EL NIÑO
&
LTER

EL NIÑO & LONG-TERM ECOLOGICAL RESEARCH (LTER) SITES

Edited by

DAVID GREENLAND

Published by:

LTER

LTER NETWORK OFFICE
University of Washington
College of Forest Resources, AR-10
Seattle, WA 98195
Phone: 206-543-4853
Fax: 206-543-7295

Recommended citation:
Greenland, D. (ed). 1994. *El Niño and Long-Term Ecological Research (LTER) Sites.* Publication No. 18. LTER Network Office: University of Washington, Seattle, WA, USA. 57 pp.

Supported by a grant from the National Science Foundation, Division of Environmental Biology (93-00679). Any opinions findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

EL NIÑO

&

LONG-TERM ECOLOGICAL

RESEARCH SITES

Edited by

David Greenland

on behalf of

the LTER Climate Committee

August 1994

PREFACE

A workshop on El Niño and Long-Term Ecological Research (LTER) sites was held on September 20, 1993 at the LTER All Scientists Meeting at Estes Park, Colorado. The workshop was initiated and organized by Dr. Bruce P. Hayden of the Virginia Coast Reserve LTER site. As part of the origination process, Dr. Hayden provided background information on El Niño in two issues of the LTER Climate Committee electronic bulletin board newsletter, *Climate/Ecosystem Dynamics (CED)*. The June 1, 1993 issue (Vol. 2, No. 5) included three El Niño data sets. They were the Quinn record starting from the year 1525, the Rasmusson record from 1726, and the Cayan and Webb record from 1901. The July 1, 1993 issue (Vol. 2, No. 6) included values of the Southern Oscillation Index by year and month from 1882, introductory information and the history of research on the El Niño/Southern Oscillation (ENSO), a brief review of El Niño-related precipitation effects in the U.S. Southwest, an article on Bill Quinn—a pioneer in El Niño research, and some information on El Niño and economic impacts.

At the workshop, Bruce Hayden also provided participants with a document called "An El Niño Primer" and made an initial presentation on the subject. The presentation included a movie illustrating tropical convection near the dateline in the Pacific and the flow of moisture toward the Southwest of the United States during an El Niño period. Presentations from six LTER sites were made at the workshop and a general discussion followed. The presentations were made by Clifford Dahm (Sevilleta), David Greenland (Andrews), Mark Losleben for Connie Woodhouse (Niwot), Dale Robertson and John Magnuson (North Temperate Lakes), John Briggs (Konza), and Lloyd Swift, Jr. (Coweeta). Papers from these authors are assembled in this monograph.

The workshop reflected an ongoing interest in ENSO-related phenomena at LTER sites. Consistent with this interest, an El Niño bulletin board was established at the LTER Network Office in 1993. (To subscribe, contact Daniel Pommert at 206-543-1135, or send a message to *Elnino-request@LTERnet.edu*.) The El Niño bulletin board is separate from the *CED* bulletin board mentioned above. Past issues of both are posted on the Internet on the LTER gopher server, *LTERnet.edu*, at LTER Electronic News Groups/El Niño and LTER Electronic News Groups/CED-Climate/Ecosystem Dynamics Bulletin Board/.

The LTER Network Office kindly agreed to publish this monograph as a Network publication. The Network Office and this publication are supported by a grant from the National Science Foundation's Division of Enviromental Biology. I would like to thank Bruce Hayden for organizing the initial El Niño workshop, the individual paper presenters, and those who provided the written version for this monograph. Stephanie Martin of the LTER Network Office played an invaluable role in preparation, production, and publication.

DAVID GREENLAND
Department of Geography, University of Oregon

Chairperson, LTER Climate Committee

Site member, H.J. Andrews Experimental Forest & Niwot Ridge LTER sites

August 1994

CONTRIBUTORS
AFFILIATIONS & LTER SITES

Wendy Anderson
Center for Limnology
University of Wisconsin
Madison, WI 53706
NORTH TEMPERATE LAKES

John M. Briggs
Division of Biology
Kansas State University
Manhattan, KS 66506-4901
KONZA PRAIRIE

Clifford Dahm
Department of Biology
University of New Mexico
Albuquerque, NM 87131
SEVILLETA

David Greenland
Department of Geography
University of Oregon
Eugene, OR 97403-1251
*H.J. ANDREWS EXPERIMEN-
TAL FOREST & NIWOT RIDGE/
GREEN LAKES VALLEY*

Bruce Hayden (*Organizer)*
Dept. of Environmental Science
University of Virginia
Charlottesville, VA 22903
VIRGINIA COAST RESERVE

John J. Magnuson
Center for Limnology
University of Wisconsin
Madison, WI 53706
NORTH TEMPERATE LAKES

Douglas I. Moore
Department of Biology
University of New Mexico
Albuquerque, NM 87131
SEVILLETA

Dale M. Robertson
U.W. Geological Survey
6417 Normandy Lane
Madison, WI 53719
NORTH TEMPERATE LAKES

Connie A. Woodhouse
Laboratory of Tree-Ring Research
University of Arizona
Tucson, AZ 85721
NIWOT RIDGE/GREEN LAKES VALLEY

CONTENTS

EL NIÑO & LONG-TERM ECOLOGICAL RESEARCH SITES

David Greenland

EL NIÑO

An intense El Niño event can have severe impacts on the ecosystems of the west coast of South America. The upwelling of nutrient rich water off the coast is suppressed. Anchovy stocks dramatically decline, as do the seabird populations who live from them. The decline of the seabird populations negatively impacts the fertilizer industry which depends upon the guano produced by the birds. The fishing industry suffers from the lack of fish. Further impacts on terrestrial ecosystems of the region are noted below. It has long been recognized that during El Niño events effects are felt in other parts of the world as well. There have been few attempts to systematically investigate El Niño signals in different ecosystems outside its primary South American source area. The Long-Term Ecological Research (LTER) Network sites provide a good opportunity to do so. This monograph represents a first attempt at a systematic investigation of the topic and points the way to some of the activities which could fruitfully take place in the future.

There have been few attempts to systematically investigate El Niño signals in different ecosystems outside its primary South American source area

The LTER Network, supported by the National Science Foundation, was established in 1980 and currently has 18 sites in a variety of different ecosystems in the United States and Antarctica (Franklin et al. 1990, Van Cleve and Martin 1991) (Figure 1). Scientists at each site study specified themes which are common across the Network. The Network is also used for intersite comparative studies in which all, or subsets, of the sites participate. The present study is such a case and arises from a workshop on the effect of El Niño at LTER sites held at the LTER All Scientists Meeting in Estes Park, Colorado in September of 1993. This introductory chapter contains a description of the El Niño/Southern Oscillation (ENSO) phenomenon, a summary of the results found at each site, and overview comments and suggestions. The ENSO is a multifaceted phenomenon and no single account will cover all of its aspects. Thus, it is fitting that further discussions of certain of its aspects are provided in some of the papers of this volume in addition to the introductory explanation below.

The ENSO is a coupled ocean/atmosphere interaction which effects the climate of the Pacific Ocean, its surroundings, and many other parts of the world on an interannual time scale. Specifically, El Niño is an unusual warming of normally cool, near-surface waters off the west coast of South America. Enfield (1992) has given a very clear account which is used for the basis of the following description. Typically, El Niño appears as an enhancement to the annual onset of a warm, southward flowing current occurring around the Christmas season. This timing gives rise to the name *El Niño*, meaning child or Christ child. Parts of the total El Niño event often last for about a year and are associated with a warming of the surface water between 2 and 8°C and the suppression of upwelling nutrient rich ocean water. Local reduction in anchovy stocks and bird populations result. Further south, water which does upwell is warm because of a deepening of the thermocline—the layer underneath the surface layer where there is a strong thermal gradient. During El Niño occurrences, South American terrestrial ecosystems are subjected to unusual storminess along the coasts of Peru and Ecuador, increased rainfall over the Andes of north and central Peru leading to coastal flooding and erosion, and drought in the Andes of Southern Peru and in northeast Brazil, and wet winters in central Chile.

The ocean phenomenon of El Niño (EN) is intimately related to the atmospheric feature called the Southern Oscillation (SO), and the two are commonly combined to create the acronym *ENSO.* The Southern Oscillation is a variation in the intensity of air circulation in a west-east aligned cell, the Walker cell, over the equatorial southern Pacific ocean. The high phase of the oscillation is characterized by higher than normal surface atmospheric pressure values over the southeast Pacific and lower than normal pressures in the area of Indonesia. During this time, air is transferred at low levels from the subsidence (high pressure) regions to the convective (low pressure) regions and is compensated by a reverse (west to east) flow at the upper tropospheric levels. During the low phase of the oscillation, the pressure distribution is reversed and the Trade winds are weakened. The state of the SO is easily measured by the difference of surface atmospheric pressure between Tahiti and Darwin, Australia. This difference is called the Southern Oscillation Index (SOI). When the SOI

