scale climate events at Little Lake is not as clear and may reflect the increase in radiocarbon error, leads and lags within the climate system, or changes in the jet stream related to a low frequency, Pacific-centered, ENSO-like forcing.

Reservoir Operation Policies Based on El Niño–Southern Oscillation: A Case Study from Colombia

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Due to its dependence on its water resources for hydropower and agriculture, Colombia has been heavily affected by ENSO events. After the El Niño event of 1991–1992, one of the strongest events since 1950, Colombia suffered a dramatic reduction in precipitation. This reduction in precipitation led to a decrease in the streamflow, and water storage in reservoirs was dramatically depleted. Because 75% of the energy in Colombia is generated by hydropower plants, this reduction in river discharges caused an energy shortage. In addition, the agriculture and the water supply system were affected significantly. By contrast, after La Niña events, precipitation and river discharges were above normal and caused major flood events. In the case of both El Niño and La Niña events, the effect of ENSO has been considerable, straining Colombia's already fragile infrastructure and causing significant social and economic problems. To avoid or greatly reduce these negative effects, ENSO-based reservoir operation policies for Colombia are proposed. As an initial step, and exploratory analysis has been carried out to determine the feasibility of such operation policies. Cross correlations have been performed between ENSO indicators (SOI, SSTs, and NEI) and streamflow. Monthly streamflow data from 47 stations that belong to the most important rivers in Colombia have been used. Different lags, as well as different periods for both ENSO indicators and streamflow, have also been used. From our preliminary results, the most suitable ENSO indicators to forecast Colombian streamflows have been determined, and we

concluded that feasible reservoir operation policies for Colombia may be based on ENSO indicators. In future work, the ENSO-based operation policies will be developed.

Alternative PCA-based Regression Techniques in Dendroclimatic Reconstructions

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Principal Components Analysis (PCA), has been used extensively for reconstructing past climatic variability by regressing the components derived from tree-ring chronologies onto the climatic variable (i.e. streamflow). However, this procedure leaves several choices to the researcher that may result in very different reconstructions. This study compares these options using the cross validation standard error (CVSE) as a criteria to estimate the predictive skill of the model. Independent testing, or the optimization of the CVSE, is a way to identify the model that best represents the physical processes using the minimum number of variables (a parsimonious model) and that reduces the influence of unrelated noise.

This study uses 17 tree-ring index chronologies from different sites in the upper Colorado River Basin to predict streamflow at Lee's Ferry, the legal point separating the upper and lower Colorado River basins. Combinations of up to seven variables with the lowest cross-validation standard error were selected from these 17 chronologies. This procedure was repeated using rotated components, using unrotated components, using all the modes, and by pre-selecting the modes with eigenvalues higher than one. Also, the final regression of the components, done traditionally by a stepwise regression, is compared with a new regression technique. Results show that in some cases stepwise regression may not be the approach that results in the most parsimonious models, and that other methods should be considered.

At the end, the model believed to give the best predictive skill is used to reconstruct the Lee's Ferry streamflow and it is compared to previous reconstructions in the basin.

Comparison of Tree Species Sensitivity in Streamflow Reconstructions in the Colorado River Basin

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Tree-ring based hydrologic reconstructions have often been based on multi-species data sets of moisture-sensitive tree species, in areas of high yield, with the intent of obtaining adequate spatial coverage of the study basin. However, it is known that sensitivity to climatic forcing varies for different species and the growing conditions at different sites. Biologically controlled differences in physiological water demands, the starting date and length of the species' growth period, and differences in the hydrological sensitivity of the site type and substrate favored by different species make some species better potential predictors of a particular hydroclimatic parameter (i.e. streamflow). The selection of the most hydrologically sensitive species in the runoff-producing areas is important for the appropriate

selection of tree-ring sites and paleohydrological model construction. A careful selection of tree-ring species will reduce the error in the reconstruction model.

In this study, we selected chronologies from six species, *Pseudotsuga menziesii*, *Pinus flexilis*, *Pinus edulis*, *Pinus longaeva*, *Pinus ponderosa* and juniper species, in the Upper Colorado River Basin (UCRB). Relative differences in species response were investigated by correlating tree-ring standardized indices with natural streamflow from the Lee's Ferry streamgage station (Ariz.), at the lowest point of the upper basin. We also include a comparative study, by species, of the shifts in probability distributions for dry, normal, and wet conditions. Wavelet power spectra and cross spectral analyses between tree ring growth and streamflow complete our analysis of species response.

Consistent with other studies, *Pinus aristata* was found to be less sensitive to soil moisture and thus less useful in predicting hydrologic variables. *Pseudotsuga menziesii*, *Pinus edulis*, and *Pinus ponderosa* were found to be more useful in estimating hydrologic variables. Our preliminary results also suggest a lower correlation between streamflow and tree ring indices for wet years than for mid to low flow years. This effect is especially evident in the species *Pinus flexilis*, *Pinus edulis* and to a lesser extent *Pinus longaeva*.