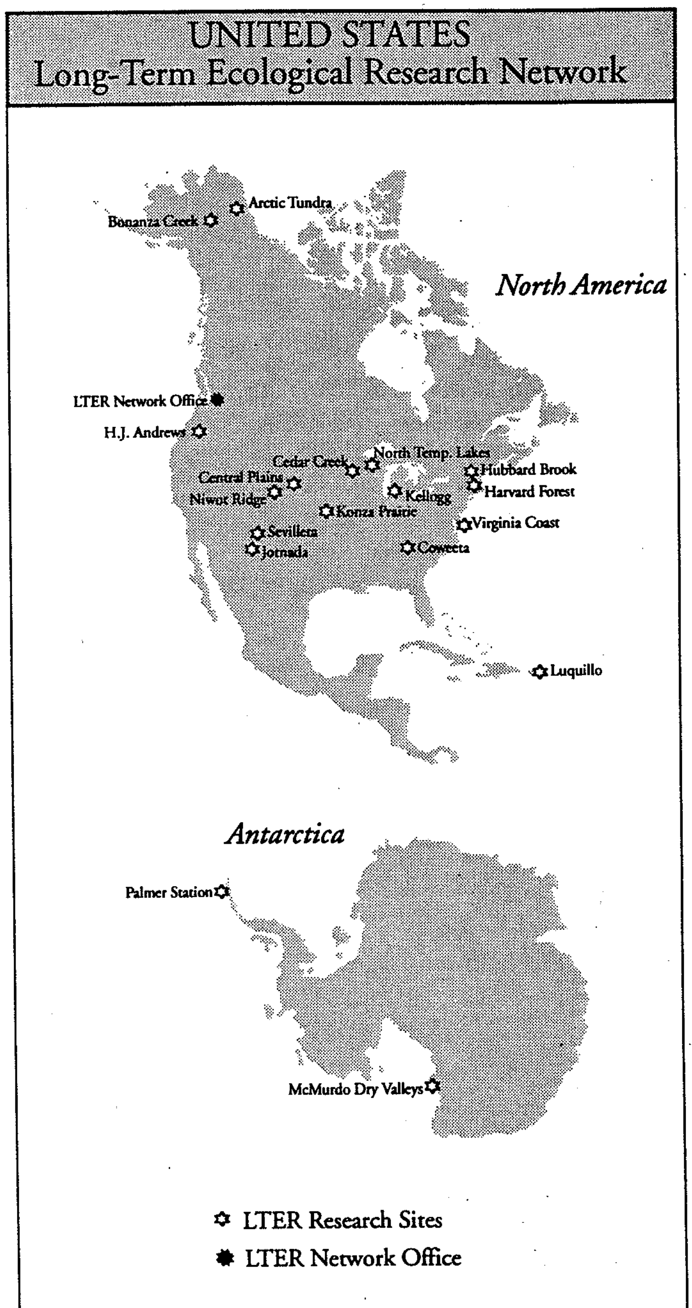
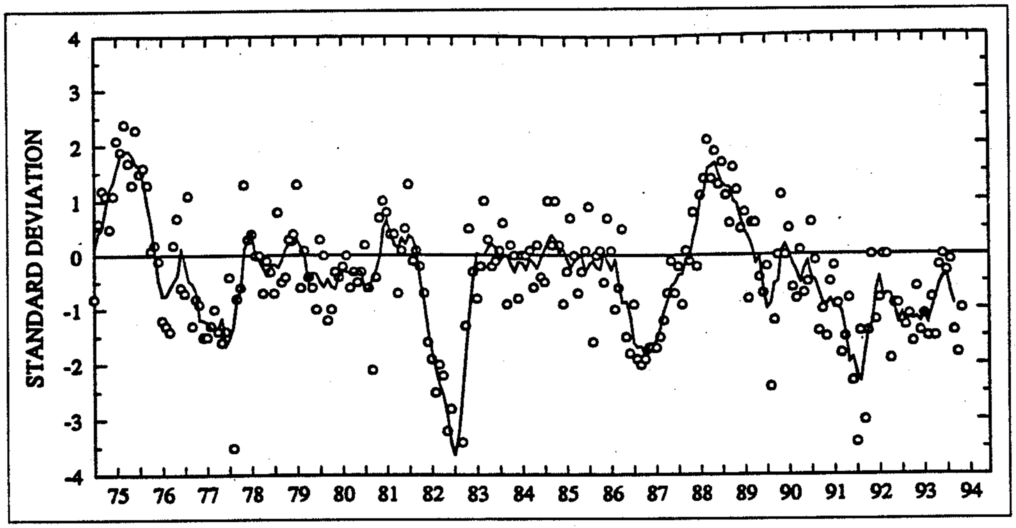
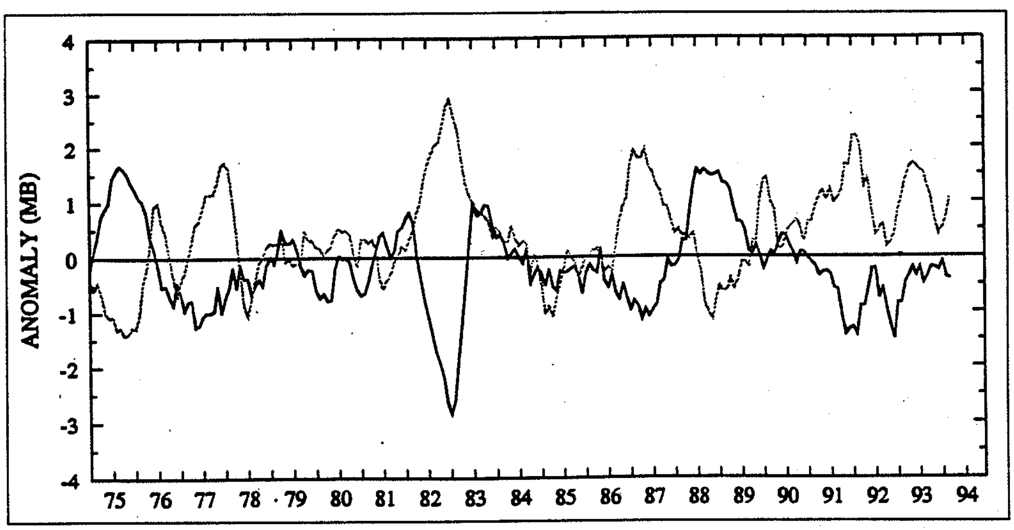


Figure 1. The location of the 18 LTER sites.

Five-month running mean of the difference between the standardized sea-level pressure anomalies at Tahiti and Darwin (Tahiti-Darwin). Values are standardized by the 1951-1980 mean annual standard deviation. The circles indicate individual monthly means. The x-axis labels are centered on July. (NOAA, Climate Diagnostics Bulletin, *May 1994, p. 6.)*





Five-month running mean of the sea-level pressure anomalies at Darwin (dashed) and Tahiti (solid). Anomalies are departures from the 1951-1980 base period monthly means. The x-axis labels are centered on July.

Figure 2. Representations of the temporal variation of the SOI index (NOAA, Climate Diagnostics Bulletin, *May 1994, p. 6.)*

value is high the SO is in its high phase; when it is low, the SO is in its low phase which corresponds to an El Niño event. The high SO phase corresponds to the opposite of an El Niño event, sometimes called *La Niña* (female child). Low SO phases are also synchronous with warm sea surface temperature (SST) anomalies in the central and eastern Pacific and are thus referred to as "warm events." High phase SO times are conversely named "cold events." Current and past SOI values and graphs are published by the U.S. National Meteorological Center of the National Oceanic and Atmospheric Administration (NOAA) in the monthly publication, *Climate Diagnostics Bulletin* (Figure 2). Figure 2 displays the interannual variation of the SOI value, its pseudo-cyclicity, and the relatively extreme nature of the 1982-83 El Niño event.

The Walker cell, existing in the Pacific, is paralleled by others all the way around the equator. In addition, changes in the SO have effects on the extra tropical atmospheric circulation of the mid-, and even high, latitudes. Mid-latitude westerly winds are energized during an El Niño, especially over the eastern Pacific and North America. Relations between pressure phenomena in one part of the world and those in another part of the world are called *teleconnections*. Yarnal (1985) has provided an excellent review of the extratropical teleconnections with ENSO and what we know of the physical reasons which explain them.

El Niño existence is well marked in a wide variety of proxy climatic data, much of which directly relates to ecosystem response

The ENSO research in the past decade was greatly stimulated by the intense El Niño of 1982-83 (Figure 2). As a result, we have acquired some important basic knowledge about the ENSO phenomenon. We know that it has occurred for at least 5.5 million years (Casey et al. 1989). We know that individual El Niños can be well modeled and are somewhat predictable (Zebiak and Cane 1987), and that there is considerable variation in the intensity, or strength, of individual El Niños. They are aperiodic (2 to 5 years), but EN time series are probably non-stationary. The latter observation makes the statistical analysis of ENSO signals particularly difficult. El Niño existence is well marked in a wide variety of proxy climatic data, much of which directly relates to ecosystem response (Peterson 1989, Enfield 1992, Diaz and Markgraf 1992).

A particularly important point from the ecological perspective is that there is some evidence that flora and fauna may make evolutionary adaptations to the presence of the ENSO. Nicholls (1992) describes the evolutionary adaptations of the red kangaroo, the long-haired rat, and various birds and other animals and plants in Australia where El Niños are associated with drought and La Niñas bring excessive rains and flooding. It is of interest, then, to ask what ENSO-related effects there might be on the ecosystems of the LTER sites.

THE CONTRIBUTED PAPERS

The investigations made for the Estes Park El Niño workshop were carried out using different methodologies at each individual site

The LTER sites fall in areas both with and without marked ENSO signals. Ropelewski and Halpert (1986) have produced maps of El Niño signals on precipitation and temperature in North America. El Niño signals on precipitation are shown to exist in three regions straddling the 40°N parallel and centered on the Mid-Atlantic, the High Plains, and the Great Basin. A fourth region is composed of the Gulf of Mexico and Mexico and the U.S. Southwest. An analysis based on climate division precipitation also identifies the Pacific Northwest as an area with an El Niño precipitation signal. The areas with an El Niño signal, therefore, potentially include the Andrews, Jornada, Sevilleta, Niwot Ridge, Central Plains, and Virginia Coast LTER sites. The temperature analysis identifies Northwest North America, Southeast United States, and Eastern Canada as having coherent ENSO-related responses. A strict interpretation of these areas includes no LTER site. We would thus expect to find an ENSO-related climate signal at some LTER sites, especially for precipitation. We are unaware of any analyses of ENSO effects for Antarctic regions and none were performed for the Palmer and McMurdo Antarctic LTER sites. The investigations made for the Estes Park workshop were carried out using different methodologies at each individual site. An absence of a signal at an LTER site can either mean that there is no signal or that the methodology employed was unable to capture it.

Researchers at the Sevilleta, in New Mexico, were the first in the LTER Network to recognize and investigate the effect of ENSO on their ecosystem. Molles and Dahm (1990) published their initial findings on the subject in a classic paper at the beginning of the decade. The paper in the present volume, by Dahm and Moore, summarizes some of the Sevilleta work. They document a clear effect of ENSO at Sevilleta on winter (October to May) precipitation with high precipitation values during El Niño years and low precipitation values during La Niña years. They predict the ENSO-related variability of precipitation at the site has a strong influence on the population dynamics, physiological conditions, and landscape patterns of flora and fauna at the site. A striking example of this is the significant dieback of pinyon pine and juniper in the late 1940s and mid-1950s associated with dry years during frequent La Niña events. This is evidence for the non-stationary nature of the ENSO time series.

Woodhouse's analysis of precipitation, based on the work of Kiladis and Diaz (1989), and tree rings near the Niwot Ridge, Colorado site show that Denver precipitation is most strongly related to ENSO events in the succeeding year. Wet springs occur the year after an El Niño and dry springs follow a La Niña. This relationship is generally reflected in the tree-ring chronologies. The tree-ring chronologies suggest that the tree responses are more marked for a La Niña than an El Niño event. Tree growth response to SOI has varied over time, possibly due to variation of strength and timing of ENSO events.

The H.J. Andrews Experimental Forest site in Oregon displays weak but significant relationships with ENSO events, such that it tends to be drier and warmer during El Niño events and wetter and cooler during La Niña events. At the Andrews, and in the region in which it exists, ENSO phenomena are related to other teleconnective phenomena and to the abundance of Coho salmon in aquatic ecosystems. Coho abundance is associated not only with ENSO variability but also with longer-term cycles as well.

John Briggs reports the search made for an ENSO signal at the Konza Prairie, Kansas LTER site. Here, they found a significant correlation between February precipitation and concurrent SOI values, but with no other time period. This result is consistent with a lack of ENSO signal found in the mid-section of the country in other studies (Ropelewski and Halpert 1986, Barnett 1981), but is also consistent with the finding for Wisconsin that it may only be one particular month which displays the signal.

Across Wisconsin, which includes the North Temperate Lakes LTER site at Trout Lake in the northern part of the state, something very interesting happens. Robertson, Anderson and Magnuson find that during winters of the mature phase of ENSO events, lake ice breakup dates were earlier (ranging on average from 5 to 14 days) and spring (primarily March) temperatures were warmer by between 3 to 4° C than in non-El Niño years. The differences in breakup are more extreme for the southern lakes than the northern lakes. Robertson and his coworkers believe this difference is caused by the average breakup dates for the southern lakes happening in late March directly following the period when air temperatures are related strongly to ENSO events, whereas average breakup dates for the northern lakes are in mid- to late April following a period when air temperatures are not significantly related to ENSO events. It is possible that these findings for Wisconsin might also apply to Minnesota, in which the neighboring Cedar Creek LTER site is located. An early breakup of ice may potentially decrease the period of stable environment required for egg incubation of some species, increase overall productivity and stratification of the lake, and increase the chances of hypolimnetic anoxia.

Preliminary searches of ENSO signals were also made at the Virginia Coast Reserve LTER site by Bruce Hayden and at the Coweeta LTER site by Lloyd Swift, but no ENSO signal was immediately found at either site.

DISCUSSION

Overall, there are a variety of ENSO relationships existing at the LTER sites where investigations were made. It is probable that only the surface of the range of ENSO-related effects at LTER sites has been touched.

An interesting feature is the importance, sometimes greater importance, of La Niña events as well as El Niño events. As expected, the LTER sites closer to known areas of ENSO response (e.g., Sevilleta) display some of the more marked responses. Extreme El Niños and La Niñas tend to be winter and/or spring events. In these cases, they do not have their clearest manifestations in the northern hemisphere growing seasons but in the preceding seasons. Thus, ecosystems that are affected by prior seasons in terms of such aspects as snowpacks, soil moisture storage, or ice breakup will be the ones with most ecological interest in ENSO. The effects of ENSO events on some parts of the ecosystems, however, may also be lagged as is shown by the Niwot tree rings where the ENSO signal shows up in the succeeding year.

The method of statistical analysis used to identify the ENSO signal is critical—some methods may miss the signal altogether

Another lesson is that the ENSO signal may be weak (Andrews) or short-lived (Northern Lakes) yet, in either case, it can be important. The method of statistical analysis used to identify the signal is critical. Some methods may miss the signal altogether. These include methods which collapse data sets into large groups, e.g., annual instead of monthly or even daily data, and methods which use the whole of a very long but non-stationary data set. When looking for ENSO signals, it is a good idea to use moving window techniques which can deal with the fact that the ENSO signals vary in magnitude and frequency over different sections of the whole time series. Another statistical problem is that the ENSO signal is rarely the only signal in the time series and it may be masked or complemented by other periodicities (Andrews).

This preliminary investigation suffered from a lack of standardization of methods. Future studies should include a component in which standardized methods of examination, at least of the climate data, would be applied at each site. On the other hand, the freedom the investigators were given provided a view of the wide range of ENSO signals and effects which do occur at the various LTER sites. However, it is unlikely that a standardized methodology could be devised which would capture the complete range of signals at every site. The ideal program for the future would have both a standardized methodology and the flexibility for each individual site to pursue ENSO-related features of interest. The LTER Network also has the opportunity to extend investigations into the southern hemisphere by virtue of its two sites in Antarctica. It is encouraging, in the context of future research, to find that, in general, LTER sites are indeed representative of the larger regions in which they exist. In the paleoclimate community, Diaz et al. (1992) have called for an integrated network of annual or better resolution records of regional-scale climatic changes. LTER sites could clearly play a major role in such a network and in future ENSO research.

REFERENCES

CASEY, R.E., A.L. WEINHEIMER and C.O. NELSON. 1989. California El Niños and related changes of the California current system from recent and fossil radiolarian records. Pages 85-92 *in:* D.H. Peterson (ed.). *Aspects of Climate Variability in the Pacific and Western Americas.* American Geophysical Union. Geophysical Monograph. No. 55. 445 pp.

DIAZ, H.F. and V. MARKGRAF (eds.).1992. El Niño: *Historical and Paleoclimate Aspects of the Southern Oscillation.* Cambridge University Press:Cambridge, U.K. and New York, NY. 472 pp.

DIAZ, H.F., V. MARKGRAF and M.K. HUGHES. 1992. Synthesis and future prospects. Pages 463-471 *in:* H.F. Diaz and V. Markgraf (eds.). *El Niño: Historical and Paleoclimate Aspects of the Southern Oscillation.* Cambridge University Press:Cambridge, U.K. and New York, NY. 472 pp.

ENFIELD, D.B. 1992. Historical and prehistorical overview of the El Niño/Southern Oscillation. Pages 95-117 *in:* H.F. Diaz and V. Markgraf (eds.). *El Niño: Historical and Paleoclimate Aspects of the Southern Oscillation.* Cambridge University Press:Cambridge, U.K. and New York, NY. 472 pp.

FRANKLIN, J.F., C.S. BLEDSOE and J.T. CALLAHAN. 1990. Contributions of the Long-Term Ecological Research Program. *BioScience* 40(7)509-523.

KILADIS, G.N. and H.F. DIAZ. 1989. Global climatic anomalies associated with extremes in the Southern Oscillation. *Journal of Climate* 2:1069-1090.

MOLLES, M.C., JR., and C. DAHM. 1990. A perspective on El Niño and La Niña: global implications for stream ecology. *Journal of the North American Benthological Society* 9:68-76.

NICHOLS, N. 1992. Historical El Niño/Southern Oscillation variability in the Australasian region. Pages 151-169 *in:* H.F. Diaz and V. Markgraf (eds.). *El Niño: Historical and Paleoclimate Aspects of the Southern Oscillation.* Cambridge University Press:Cambridge, U.K. and New York, NY. 472 pp.

PETERSON, D.H. (ed.). 1987. Aspects of climate variability in the Pacific and Western Americas. American Geophysical Union. Geophysical Monograph No. 55. 445 pp.

ROPELEWSKI, C.F. and M.S. HALPERT. 1986. North American precipitation and temperature patterns associated with the El Niño/Southern Oscillation (ENSO). *Monthly Weather Review* 114:2352-2362.

VAN CLEVE, K. and S.J. MARTIN. 1991. *Long-Term Ecological Research in the United States: A Network of Research Sites—1991*. 6th edition revised. LTER Publication Number 11. LTER Network Office:University of Washington, Seattle, Washington. 178 pp.

YARNAL, B. 1985. Extratropical teleconnections with El Niño/Southern Oscillation (ENSO) events. *Progress in Physical Geography* 9:315-352.