Additionally, for dry years of extreme low growth, there is evidence that the relationship of streamflow to the tree ring index no longer follows the original regression line inferred for mid and high index values. For the species *Pseudotsuga menziesii*, *Pinus edulis* and *Pinus ponderosa*, the results suggest a different streamflow/tree ring relationship when ring width is small due to low soil moisture conditions. As the Colorado River's base flow is not reflected by ring width in dry years, it may result in an underestimation of low flows during severe drought periods. This research will have important implications in the identification of the duration and magnitude of severe sustained drought in the Upper Colorado River Basin.

Update of Winter 1901–1999 PAPA Trajector Index Computed with the OSCURS Model for the Gulf of Alaska Suggests New Shift in Decadal North-South/Wet-Dry Oscillation Patterns for the Pacific Northwest

W. James Ingraham, Jr.
Alaska Fisheries Science Center-NMFS-NOAA, Seattle, Washington

Sea surface drift trajectories with start-points from Ocean Weather Station PAPA (50°N, 145°W) were simulated using the OSCURS (Ocean Surface Current Simulations) model for each winter (December 1 to February 28) during 1901–1999. To reveal decadal fluctuations in the oceanic current structure, the trajectories were smoothed in time with a five-year running boxcar filter. The strongly decadal drift from Ocean Weather Station PAPA have fluctuated over the last century between north and south modes about every 20 years. From the 1999 calculations, it appears that a new regime to the south is starting. Development of OSCURS was motivated by the need in fisheries research for indices that describe variability in ocean surface currents.

These synthetic data, derived through empirical modeling and calibration, provide insight which far exceeds their accuracy limitations. OSCURS daily surface current vector fields are computed using empirical functions on a 90-km oceanwide grid based on monthly mean sea level pressures (1900–1945) and daily sea level pressures (1946–1997); long-term mean geostrophic currents (0/2000 db) were added.

The model was tuned to reproduce trajectories of satellite-tracked drifters with shallow drogues from the eastern North Pacific.

Southwest Climate and the Quasi-Biennial Oscillation, The El Niño-Southern Oscillation, The Arctic Oscillation, and Tidal Resonances

Thor Karlstrom, U.S. Geological Survey, Seattle, Washington

Southwest precipitation records (both tree ring and instrumental) are analyzed to further test regional response to atmospheric circulation systems including the Quasi-Biennial Stratospheric Oscillation (QBO), the El Niño–Southern Oscillation (ENSO), the Arctic Oscillation (AO) and modulating Tidal Resonances (TR). Winter precipitation from Pacific sources dominate the climate of the western sector of the Southwest. Summer precipitation, primarily from Gulf of Mexico sources, dominate that of the eastern sector. Generally, precipitation increases and temperature decreases with increasing elevations ranging regionally from sea level to over 14,000 feet. Half-cycle analyses of additional tree-ring records continue to reveal differing response functions to elements of the TR Climate Model. These differences are evidently dependent on location in different air masses and/or on differing physiological sensitivities and signal-to-noise ratios. Some tree-ring records phase predominantly with the 556-year Phase Cycle; other predominantly with one or more of the high frequency subharmonics including the 2/1 (278-yr) Subphase or Douglas Cycle, the 4/1 (139-yr) Event Cycle, the 8/1 (69.5-yr) Subevent cycle, the 16/1 (34.75-yr) Bruckner Cycle, and the 24/1 (23.167-yr) Hale Cycle. At higher frequencies the QBO phases most strongly with the 240/1 (2.3-yr) resonance and, in turn, correlates more weakly but still significantly with the SO. In contrast, the El Niño series correlates, although poorly, with the SO, suggesting factors other than tropical air pressure and ocean temperatures are involved (see discussion in Karlstrom 1996). Further, no clear-cut correlations are evident among the QBO, ENSO, AO, and instrumental regional precipitation time series. This is consistent with other analyses of Southwest climate, hydrology, and El Niño years that also indicate great spatial and event-to-event variability in regional responses that seriously reduce predictability.

The Influence of Climate on Long-term Trends in Northern San Francisco Bay Estuary

Peggy W. Lehman
California Department of Water Resources, Sacramento

Causes of the many changes in environmental conditions and biological variables in the northern San Francisco Bay Estuary between 1975 and 1993 are unknown. Streamflow and variables directly affected by streamflow, including nutrients and salinity, varied with climatic conditions that produced wet conditions in the late 1970s and early 1980s and drought conditions in the late 1980s and early 1990s. An increase in water transparency, wind velocity, water temperature, and precipitation after 1980 was superimposed on the wet and dry pattern, but differed among regions and seasons. The largest cumulative change occurred upstream during the spring when water transparency, water temperature, wind velocity, and precipitation simultaneously increased after 1980. These physical changes upstream were accompanied by a decrease in organic carbon and phytoplankton and zooplankton biomass. Significant cross correlation among trends in environmental and biological variables calculated using time series analysis suggested estuarine production

was at least partially a function of natural changes in environmental conditions produced by climate.

Relationships of Precipitation Chemistry, Atmospheric Circulation and Elevation at Two Sites on the Colorado Front Range

Mark Losleben[1], Nick Pepin[2], Sandra Pedrick[3]
[1] University of Colorado, Mountain Research Station
[2] University of Portsmouth, United Kingdom
[3] Visiting Scientist, INSTAAR, University of Colorado

The importance of the quality and quantity of precipitation includes the effect on the local ecology as well as on municipal water budgets and treatment facilities. Atmospheric circulation is an important factor contributing to the amount and degree of purity of the precipitation that falls at a particular locale. This study quantifies the role of atmospheric circulation as a factor in both the amount and quality of precipitation at two elevationally separated sites in the mountains just west of the Boulder–Denver metropolitan area in Colorado. Precipitation at the lower site, which is closer to the metropolitan area, has slower acidity and conductivity than the higher site, which is just east of the Continental Divide, and circulation accounts for up to one-third of the variability in the precipitation chemistry. Precipitation intensity and amount have significant relationships with circulation as well as differences at the two elevations. These findings, which may have predictive value, as well as the development of the circulation indices are detailed in this poster.

Molecular Indicators of Climatic and Oceanographic Conditions on the California Continental Margin During the Last 160 kyr (ODP Leg 167)

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Institute of Chemistry and Biology of the Marine Environment (ICBM),
Carl von Ossietzky University of Oldenburg, Germany

Sedimentation on the California continental margin is strongly influenced by the California Current. The structure of the California Current and the associated coastal upwelling are highly sensitive to climatic changes. The response of planktonic primary productivity to these changes provides climatic and oceanographic information based on organic geochemical data. During ODP Leg 167 a series of holes was drilled along the California coast. We selected three locations (Sites 1017 [34°N], 1018 [36°N] and 1019 [41°N]) representing a north-south transect and analyzed 76 sediment samples for the compositions of their extractable lipids.

The paleosea surface temperature (SST) profiles (based on long-chain alkenones) at Sites 1017 and 1018 indicate a distinct relationship with the climatic stages of the northern hemisphere. This appears to be valid also for Hole 1019C, but with stronger fluctuations during the Holocene and the last glacial. Comparison with the SST data of the Santa Barbara basin (SSB) reveals little or no coincidence for the last glacial period. During that time, the SST profile of the SSB essentially reflects local influence. In contrast, the SST profiles of all Holes show distinctly elevated paleosea surface temperatures during the last interglacial (Eemian, 125 ka). This strongly pronounced signal points to an extraordinary climatic situation dominating the entire area during that time.

The California Current and the coastal California upwelling are closely connected to each other by the wind systems in this area. Thus, studying the coastal upwelling should provide information on the dynamics of the California Current. On the California continental margin, higher TOC contents often coincide with higher SST values and vice versa, which is unusual for upwelling systems. This indicates, that the SST data, at least of Holes 1017B and 1018A, reflect a global current-dominated temperature signal and that coastal upwelling plays a subordinate role. Furthermore, during times of strong coastal upwelling marine productivity should be enhanced. The $\delta^{13}C$ data of the organic matter from Hole 1017B (–21.4‰ to –22.5‰) are consistent with a predominantly marine character of the organic matter, but variations in the $\delta^{13}C$ signal indicate changes in the proportions of marine and terrestrial organic matter or a change of the isotopic composition of the CO_2 source due to enhanced primary productivity. Isotopically heavier marine organic material was preferentially deposited during warmer rather than colder periods.

Temperature-related Molecular Proxies: Degree of Alkenone Unsaturation and Average Chain Length of *n*-Alkanes

Joachim Rinna, Ute Güntner, Kai-Uwe Hinrichs, Kai Mangelsdorf, Jan Hendrik van der Smissen, and Jürgen Rullkötter
Institute of Chemistry and Biology of the Marine Environment (ICBM), Carl von Ossietzky University of Oldenburg, Germany

Since their first detection, alkenones have been found in numerous marine sediments. Their application for estimating paleosea surface temperatures has been demonstrated in many different marine environments and is not restricted to sediments younger than ca. 268 ka, the first occurrence of *Emiliania huxleyi*, nor to the occurrence of the previously dominant *Geophyrocapsa oceanica*. Other living and extinct members of the family Geophyrocapsaceae have or had the capability of synthesizing alkenones whose degree of unsaturation changes with growth temperature. Samples from the New Jersey continental slope (ODP Leg 150) clearly support the applicability of the alkenone proxy for sediments back to the Eocene. For example, sea-surface temperatures of more than 20 °C in the Eocene, rapid cooling in the late Oligocene and warming in the early Miocene excellently fit to global sea-level-change reconstructions by Haq et al.