ZEBIAK, S.E. and M.A. CANE. 1987. A model El Niño-Southern Oscillation. *Monthly Weather Review* 115:2262-2278.

THE EL NIÑO/SOUTHERN OSCILLATION PHENOMENON & THE SEVILLETA LONG-TERM ECOLOGICAL RESEARCH SITE

Clifford N. Dahm & Douglas I. Moore

INTRODUCTION

The El Niño/Southern Oscillation (ENSO) phenomenon is an atmosphere-ocean coupling across the central tropical Pacific which influences climate in many regions of Earth (Rasmusson and Wallace 1983, Ropelewski and Halpert 1987, Enfield 1989). Much of the North American continent is influenced to some extent by the ENSO phenomenon (Ropelewski and Halpert 1986, Nicholls 1988, Redmond and Koch 1991, Cayan and Webb 1992, Kahya and Dracup 1993). The semi-arid and arid ecosystems of the southwestern United States are strongly teleconnected to the ENSO phenomenon during fall, winter, and spring when regional climate derives predominantly from the Pacific Ocean (Andrade and Sellers 1988, Molles and Dahm 1990, Swetnam and Betancourt 1990, Redmond and Koch 1991, Molles et al. 1992).

Water is the lifeblood of arid and semi-arid ecosystems of the southwestern United States. The timing and amount of precipitation are fundamental agents structuring the biological communities. Semi-arid regions worldwide are commonly areas where variance in precipitation is high (Conrad 1941). In other words, runs of drought and unusually heavy rains are common-place. A major cause for the variability of rainfall in many semi-arid regions is the ENSO phenomenon (Nicholls 1988). In the following discussion, we will highlight the connections between the ENSO phenomenon and precipitation at the Sevilleta Long-Term Ecological Research (LTER) site in central New Mexico.

RESULTS & DISCUSSION

A central theme of the research at the Sevilleta LTER is that fall, winter and spring precipitation at the Sevilleta LTER responds to extremes in the phases of the ENSO phenomenon. Warm-phase episodes (commonly called El Niño events) and cold-phase episodes (recently dubbed La Niña events) are predicted to produce wet and dry periods, respectively. An index of the ENSO phenomenon, termed the Southern Oscillation Index (SOI), is one measure of the status of this climate system of the tropical Pacific. A long-term record of the SOI is available (Environmental Data Center, National Oceanic and Atmospheric Administration, Asheville, North Carolina). The SOI is derived by subtracting the normalized monthly mean pressure differential at Darwin, Australia from that at Tahiti. The index is usually presented as a five-month running mean. Periods of low index correspond to El Niño events and periods of high index correspond with La Niña events (Figure 1).

Figure 1. Southern Oscillation Index (SOI) for 1914-1993. This is a five-month running mean of the normalized monthly mean pressure differential between Tahiti and Darwin, Australia.

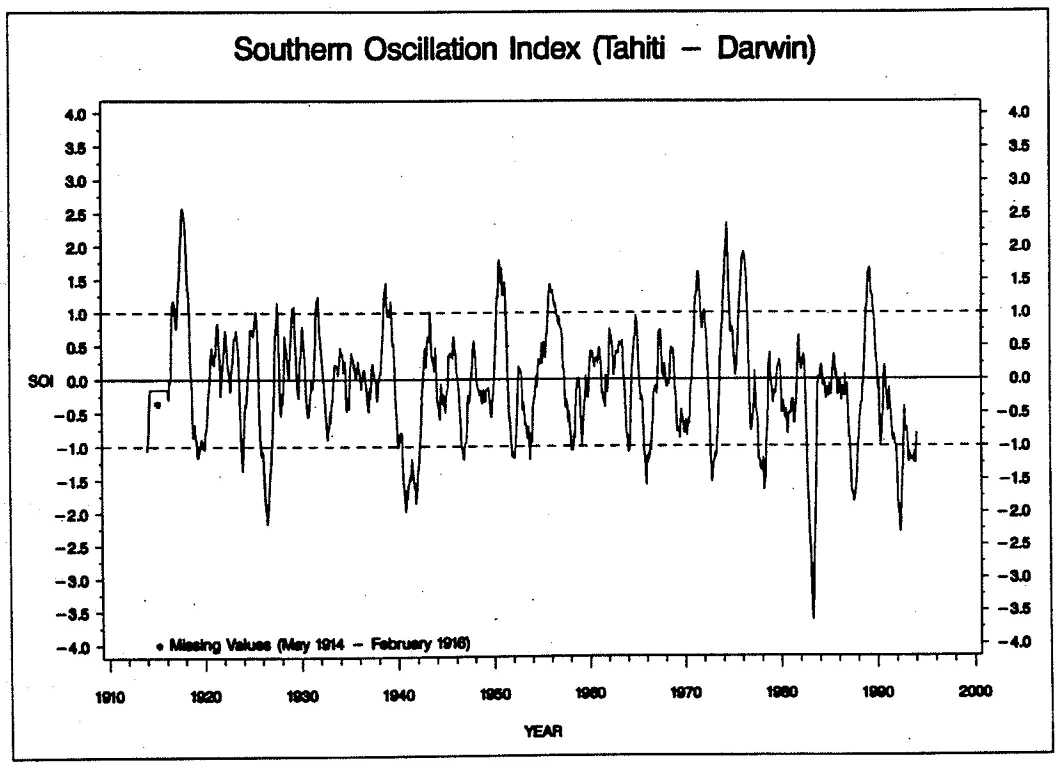


Table 1. Years classified as El Niño and La Niña for the period 1914-1993 using SOI only.

El Niño	La Niña
1919	1918
1926	1939
1940	1950
1941	1951
1942	1956
1952	1971
1958	1974
1964	1976
1966	1989
1973	
1978	
1983	
1987	
1992	
1993	
n=15	n=9

The SOI was used to distinguish El Niño, La Niña, and modal years for use in analyzing historical precipitation and runoff data from New Mexico (Molles and Dahm 1990, Dahm and Molles 1992, Molles et al. 1992). El Niño years were designated for those times when the five-month running mean of the SOI during fall and winter was less than -1. La Niña years were designated for years when the running mean was above +1. A summary of the years from 1914 to 1993, which were designated as El Niño and La Niña years, is presented in Table 1. It should be noted that this classification scheme has some minor differences from designations made by other authors (Quinn et al. 1987, Kiladis and Diaz 1989, 1992, Cayan and Webb 1992) who used somewhat different criteria for classification. For example, our classification scheme does not include the weaker El Niño years of 1923-24, 1930-31, 1932-33, 1953-54, and 1969-70 that are included in the Kiladis and Diaz (1989) classification method, but it does include the extended El Niño from 1939-41, which is given as one year in the Kiladis and Diaz (1989) listing. Similarly, a number of weaker La Niña events (1920-21, 1924-25, 1928-29, 1931-32, and 1942-43) are not classified as La Niña events by our classification method, but are listed as La Niña years by Kiladis and Diaz (1989). Regardless of which classification scheme is used, however, the trends in amounts of precipitation at the Sevilleta are the same.

The SOI-based classification scheme can be used to analyze long-term precipitation data from the long-term precipitation record at Socorro, New Mexico, a town 24 km south of the Sevilleta (Figure 2). Socorro is the nearest site to the Sevilleta with a class A weather station. An analysis of a record of 80 years, from 1914 to 1993, shows the importance of the status of the ENSO system on fall/winter/spring (October through May) precipitation in the region of the Sevilleta LTER. Precipitation from October through May increased by 53% in El Niño years. Precipitation decreased by slightly more by than half in La Niña years when compared to medial years over the past eight decades (Table 2). These differences were significant ($p < .05$) between the three classes of years for the October through May periods. Summer precipitation, which derives increasingly from moist air originating in the Gulf of Mexico, was not significantly different for the three year classes. ENSO-affected precipitation at the Sevilleta occurs primarily during the period from October to May.

Table 2. Mean annual, mean October-May and mean June-September precipitation for past 80 years (1914-1993) at Socorro, NM during El Niño, La Niña and medial years.

Precipitation - Socorro N.M. 1914-1993

ENSO Classs	N	Annual	Oct-May	Jun-Sep
		Precipitation (mm)		
El Niño	15	275.8 a	156.2 a	119.6 a
Medial	56	239.4 a	102.3 b	137.1 a
La Niña	9	162.5 b	49.9 c	112.5 a

ENSO classes with the same letters are not significantly different (p=.05).

A year-by-year summary of precipitation at Socorro, New Mexico for the period from 1914-1993 shows the overall impact of El Niño and La Niña years on seasonal and annual precipitation (Figure 3). Many of the wettest years on record are during El Niño events which yielded increased precipitation from October to May. Years with strong El Niño conditions in the Pacific Ocean, such as 1919, 1941, 1958, 1973 and 1987, were unusually wet in central New Mexico. Similarly, dry fall/winter/spring conditions prevailed in most La Niña years with a series of dry years associated with La Niña episodes grouped in the late 1940s and mid-1950s. These extended periods of drought led to significant die-back of pinyon pine (*Pinus edulis*) and juniper (*Juniperus monosperma*) at lower elevations of their extent throughout the Sevilleta (Betancourt et al. 1994).