Another temperature-sensitive proxy is the average chain length (ACL) of terrestrial n-alkanes. Poynter (1989) found a correlation between pollen record and ACL values for West African continental margin sediments (ODP Holes 658A and 658B) during the last 24 ka. A coupling with alkenone temperatures is obvious at the New Jersey continental rise and slope back to the Miocene (ODP Leg 150), for late Quaternary sediments from the California continental margin (ODP Site 893, Santa Barbara Basin, and ODP Leg 167) and for Pliocene–Pleistocene Mediterranean sapropels (ODP Leg 160).

Warm and Cool Events: The Long View

Gary D. Sharp
Center for Climate and Ocean Resources Study, Monterey, California

The recent decade's climate patterns are not unique, particularly when one considers the Long View available from various climate records. A volume by John Goad, printed in London in 1686, provides novel insights and perspectives into the climate-related societal issues that characterized the depths of the Little Ice Age and Maunder Minimum. The volume is entitled *Astro-meteorologica; or Aphorisms and Discourses of the Bodies Coelestial, Their Natures and Influences*. The treatise is about how Natural Philosophers of the era were in transition, as was most of society. What leaps out of the text is that the transition from looking outward—away from earth-bound processes, into the night skies to explain climate, weather, and many other natural and social phenomena, to the clockworks-like reductionism and process isolation that characterizes modern science—was a traumatic change for the Olde School. The various text sections are organized around selected astrological conjunctions, rather than chronological time, per se. Remarkable tables of events and observations are arrayed, and linked, via astrological codes that define these various conditions. One of the treatise's final messages was the following, that I will refer to as John Goad's Goad: "It grieveth me to see learned men to speak of pressures of aire and therebye solve problems concerning the ocean's ebb and flow." For me, the take-home messages was that perhaps it is just as great a folly to deny external forcing functions as is too often the case in modern climate science. Solar and Lunar tidal forces and earthly pressure patterns are indeed now well known. Are they sufficient to explain all that we need to understand? Apparently not.

What emerged from incorporating some of this material into my *Chronology of Warm and Cold Events, Their Societal and Ecological Consequences* were remarkably similar low numbers of ENSO Warm Events in the 17th and 20th centuries. At the very coolest epoch of the most recent Global Cold period, the number of ENSO Warm Events (29) was one more than we have observed in the 20th century (28). The prior, cool 16th century saw 32. The generally warming 18th century (49) and 19th century (47). R.Y. Anderson's graph of the Sunspot Numbers vs. El Niño frequency may provide more clues. We must all look up from our clockworks every once in a while, to appreciate the Long View.

Where Was the Sonoran Desert at the Last Glacial?

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Dept. of Geology, Kent State University, Ohio

Some authors define the geographic limits of the Sonoran desert by the occurrence of particular species (such as Saguaro, *Carnegiea gigantea*). We use the local climate model (LCM) developed at Kent State University to examine changes in the distribution of desert species over time. The study area is between 22.3°N to 35.1°N latitude and 107.6°W to 117.8°W longitude and includes the entire (modern) Sonoran Desert. The LCM has been solved for a scenario representing the last glacial as well as a control (modern) scenario at a resolution of 15 km x 15 km grid cells, and results have been interpolated for 19 intermediate time steps. We use data of Turner, Bowers, and Burgess (1995, Sonoran Desert Plants, An Ecological Atlas) for eight plants[1] to compute their climate limits. The range of two climate variables (mean total monthly precipitation and monthly mean of the maximum daily temperature) were estimated from control solutions of the LCM at locations where the species are documented. Three experiments are reported.

1. *Carnegiea gigantea* (Saguaro); *Larrea tridentata* (Creosote Bush); *Encelia farinosa* (Brittle Bush); *Ambrosia cordifolia* (Chicurilla); *Peucephyllum schottii* (Pygmy cedar); *Prosopis glandulosa* var. *torreyana* (Honey mesquite); *A. deltoidea* (Triangle-leaf bursage); and *A. dumosa* (White bursage).

1. During the first few years of a Saguaro's life, the plant is most vulnerable to climate conditions. After five years it is only about 2-cm tall (Steenberg and Lowe, 1983, Ecology of the Saguaro III) and has very limited water storage capacity. Both cold and heat that a more mature plant could withstand would destroy a juvenile plant. For each cell, we compute (using appropriate distribution assumptions and parameters specific to that grid cell) the probability that, during 100 years (the approximate flowering time of an adult Saguaro), there will be a consecutive sequence of five good years, so a Saguaro could reach a survival stage. Solutions show that the distribution of Saguaro shrinks markedly under glacial conditions, but that Saguaro might survive a climate like the last glacial in a restricted area between Hermosillo and Guaymas in Sonora, Mexico.

2. For each of the eight species, we find the number of cells in our study area that might be suitable during each of the twenty-one steps from modern to last glacial. For two species, *Larrea tridentata* and *Ambrosia deltoidea*, conditions actually are better in the Late Holocene, but at the last glacial all the plants are confined to an area near the limits of Saguaro or have been eliminated (at the 0.05 probability level).

3. We also estimate how competition among three species of *Ambrosia* could have changed at various stages between modern conditions and last glacial. This is based on the climatically induced range overlap. At the last glacial the range of *A. cordifolia* is included within that of *A. deltoidea* and both ranges are included in that of *A. dumosa*. This would suggest greater competition under glacial climates.

Development and Persistence of North America Mid-continental Moisture Anomalies

Jacqueline J. Shinker
Dept. of Geography, University of Oregon, Eugene

Droughts and floods have large socioeconomic consequences for both agriculture and water resources. Understanding the climatic mechanisms that cause extreme droughts and floods may aid in the prediction and prevention of losses. The 40-year-long NCAR/NCEP reanalysis data set was analyzed to determine the interactions among surface energy- and water-balance and atmospheric circulation that control anomalous wet and dry periods in the mid continent of North America. Composite anomalies reveal the surface energy- and water-balance and circulation patterns, which prevail during extreme, dry and wet years. The composite anomalies were calculated based on a precipitation index for a homogenous region within the mid-continent of North America. Results show negative water-balance anomalies occur throughout the seasonal cycle during anomalously dry years suggesting feedbacks are created with low moisture availability at the surface enhancing dry conditions. Positive water-balance anomalies occur during late spring and early summer and coincide with positive anomalies of vertical velocity at 500 mb indicate rising air, consistent with increased convection. Wet years also coincide with higher than normal Pacific sea-surface temperatures associated with El Niño events. Results indicate extreme wet years are not the climatic opposites of extreme dry years. This analysis has important implications for understanding the genesis and spatial variability of anomalous moisture events in the mid-continent of North America.

Calculating Precipitation at 10-km and at 1-km Grid Spacing in Mountainous Areas and the Effect on Discharge Estimates

Marina Timofeyeva and Rachael Craig
Dept. of Geology, Kent State University, Ohio

The Kent State University Local Climate Model has been linked to a hydrology model to estimate mean and variance of monthly discharge. We find that spatial resolution of 10 km is insufficient to represent the critical high elevation areas where snowpack, the key contributor to streamflow, accumulates leading to serious underestimates of discharge, especially in the melt season. To avoid this bias we solve climate estimates at 1-km resolution. We represent temperature as a sample from a normally distributed population and precipitation as a sample from a log normally distributed population. Parameters of each population are estimated separately for each grid point. Both mean and variance are needed. Estimation of parameters in the case of the log normal distribution is made difficult since mean and variance are not independent, an estimate of the one requires knowledge of the other. To estimate variance for the points within the basin we have used the fact that, in the log space, parameters of the log-normal distribution are independent. Thus all estimates of these parameters are made in log space. Estimates of mean total monthly precipitation are done using canonical regression as for temperature. To estimate variance we have used the standard error of the regression (temperature) and the standard error of the predication (precipitation). The former is an estimate of uncertainty in means while the latter is more appropriate when estimating totals as in the case of precipitation.

An Upper Modesto Age Fossil Record from the Laguna De Santa Rosa, Sonoma County, California: Climatic Implications

G. James West[1], Jack Meyer[2], and Eric Wohlgemuth[3]
[1] Bureau of Reclamation, Sacramento, California
[2] Anthropological Studies Center, Sonoma State University, Rohnert Park, California
[3] Anthropology Dept., University of California, Davis, California

Pollen and seeds from a 38,000 year old peat deposit on the Santa Rosa Plain (Llano de Santa Rosa) attest to significantly different vegetation and climate than today. High pine (*Pinus*) (51%), TCT (Taxaceae, Cupressaceae, and Taxodiaceae-excluding redwood, *Sequoia sempervirens*) (26%), and fir (*Abies*) (1.2%) pollen values indicate a Pine-Cedar Forest containing a few isolated fir trees. These pollen values are in great contrast to the pollen rain of the Valley Oak Savanna that occurs in the area today. Temperatures, 3 to 5° C cooler than today are inferred. Similar age sediments from Clear Lake contain sagebrush (*Artemisia* spp.) pollen grains. Sagebrush pollen is not present in the Laguna de Santa Rosa peat, suggesting that the climatic gradient was similar to today with greater Continental conditions eastward.