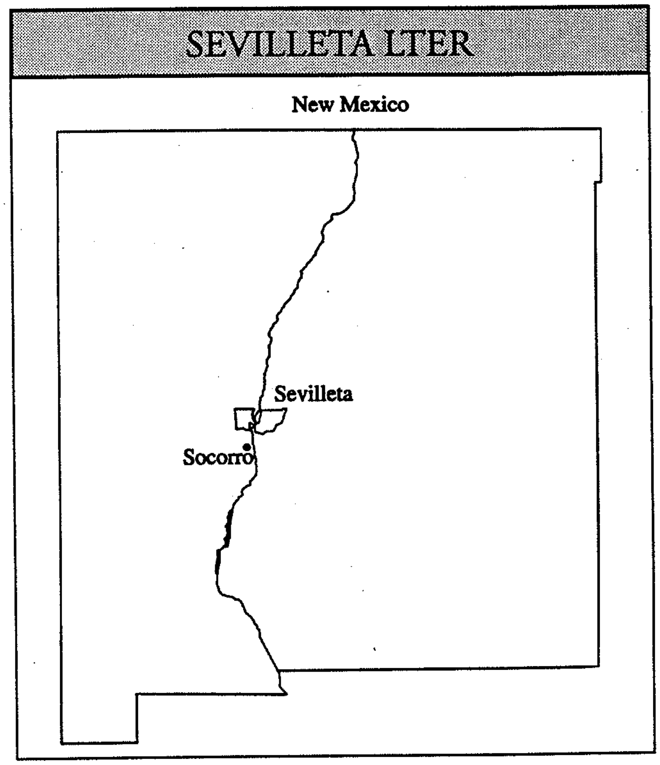


Figure 2. Map of New Mexico showing the location of Socorro and the Sevilleta National Wildlife Refuge.

Mean monthly precipitation at Socorro, New Mexico for the period from 1914-1993 further demonstrates the influence of the ENSO phenomenon on rainfall in the area of the Sevilleta (Figure 4). The El Niño years of record had mean average monthly precipitation values which were higher than medial years or La Niña years for the months from October through May. La Niña years had lower average monthly precipitation for October, November, December, February, March, May, June, and September than either medial years or El Niño years. These extended periods of lower than average or higher than average precipitation accumulate deviations from the long-term mean, which results in October-to-May precipitation of about 50% above the mean during warm events (El Niño) and 50% below the mean during cold events (La Niña).

During the first five years of the Sevilleta LTER, one La Niña (1988-89) and an extended two-year El Niño (1991-93) have occurred (Figure 5). Fall/winter/spring precipitation from a network of six weather stations on the Sevilleta ranged from a minimum average of 37 mm during the La Niña of October through May 1989 to a maximum average of 237 mm during the El Niño of early 1992 (Table 3). Mean annual precipitation has ranged from a low of 128 mm in the La Niña of 1988-1989 to a high of 372 mm in 1991-1992. High variability, especially in the fall/winter/spring period of the year, has been characteristic of the Sevilleta LTER site during the first years of research, and this variability outside of the summer monsoon period (July to September) has closely followed the SOI (Figure 5, Table 3).

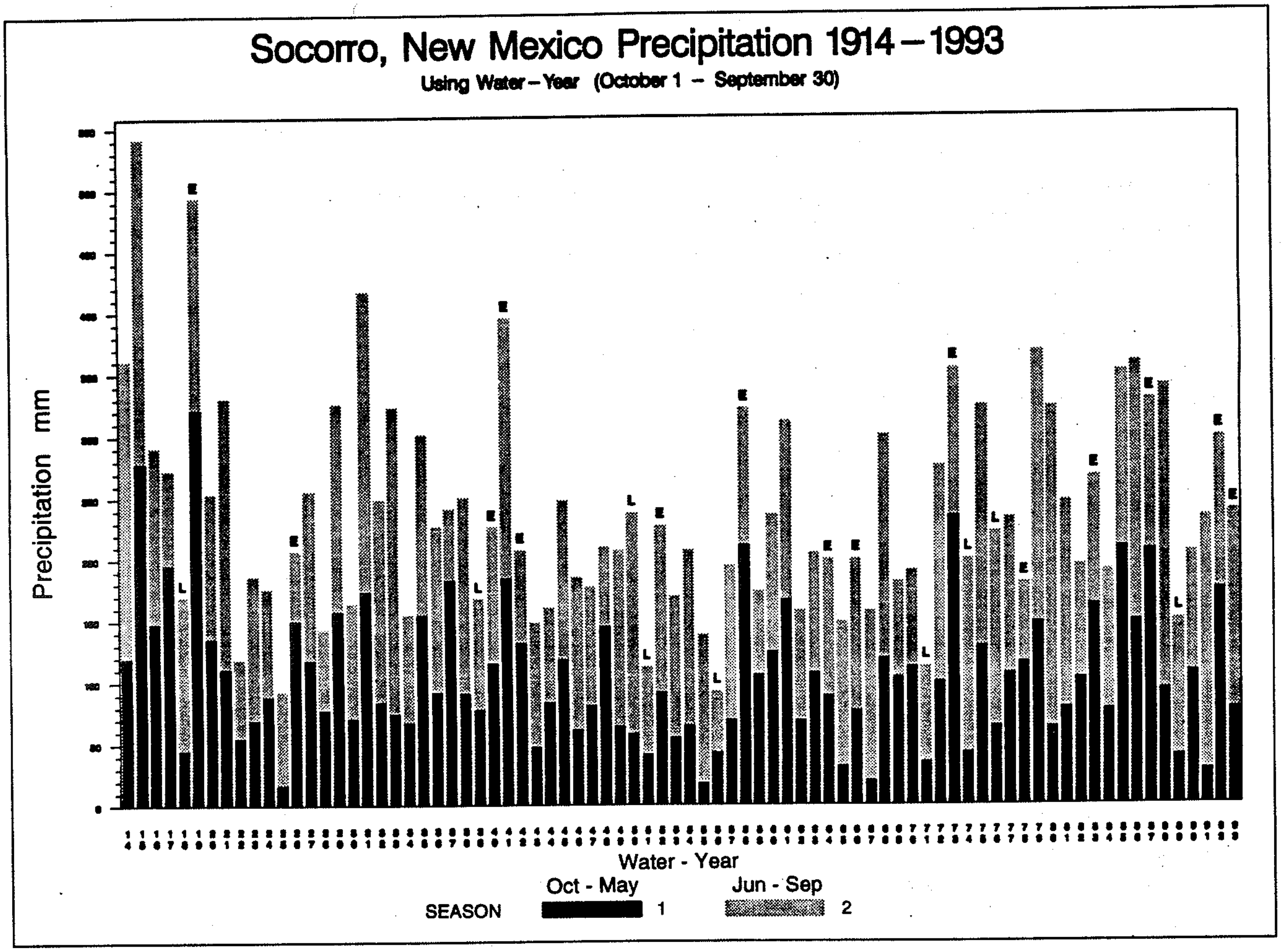
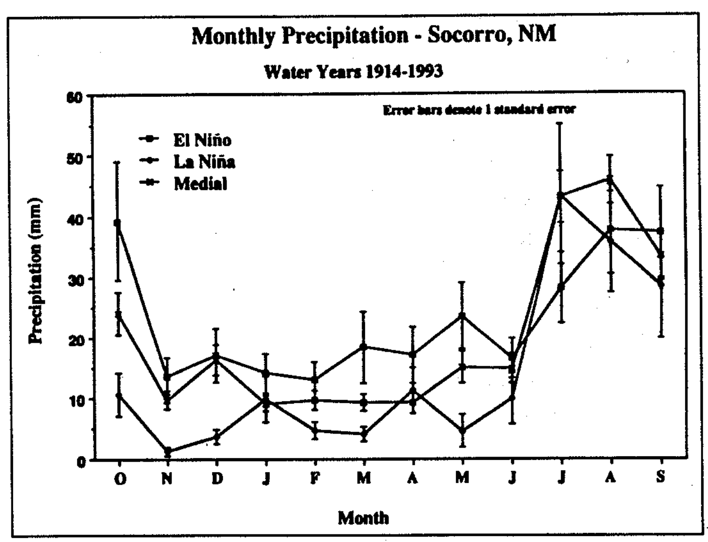


Figure 3 (above). Precipitation for Socorro, NM for 1914-1993. Season 1 includes the October of the previous year through May of the listed year. Season 2 includes summer months of July through September. El Niño and La Niña years are denoted by E and L, respectively.

Figure 4 (right). Mean monthly precipitation at Socorro, NM for 1914-1993 for El Niño, La Niña, and medial years.



Normal periods of greatest precipitation on the Sevilleta occur during the months of July and August and are associated with convective thunderstorms during the summer monsoon (Figure 3). The linkage between the ENSO phenomenon and summer precipitation in New Mexico is weak (Andrade and Sellers 1988, Molles et al. 1992). Summer precipitation is derived increasingly from moist air masses originating from the Gulf of Mexico and directed into the Southwest by the location of the Bermuda High (Mitchell 1976, Neilson 1986). The resulting precipitation is heterogeneously distributed on the landscape by thunderstorms originating over montane zones and moving over the lowlands. High spatial variability in precipitation is common and no clear links to the status of the SOI have been found at the Sevilleta during the summer monsoon period (Table 3).

Table 3. Sevilleta quarterly precipitation for water-years 1989-1993. Quarter 1 is October-December, quarter 2 is January-March, quarter 3 is April-June and quarter 4 is July-September.