Appendix A: Agenda

Sixteenth Annual PACLIM Workshop
Wrigley Institute for Environmental Studies
Two Harbors, Santa Catalina Island, California
May 24–27, 1999

PACLIM is a multidisciplinary workshop broadly focused on climate phenomena occurring in the eastern Pacific and western America. Its purpose is to understand climate effects in this region by bringing together specialists from diverse fields, including both physical and biological sciences. Time scales range from weather to paleoclimate.

Our theme sessions this year deal with the interactions of climate variability with society. These interactions are reported through studies addressing public sector, private sector, and prehistoric societal influences and responses.

The atmosphere of the Workshop is intentionally informal, and room and board are provided for the participants. The Workshop is organized by a committee of representatives from several organizations, but historically it has been spearheaded by U.S. Geological Survey scientists. Held annually, the Workshop has benefited from funding and other forms of support from several agencies public and private (see "Sponsors" on page ix).

Agenda

Sixteenth Annual PACLIM Workshop
Wrigley Institute for Environmental Studies
Two Harbors, Santa Catalina Island, California
May 24–27, 1999

Monday Evening **May 24, 1999**

Introductory Session

Moderator:	Mike Dettinger, U.S. Geological Survey
6:10–6:20 PM	Welcome and Announcements
6:20–7:00 PM	*A Special Treat: Climate-Science Links for Business* Michael Hamer, CEO, Centre Solutions
7:00–7:10 PM	*Break/Discussion*
7:10–7:50 PM	*Western Climate Events Since PACLIM 1998: First El Niño, Then La Niña, Now What?* Kelly Redmond, Western Regional Climate Center
7:40–8:00 PM	*Water Year 1999—A Classic La Niña Pattern* Maurice Roos, California Department of Water Resources
8:00–8:50 PM	*Water, Earth and Sky: The Colorado River Basin* Mike Collier
8:50 PM	*Social Time*

Tuesday Morning | **May 25, 1999**

Climate and Society

Moderators:	Kelly Redmond and Roger Pulwarty, WRCC & OGP
8:00–8:30 AM	*Introduction: Comparing the Basins* Roger Pulwarty and Kelly Redmond, NOAA Office of Global Programs and Western Regional Climate Center
8:30–9:00 AM	*Impacts of Climate Variability on Monitoring Restoration Efforts in Two Sierra Nevada Watersheds* John Tracy, Desert Research Institute
9:00–9:30 AM	*El Niño and La Niña Effects on Snowpack Evolution in the Columbia and Colorado River Basins* Martyn Clark, Colorado Institute for Research on Environmental Science
9:30–10:00 AM	*Water Resource Management in the Colorado River Basin: A Historical and Hydrologic Perspective* John Dracup, Civil and Environmental Engineering, UCLA
10:00–10:30 AM	*Break*
10:30–11:00 AM	*Climate Extremes and Adaptive Management on the Colorado River* Roger Pulwarty, OGP, and Ted Melis, Grand Canyon Monitoring and Research Center
11:00–11:30 AM	*American Indian Cultural Adaptations and Climate Change in the Colorado and Columbia River Basins* Richard Stoffle, Paul Mickens, and Nieves Zedeno, University of Arizona
11:30–12:00 PM	*Pacific Northwest Integrated Assessment, Potential Role of Spatial Comparisons and Synthesis* Ed Miles, JISAO, University of Washington
12:00–1:30 PM	*Lunch*

Tuesday Afternoon **May 25, 1999**

Climate and Society

Moderator:	Tony Michaels, USC/WIES
1:30–2:00 PM	*NOAA's Strategies for Applying Climate Research—Arcs and Applications and Assessments, Oh My!* Panel: M. Eakin, R. Pulwarty, E. Miles, and D. Cayan, NOAA OCG, University of Washington, and Scripps Institution of Oceanography
2:00–2:20 PM	*Introduction to Climate Issues in the Marketplace* Tony Michaels, University of Southern California
2:20–2:50 PM	*Climate and Power* Con Edison Representative
2:50–3:20 PM	*Decisionmaking Under EXTREME Climate Uncertainty* Rob Lempert, Rand Corp.
3:20–3:30 PM	*Discussion* Facilitator: Tony Michaels
3:30–3:45 PM	*Break: Readjorning at Cafeteria (Posters)*

General Posters

3:45–4:30 PM	*Posters Introductions (Two Minutes Each)*
4:30–6:00 PM	*Posters and Refreshments*
5:30–7:00 PM	*Dinner*

Tuesday Evening **May 25, 1999**

Climate and Society

7:30–8:30 PM	*Environment and the Anasazi of the Colorado Plateau* Jeff Dean, LTRR, University of Arizona

Wednesday Morning	May 26, 1999

Climate and Society

Moderator:	Dan Cayan, Scripps Institution of Oceanography/U.S. Geological Survey
8:00–8:20 AM	*Climate Assessment in the Southwest: The Centrality of Stakeholders* Barbara Morehouse, ISPE, University of Arizona
8:20–8:40 AM	*Coping with El Niño-related Droughts in Peasant Agriculture, Northern Costa Rica, 1997–1998* Sarah Otterstrom and Benjamin Orlove, University of California, Davis
8:40–9:00 AM	*A Possible Connection Between the 1877–1878 Yellow Fever Epidemic in the Southern United States and the 1877–1878 El Niño Episode* Henry Diaz and Greg McCabe, Climate Diagnostics Center and U.S. Geological Survey
9:00–9:20 AM	*Role of Climate Change and Historic Ecosystem Analysis in Land Management Planning* Wally Woolfenden and Connie Millar, U.S. Department of Agriculture, Forest Service
9:20–9:40 AM	*Climate Forecasts and Pacific Northwest Public Agencies: Is Anyone Listening?* Ed Miles, Bridgette Callahan, David Fluharty, and Nathan Mantua, Climate Impacts Group, JISAO, University of Washington
9:40–10:00 AM	*Climate and Water Management in the Interior West* Andrea Ray, NOAA/ERL, University of Colorado
10:20–10:40 AM	*Break*

Wednesday Morning **May 26, 1999**

General Sessions

Moderator:	Greg McCabe, U.S. Geological Survey
10:40–11:00 AM	*El Niño and 100 Years of Storm Surge in the Northeast Pacific* Tony Westerling, Economics and International Affairs, University of California, San Diego
11:00–11:20 AM	*Changes in Magnitude and Ting of Annual Maximum Floods* Shaleen Jain and Upmanu Lall, Utah State University
11:20–11:40 AM	*Solar Irradiance Variations and Annual Streamflow in the Upper Mississippi River Basin* Charles Perry, U.S. Geological Survey
11:40–12:00 PM	*Evaluating Local Climate Model Results: Validation and Confidence Building* Marina Timofeyeva and Rachael Craig, Kent State University
12:00–1:30 PM	*Lunch*

Wednesday Afternoon — May 26, 1999

General Sessions

Moderator: Bob Webb, U.S. Geological Survey

1:30–1:50 PM — *High-Resolution Solutions of Climate Mean and Variance for a Doubled CO_2 Scenario in the Western US*
Rachael Craig and Marina Timofeyeva, Kent State University

1:50–2:10 PM — *Statistical-Physical Precipitation Downscaling for the Sierra Nevada*
Ganesh Pandey, Dan Cayan, and Kosta Georgakakos, Scripps Institution of Oceanography

2:10–2:30 PM — *Interaction Between Topography and Regional Rainfall Patterns in the San Francisco Bay Region*
Ray Wilson, U.S. Geological Survey

2:30–2:50 PM — *Amplification of Climate Signals Through Fluvial Sediment Transport*
David Jay and Pradeep Naik, Oregon Graduate Institute

2:50–3:10 PM — *Climate Effects on Seasonal Variability of Streamflow and Suspended Sediment Transport in West Coast Rivers*
Pradeep Naik and David Jay, Oregon Graduate Institute

3:10–3:30 PM — *Environmental Variability and Prerecruit Survival of Pelagic Fish Off California: GIS Mapping an Hypothesis Formulation*
Elizabeth Logerwell and Paul Smith, Southwest Fisheries Science Center

3:30–5:30 PM — *Free Time, featuring a Geologic Walkabout on WIES Campus*
Walkabout led by Ray Wilson, U.S. Geological Survey

5:30–7:00 PM — *Dinner*

Wednesday Evening — May 26, 1999

General Sessions

7:30–8:15 PM — *The Pacific Decadal Climate Oscillation*
Nathan Mantua, JISAO, University of Washington

Thursday Morning **May 27, 1999**

General Sessions

Moderator:	Janice Tomson, Long Beach City College
8:00–8:20 AM	*Snowpack, ENSO, and Atmospheric Circulation in the Colorado Front Range* Mark Losleben, INSTAAR, University of Colorado
8:20–8:40 AM	*Spatial and Temporal Variability of Snow Avalanche Climate of Western United States* Cary Mock, Karl Birkeland, Gerald Gress, and Joshua Robino, University of Oregon and Montana State University
9:00–9:20 AM	*Forecasting San Francisco Bay Estuarine Conditions* Noah Knowles, Scripps Institution of Oceanography
9:20–9:40 AM	*Neural Networks as a Data Extraction Tool for California's Long Range Precipitation Prediction* David Silverman and John Dracup, Civil and Environmental Engineering, UCLA
9:40–10:00 AM	*Break*
10:00–10:20 AM	*Late Holocene Paleoenvironments of Los Peñasquitos Lagoon* Ken Cole and Eugene Wahl, U.S. Geological Survey/Northern Arizona University and University of Minnesota
10:20–10:40 AM	*Reconstructed Record of Marine Productivity Variability Within the California Current, AD 1500–1995* Lowell Stott, William Berelson, Donn Gorsline, Robert Douglas, and Douglas Hammon, University of Southern California
10:40–11:00 AM	*Lake Level and Climate Changes in Mono Basin During the Last Millennium* Teh-Lung Ku, H. C. Li, Steve Lund, and Lowell Stott, University of Southern California
11:00–11:10 AM	*Good-byes and Plans*
12:00 PM	*Departure*