Year	Quarter	Precipitation mm
1988	4	7.7*
1989	1	23.5*
1989	2	5.3
1989	3	91.4
1988-1989	Total	127.9
1989	4	38.4
1990	1	30.7
1990	2	71.3
1990	3	145.8
1989-1990	Total	286.2
1990	4	34.8
1991	1	18.1
1991	2	41.8
1991	3	159.2
1990-1991	Total	253.9
1991	4	107.9
1992	1	45.4
1992	2	83.3
1992	3	134.9
1991-1992	Total	371.5
1992	4	27.1
1993	1	43.8
1993	2	38.4
1993	3	125.7
1992-1993	Total	235.0

*Sevilleta precipitation gauge network was not completed, so averages came from one station on the Sevilleta and the Socorro station.

SUMMARY

The ENSO phenomenon has a predictable effect on the precipitation regime of the Sevilleta LTER during the period from October to May. Low SOI periods (El Niño or warm events) are generally times of enhanced precipitation relative to the long-term mean. High SOI periods (La Niña or cold events) are, predictably, times when precipitation is below the long-term average. This added variability in precipitation, which is linked to the ENSO phenomenon, is predicted to have a strong influence on the population dynamics, physiological condition, and the landscape pattern of flora and fauna at the Sevilleta LTER site. These linkages are being examined in detail as the first six years of the Sevilleta LTER site program are nearing completion.

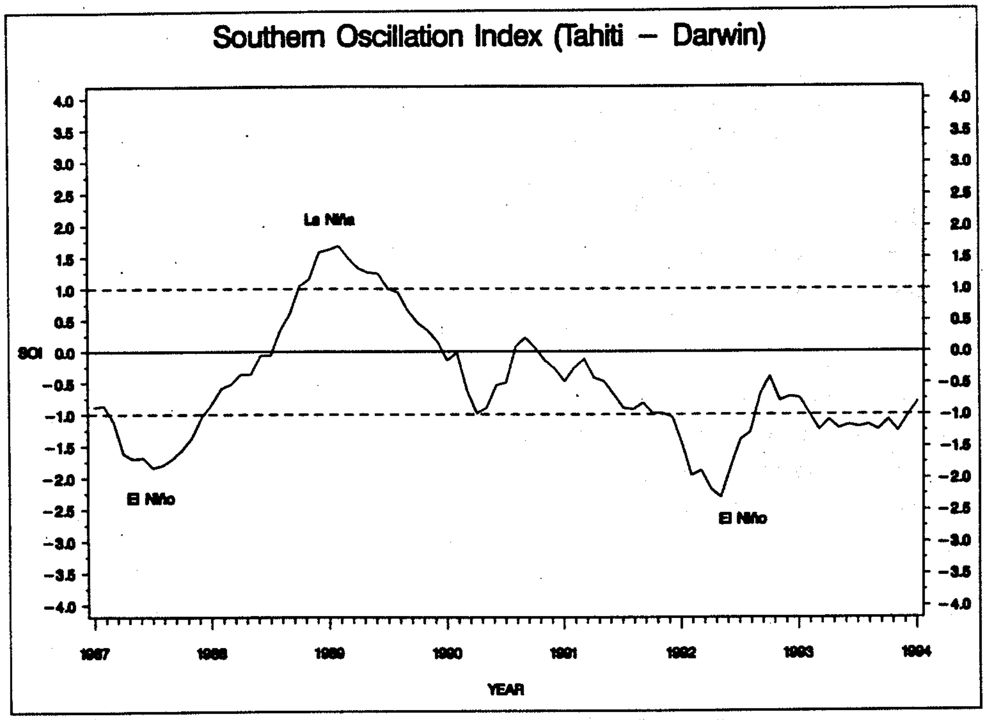


Figure 5. Southern Oscillation Index (Tahiti-Darwin).

REFERENCES

ANDRADE, E.R., and W.D. SELLERS. 1988. El Niño and its effect on precipitation in Arizona. *Journal of Climatology* 8:403-410.

BETANCOURT, J.L., E.A. PIERSON, K.A. RYLANDER, J. PARKS and J.S. DEAN. 1994. Influence of history and climate on New Mexico pinyon-juniper woodlands. *In* Managing Pinyon-Juniper Ecosystems for Sustainability and Social Needs. (*In press*).

CAYAN, D.R. and R.H. WEBB. 1992. El Niño/Southern Oscillation and streamflow in the western United States. Pages 29-68 *in* H.F. Diaz and V. Markgraf (eds.). *El Niño Historical and Paleoclimatic Aspects of the Southern Oscillation.* Cambridge University Press, Cambridge, U.K. and New York, NY. 472 pp.

CONRAD, V. 1941. The variability of precipitation. *Monthly Weather Review* 69:5-11.

DAHM, C.N. and M.C. MOLLES, JR. 1992. Streams in semiarid regions as sensitive indicators of global climate change. Pages 250-260 *in* P. Firth and S. Fisher (eds.). *Troubled Waters of the Greenhouse Earth.* Springer-Verlag, New York, NY.

ENFIELD, D.B. 1989. El Niño, past and present. *Reviews of Geophysics* 27:159-187.

KAHYA, E. and J.A. Dracup. 1993. U.S. streamflow patterns in relation to the El Niño/ Southern Oscillation. *Water Resources Research* 29:2491-2503.

KILADIS, G.N. and H.F. DIAZ. 1992. Atmospheric teleconnections associated with the extreme phases of the Southern Oscillation. Pages 7-28 *in* H.F. Diaz and V. Markgraf (eds.). *El Niño Historical and Paleoclimatic Aspects of the Southern Oscillation.* Cambridge University Press, Cambridge, U.K. and New York, NY. 472 pp.

KILADIS, G.N. and H.F. DIAZ. 1989. Global climatic anomalies associated with extremes of the Southern Oscillation. *Journal of Climate* 2:1069-1090.

MITCHELL, V.L. 1976. The regionalization of climate in the western United States. *Journal of Applied Meteorology* 15:920-927.

MOLLES, M.C., JR. and C.N. DAHM. 1990. A perspective on El Niño and La Niña: global implications for stream ecology. *Journal of the North American Benthological Society* 9:68-76.

MOLLES, M.C., JR., C.N. DAHM and M.T. CROCKER. 1992. Climatic variability and streams and rivers in semi-arid regions. Pages 197-202 *in* R.D. Robarts and M.L. Bothwell (eds.). *Aquatic Ecosystems in Semi-Arid Regions: Implications for Resource Management.* Environment Canada, Saskatoon, Canada.

NICHOLLS, N. 1988. El Niño-Southern Oscillation and rainfall variability. *Journal of Climate* 1:418-421.

NEILSON, R.P. 1986. High-resolution climatic analysis and southwest biogeography. *Science* 232:27-34.

QUINN, W.H., V.T. NEAL and S.E. ANTUNEZ DE MAYOLO. 1987. El Niño over the past four and a half centuries. *Journal of Geophysical Research* 92:14,449-14,461.

RASMUSSON, E.M. and J.M. WALLACE. 1983. Meteorological aspects of the El Niño/ Southern Oscillation. *Science* 222:1195-1202.

REDMOND, K.T. and R.W. KOCH. 1991. Surface climate and streamflow variability in the western United States and their relationship to large-scale circulation indices. *Water Resources Research* 27:2381-2399.

ROPELEWSKI, C.F. and M.S. HALPERT. 1987. Global and regional scale precipitation patterns associated with the El Niño/Southern Oscillation. *Monthly Weather Review* 115:1606-1626.

ROPELEWSKI, C.F. and M.S. HALPERT. 1986. North American precipitation and temperature patterns associated with the El Niño/Southern Oscillation (ENSO). *Monthly Weather Review* 114:2352-2362.

SWETNAM, T.W. and J.L. BETANCOURT. 1990. Fire-Southern Oscillation relations in the southwestern United States. *Science* 249:1017-1020.

A N E X T E N D E D A B S T R A C T

TREE-GROWTH RESPONSE TO ENSO EVENTS NEAR NIWOT RIDGE IN THE CENTRAL COLORADO FRONT RANGE

Connie A. Woodhouse

INTRODUCTION

The El Niño/Southern Oscillation (ENSO) has been shown to influence mid-latitude climate. In North America, El Niño is often associated with warm, dry conditions in Alaska and southern Canada and wet, cool conditions in the southern United States, with opposite conditions in La Niña years (Kiladis and Diaz 1989). In Colorado, the southern half of the state tends to experience wet springs the year following an El Niño event and dry springs the year following a La Niña event (Kiladis and Diaz 1989). The central Colorado Front Range area is north and west of the region that is consistently affected by ENSO. Past research has indicated that the El Niño signal is fairly reliable in the Denver area, although it is less consistent in Boulder, about 48 kilometers north. The La Niña signal is stronger than the El Niño signal in both Denver and Boulder (Kiladis and Diaz 1989, Kiladis pers. comm.). This suggests that the region of the central Colorado Front Range represents a transition in sensitivity to ENSO.

Research has shown that many tree species in the Front Range tend to respond to winter and spring moisture (Keinast et al. 1987), which is often influenced by ENSO events. Therefore, it is likely that patterns of tree-ring widths will reflect ENSO events. In the Front Range, an increase in tree growth would be expected to follow El Niño events (wet springs) and a decrease in growth would be expected to follow La Niña events (dry springs).

I have examined chronologies from two different sites and species in order to determine: (1) if trees in the Front Range are responding to ENSO, (2) what form the response takes, and (3) how variable the response is over time.