Appendix B: Poster Presentations

Climate Variability in the Southwest for an Integrated Assessment
Kurt Angersbach[1], Andrew C. Comrie[1], Paul R. Sheppard[2], Gregory D. Packin[1], and Malcolm K. Hughes[2]
[1] Dept. of Geography and Regional Development, University of Arizona, Tucson
[2] Laboratory of Tree-Ring Research, University of Arizona, Tucson

Lake System Dynamics and Paleoclimate Interpretations
Rachael Craig and Susanne Clement
Dept. of Geology, Kent State University, Ohio

Global Characteristics of Streamflow Seasonality and Variability
Mike Dettinger[1] and Henry Diaz[2]
[1] U.S. Geological Survey, Scripps Institution of Oceanography, La Jolla, California
[2] NOAA/ERL, Climate Diagnostics Center, Boulder, Colorado

Documented Validation of Extreme Precipitation Events Reconstructed from Northwest Mexico (1860–1997)
Sara C. Diaz and C. A. Salinas-Zavala
Centro de Investigaciones Biologicas del Noroeste (CIBNOR)
La Paz, B.C.S., Mexico

Public Policy Changes: Land Use, CO_2, and the "Tom Sawyer" Effect
Bonnie C. Gee
Dept. of Geography Graduate Program, University of Montana, Missoula

Millennial-scale Fluctuations in Vegetation and Climate During the Last Glacial Period in Western Oregon
Laurie D. Grigg[1], Cathy Whitlock[1], and Walter D. Dean[2]
[1] Dept. of Geography, University of Oregon Eugene, Oregon
[2] U.S. Geological Survey, Denver, Colorado

Reservoir Operation Policies Based on El Niño–Southern Oscillation: A Case Study from Colombia
Felipe Gutierrez and John A. Dracup
Civil and Environmental Engineering Dept., University of California, Los Angeles

Alternative PCA-based Regression Techniques in Dendroclimatic Reconstructions
Hugo Hidalgo, John Dracup, and Thomas Piechota
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Comparison of Tree Species Sensitivity in Streamflow Reconstructions in the Colorado River Basin
Hugo Hidalgo[1], Judith A. King[2], John A. Dracup[1], and Glen M. Macdonald[2]
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Update of Winter Papa Trajectory Index for the Gulf of Alaska Suggests New Shift in Decadal Oscillation Patterns for Northwest
W. James Ingraham, Jr.
Alaska Fisheries Science Center-NMFS-NOAA, Seattle, Washington

Southwest Climate and the Quasi-Biennial Oscillation, The El Niño-Southern Oscillation, The Arctic Oscillation, and Tidal Resonances
Thor Karlstrom
U.S. Geological Survey, Seattle, Washington

The Influence of Climate on Long-term Trends in Northern San Francisco Bay Estuary
P. W. Lehman
California Department of Water Resources

Relationships of Precipitation Chemistry, Atmospheric Circulation and Elevation at Two Sites on the Colorado Front Range
Mark Losleben[1], Nick Pepin[2], and Sandra Pedrick[3]
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Molecular Indicators of Climatic and Oceanographic Conditions on the California Continental Margin During the Last 160 kyr (ODP Leg 167)
Kai Mangelsdorf, Ute Güntner, and Jürgen Rullkötter
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Temperature-related Molecular Proxies: Degree of Alkenone Unsaturation and Average Chain Length of n-Alkanes
Joachim Rinna, Ute Güntner, Kai-Uwe Hinrichs, Kai Mangelsdorf, Jan Hendrik van der Smissen, and Jürgen Rullkötter
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Warm and Cool Events: The Long View
Gary D. Sharp
Center for Climate and Ocean Resources Study, Monterey, California

Where Was the Sonoran Desert at the Last Glacial?
Leila Shozawa and Rachael Craig
Dept. of Geology, Kent State University, Ohio

Development and Persistence of North American Mid-continental Moisture Anomalies
Jacqueline J. Shinker
Dept. of Geography, University of Oregon, Eugene

Calculating Precipitation at 10-km and at 1-km Grid Spacing in Mountainous Areas and the Effects on Discharge Estimates
Marina Timofeyeva and Rachael Craig
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An Upper Modesto Age Fossil Record from the Laguna De Santa Rosa, Sonoma County, California: Climatic Implications
G. James West[1], Jack Meyer[2], and Eric Wohlgemuth[3]
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Appendix C: Attendees

Sixteenth Annual PACLIM Workshop
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