DATA

Tree-Ring Chronologies

Two tree-ring chronologies from the central Colorado Front Range were used for this study. The Engelmann spruce (*Picea engelmannii*) chronology, Niwot, was developed by Kienast and Schweingruber (1986). The second chronology, Island Lake, was developed from limber pine (*Pinus flexilis*) by the author. Both sites are on dry, southeast facing slopes and are at 3,400 and 3,200 meters, respectively. The Niwot chronology was obtained from the International Tree-Ring Data Bank. I developed the Island Lake chronology using standard dendrochronological techniques (Stokes and Smiley 1968, Cook and Holmes 1984, Swetnam et al. 1985). Both chronologies have had growth trends removed and are in the form of standardized indices of tree-ring widths that reflect annual variations in climate. The chronologies had significant first-order autocorrelation. Box-Jenkins ARMA models were fitted to each chronology to remove this autocorrelation (Box and Jenkins 1976). The residual series were used in the correlation analyses.

NIWOT RIDGE/GREEN LAKES VALLEY LTER

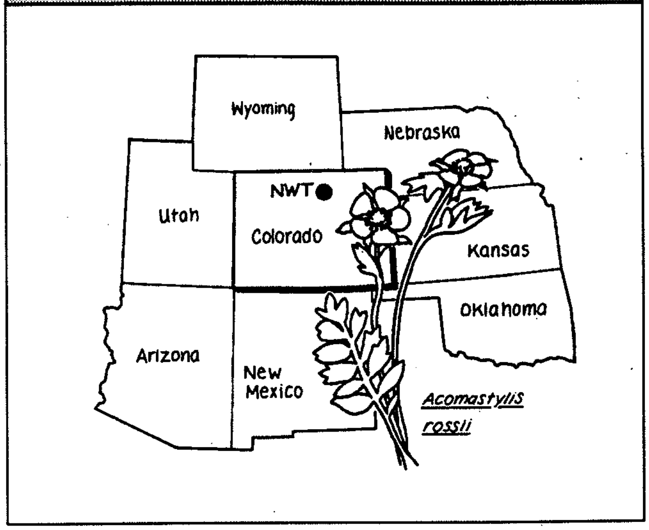


***Figure 1.** The location of the Niwot Ridge/Green Lakes Valley, Colorado LTER Site.*

Southern Oscillation Index (SOI)

I used Wright's (1989) SOI, dating from 1853 to 1984, to examine the relationship between ENSO and tree growth in the Front Range. The Wright Index, based on mean monthly pressure anomalies, is defined as the sea-level pressure at Darwin, Australia minus sea-level pressure at Tahiti. This index differs from others commonly used (Trenbarth 1976, Ropelewski and Jones 1987) in that positive values indicate El Niño events and negative values indicate La Niña events. Wright's index is divided into seasons; winter (December, January, February), spring (March, April, May), summer (June, July, August), and fall (September, October, November).

ENSO Events

Years of El Niño and La Niña events were taken primarily from Kiladis and Diaz (1989), and are based on sea surface temperatures in the eastern equatorial Pacific and Tahiti-Darwin pressure, between 1882 and 1989. Kiladis and Diaz also added the years 1877 and 1880, based on historical evidence in previous work. To document tree-growth response to events before 1877, proxy data for El Niño event years were used. These included El Niño event dates from historical accounts between 1525 and 1983 that were rated strong to very strong from Quinn et al. (1987) and El Niño events reconstructed from tree-ring chronologies in the southwestern United States and northwestern Mexico (Michaelson 1989).

Superposed epoch analysis (SEA) was used to investigate the characteristic time-dependent relationship between the occurrence of an ENSO event and the associated tree-growth response

RESEARCH STRATEGY

A variety of techniques was used to investigate the relationship between ENSO and tree growth in the Colorado Front Range. The relationships were first graphically examined with time-series plots of annual tree-ring widths and spring SOI. Chi-square tests were used to determine if a decrease in growth coincided with La Niña events and increased following El Niño events. Superposed epoch analysis (SEA) (after Lough and Fritts 1987) was used to investigate the characteristic time-dependent relationship between the occurrence of an ENSO event and the associated tree-growth response. Correlation analyses were used to investigate the statistical relationships between SOI and tree growth, for both the common period of time, 1853-1982, and for 30-year time periods, overlapped by ten years. In order to determine if ENSO events influenced extremes in tree growth, tree-ring widths were ranked and compared with ENSO event years. Finally, extremes in tree growth were compared with proxy data.

RESULTS

Details of the results may be found in Woodhouse (1993). The analysis shows relationships between SOI, Denver precipitation, and tree growth, and ENSO events, for the years concurrent with and following an event. Denver precipitation is most strongly related to conditions the year after ENSO events, especially in spring, with wet springs the year after an El

Niño and dry springs following a La Niña (Kiladis and Diaz 1989). This relationship is generally reflected in the tree-ring chronologies. The direction of the responses are the same for the Island Lake chronology as for Denver precipitation. The Niwot chronology responses are weaker and agree with Denver precipitation and the Island Lake record the year after an ENSO event.

Analysis of ENSO event years suggests that tree-ring chronology responses are more consistent for La Niña events than for El Niño events. The decrease in growth in the year following a La Niña event is likely related to the dry spring conditions that characterize a La Niña event. Trees at these sites are sensitive to a lack of precipitation, especially in winter and spring; therefore, a stronger relationship to La Niña (dry springs) than to El Niño (wet springs) events is expected. Although tree-growth response is more consistent and statistically meaningful for La Niña events, a strong tree-growth response to some El Niño events is suggested by seven of the ten widest Island Lake rings occurring within a year of an El Niño event.

Correlation results indicate that tree growth, especially at the Island site, is in phase with variations in SOI. These results are compatible with the event analyses (Chi-square and SEA), when it is understood how designated ENSO event years are related to fluctuations in winter and spring SOI. When the event years are used for analysis, the relationship with tree growth appears to be strongest the year following the calendar year that has been designated as the event year. The year of the event does not reflect the sequence of change in seasonal SOI, which is what the correlation analysis is picking up, but only reflects the year in which the event was first acknowledged, i.e., the calendar year of the third season of positive sea surface temperatures in the equatorial Pacific and SOI below -1.0 (Kiladis and Diaz 1989). Since events commonly begin to develop in the spring, summer, or fall, and last at least a year (Diaz and Kiladis 1992), the year in which the event develops is named the event year, while the greatest impact on Northern Hemisphere climate is usually the following year. The more extreme values for winter or spring SOI would occur that following year as well, which is why tree-response to event years seems to lag a year while it is in phase with the seasonal SOI values.

Analysis of ENSO event years suggests that tree-ring chronology responses are more consistent for La Niña events than for El Niño events

Analysis of the correlations of SOI with tree-ring indices in 30-year time periods indicates the tree-growth response to fluctuations in SOI has varied over time. This is likely due to the variations in strength and timing of ENSO events.

The actual response of tree growth to ENSO events may be difficult to define in statistical terms because the signal is sometimes obscured by season of event onset and by response lags. The lag between conditions in the equatorial Pacific and mid-latitude climate is variable, as well as the lag in tree-growth response to climate. The time of event onset and the calendar-year date of an event may not reflect the same year of greatest influence on tree growth. Additional clouding of the signal may be caused by a long-term effect of an event on tree growth, obscuring the effects of other events that follow closely. One final reason for a lack of complete clarity in the tree-growth response to ENSO events is related to the location of the study area. This area was selected with the knowledge that the ENSO signal reverses sign somewhere between the southern United States and southern Canada. Thus, the Front Range is a transition area and a less-than-distinct signal is not unexpected.

The time of event onset and the calendar-year date of an event may not reflect the same year of greatest influence on tree growth

CONCLUSION

The trees in this study are integrating the large-scale influence of climate into their growth patterns. This relationship may prove to be useful for determining the extent of the influence of ENSO in transitional or border areas. A record of ENSO events cannot be reconstructed from these tree-ring chronologies, but further study at additional sites north and south of this area, as well as at lower-elevation sites more sensitive to drought conditions, may yield more information about the extent of the influence of the ENSO phenomenon.

REFERENCES

BOX, G.E.P. and G.M. JENKINS. 1976. *Time Series Analysis:Forecasting and Control.* Revised edition. Holden Day:San Francisco, California.

COOK, E.R. and R.L. HOLMES. 1984. *Program ARSTND Users Manual.* Laboratory of Tree-Ring Research:University of Arizona, Tucson.

DIAZ, H.F. and G.N. KILADIS. 1992. Atmospheric teleconnections associated with the extreme phase of the Southern Oscillation. Pages 7-28 *in:* H.F. Diaz and V. Markgraf (eds.). *El Niño: Historical and Paleoclimatic Aspects of the Southern Oscillation.* Cambridge University Press: Cambridge, U.K. and New York, NY. 472 pp.

KIENAST, F. and F.H. SCHWEINGRUBER. 1986. Dendro-ecological studies in the Front Range, Colorado, U.S.A. *Arctic and Alpine Research 18*:277-288.

KEINAST, F., F.H. SCHWEINGRUBER, O.U. BRAKER and E. SCHAR. 1987. Tree-ring studies on conifers along ecological gradients and the potential of single-year analysis. *Canadian Journal of Forestry* 17:683-696.

KILADIS, G.N. and H.F. DIAZ. 1989. Global climatic anomalies associated with extremes in the Southern Oscillation. *Journal of Climate* 2:1069-1090.

LOUGH, J.M. and H.C. FRITTS. 1987. An assessment of the possible effects of volcanic eruptions on North American climate using tree-ring data, 1602-1900 AD. *Climatic Change* 10:219-239.

MICHAELSON, J. 1989. Long-period fluctuations in El Niño amplitude and frequency reconstructed from tree-rings. *In* : D.H. Peterson (ed.). *Geophysical Monograph* Vol. 55. American Geophysical Union:Washington, DC.

QUINN, W.H., V.T. NEAL and S.E. ANTUNEZ DE MAYOLO. 1987. El Niño occurrences over the past four and a half centuries. *Journal of Geophysical Research* 92:14449-14461.

ROPELEWSKI, C.F. and P.D. JONES. 1987. An extension of the Tahiti-Darwin Southern Oscillation index. *Monthly Weather Review* 115:2161-2165.

STOKES, M.A. and T.L. SMILEY. 1968. *An Introduction to Tree-Ring Dating.* Chicago: University of Chicago Press:Chicago, IL. 73 pp.

SWETNAM, T.W., M.A.THOMPSON and E.K. SUTHERLAND. 1985. Using dendrochronology to measure radial growth of defoliated trees. *USDA Forest Service Agriculture Handbook,* No. 639. USDA Forest Service, Washington, D.C. 39 pp.

TRENBARTH, K.E. 1976. Spatial and temporal variations of the Southern Oscillation. *Quarterly Journal of the Royal Meteorological Society* 102:639-653.

WOODHOUSE, C.A. 1993. Tree growth response to ENSO events in the Central Colorado Front Range. *Physical Geography* 14:417-345.

WRIGHT, P.B. 1989. Homogenized long-period Southern-Oscillation indices. *International Journal of Climatology* 9:33-54.

THE EL NIÑO PHENOMENON AT THE H.J. ANDREWS EXPERIMENTAL FOREST, OREGON

David Greenland

INTRODUCTION

The El Niño phenomenon and the Southern Oscillation, in which it is embedded, together represent one of the major factors in the world's interannual climatic variability. Often noted during El Niño events is a seesaw effect between the Southwest of the United States, which tends to be wetter and cooler than usual, and the Pacific Northwest, which tends to be anomalously drier and warmer. The discussion in this paper focuses on the Long-Term Ecological Research site of the H. J. Andrews Experimental Forest (HJA), taken to be representative of the Pacific Northwest. Elsewhere it has been shown that the site is quite representative of at least quite a large area of Oregon (Greenland, 1993). The HJA is a 6,400-ha forest of Douglas Fir, Western Hemlock, and Pacific Silver Fir located in, and typical of, the central portion of the western slope of the Cascade mountain range of Oregon. Because of the large scientific significance of the HJA, it is important to investigate the temporal variability of annual and seasonal temperature and precipitation values at the site and identify past times of anomalous climatic conditions. It is also important to establish the relationships between the climate of the HJA and key ecological processes. Within this context, this paper examines some of the potential relationships between El Niño/Southern Oscillation, decadal time-scale variation, and salmon population in the Pacific Northwest and related areas.

BACKGROUND

The El Niño/Southern Oscillation (ENSO) Phenomena

The El Niño (EN) is an unusual warming of the normally cool near-surface waters off the west coast of South America (Enfield, 1992). It is often accompanied by sea surface temperature (SST) warm anomalies off the coast of central and north America. The oceanic event of EN is usually embedded in the atmospheric phenomenon of the Southern Oscillation (SO), an oscillation in the value of the atmospheric pressure difference between the south east Pacific and the Indonesian area. This is often represented by the pressure difference between Tahiti and Darwin, Australia, which is called the Southern Oscillation Index (SOI). During "normal" conditions (and/or the opposite extreme of El Niño conditions, known as La Niña) SOI is positive while, during EN, the SOI is usually negative. Although ENSO is primarily a tropical occurrence, EN events frequently have effects in the extra tropics, such as the development in the northern hemisphere of a meridional circulation pattern called the Pacific North American (PNA) pattern (Yarnal and Diaz 1986). This can have a noteworthy effect on the climate of the HJA.

H.J. ANDREWS LTER

Figure 1. Location of the H.J. Andrews Experimental Forest, Oregon LTER site.

The Climate of the H.J. Andrews Experimental Forest

The primary meteorological station of HJA is at an elevation of 426 m (1,397 ft) at latitude 44° 15' N and longitude 122° 10' W. Bierlmaier and McKee (1989) have described the HJA climate as being wet and fairly mild in winter and warm and dry in summer. During the period 1973 to 1984, the average annual temperature was 8.5° C (47.3° F). Monthly temperatures ranged from 0.6° C (33.1° F) in January to 17.8° C (64.0° F) in July. The annual average precipitation was 2,302 mm (90.6 inches) 71% of which fell from November through March. Further details of the climatography of HJA may be found in Emmingham and Lundburg (1977, quoted by Bierlmaier and McKee 1989), Waring et al. (1978), and McKee and Bierlmaier (1987).

The Regional Climate of Oregon and the Pacific Northwest and the Importance of the Pacific Ocean

Regional climatologies of Oregon and the Pacific Northwest (PNW) have been given by Phillips (1960), Sternes (1960), the PNW River Basins Commission (1969) and Loy et al. (1976). No understanding of the climate of the PNW would be complete without reference to the seminal role played by interactions between the ocean and atmosphere in the area of the northern Pacific Ocean and, to some degree, the tropical and southern parts of the Pacific as well. Namias pioneered this concept in a long series of important papers (Namias 1969).

Depending on the data used, the Pacific Northwest is either in, or is on the southern edge of, an area having lower rainfalls when El Niños are in progress and in many of the months following the El Niño maximum

One way of approaching the importance of atmosphere-ocean interaction is by the use of teleconnective indices. Teleconnective studies are designed to investigate particular parts of the world; those studies relevant for the PNW are based on the Southern Oscillation Index (SOI), the Pacific-North American Index (PNA) and the Central North Pacific Index (CNP). These three indices exhibit a certain degree of intercorrelation (Cayan and Peterson, 1989). However, it should-be noted that the strength of the teleconnective patterns is not necessarily stable over time. Ropelewski and Halpert (1986) have shown that, depending on the data used, the PNW is either in, or is on the southern edge of, an area having lower rainfalls when El Niños are in progress and in many of the months following the El Niño maximum. The PNA index designed by Leathers et al. (1991) following Yarnal and Diaz (1986) is the one used in this study. The PNA describes the amplitude of the 700 mb flow pattern over the United States, which has a basic pattern of troughs of low pressure in the eastern Pacific and the eastern United States, and a ridge of high pressure over the Rocky Mountain cordillera. The meridional extreme of the pattern produces positive PNA values (and potentially more southwest winds over the HJA), while the zonal extreme produces negative PNA values (and potentially more west winds over the HJA). Yarnal and Diaz (1986) demonstrated how strongly positive PNA and negative (reverse) PNA patterns are associated respectively with warm and cold El Niño Southern Oscillation (ENSO) events and, in turn, with precipitation and temperature anomalies on the west coast of North America.

Cayan and Peterson (1989) designed the CNP index as being the mean sea-level pressure (SLP) over the region 35-55° N and 170° E to 150° W. They show that streamflows in the West have correlations in the range 0.3 to 0.6 with SLP anomalies in the North Pacific. During times of a weak CNP, streamflows are high in Washington and Oregon. During times of a strong CNP, the polar front jet stream flows north of the PNW and periods of below-average streamflow are observed. This is also often observed during El Niño events (Cayan and Peterson 1989, Figure 9). All of the synoptic studies indicate quite clearly the linkages which exist between SSTs and particular pressure and teleconnective patterns in the Pacific Ocean and various aspects of climate on the West Coast and in the PNW.

COMPILATION OF THE SYNTHETIC RECORD

Multiple regression analysis (Greenland 1993) was used to compile a synthetic record of the monthly values of mean temperature and total precipitation at the HJA. These were from values at the stations which had been selected as a result of the previous screening procedures. The same multiple regression program was used to produce all correlation coefficients in this paper. The analysis was performed for the calendar year, the water year, and the winter part of the water year (October to April). This method of selecting seasons has obvious practical and hydrological advantages. As might be expected, the water year and winter water year correlations carry a higher degree of accuracy than those for the calendar year.

ANALYSIS OF THE SYNTHETIC & OBSERVED RECORD

Precipitation

The precipitation record from 1911 to 1991, as represented by the total annual precipitation by water year displays considerable interannual variability. The trends represented by the five- year running mean of the same data plainly shows the prolonged and severe drought of the 1930s and the wetter years of the late 1940s and the 1950s. The record exhibits greater variability in more recent years, with two peaks of precipitation centered on 1973 and 1984 and with droughts centered on the late 1970s, one which persisted through at least 1991.

Temperature

The observed and synthetic annual mean temperature record for the HJA from 1890 to 1991 also shows considerable interannual variability. Analysis of the record in terms of five-year running means displays a warming trend between the beginning of the record and the early 1940s, punctuated by two cool periods in the early 1910s and the early 1920s, respectively.

A cool period is seen from the late 1940s to the mid-1970s with the exception of one warm year (1958). Finally, a warming trend is seen from the mid-1970s to the present time, the magnitude of which, at least up to 1991, is similar to that of the warming trend at the beginning of the century.

Step Functions

Several investigators have identified step functions in certain of the meteorological time series during the period of the modern record. Ebbesmeyer et al. (1991) have investigated a step function occurring in biogeophysical time series of the PNW and the Pacific in 1976. Leathers and Palecki (1992) have identified a step function occurring in the value of the PNA index during the late 1950s and centered approximately on 1957. The 1957 step was also noticed in records of the mean height of sea level along the West Coast (Namias 1972). An analysis was performed to investigate whether such steps exist in the climatic data for the HJA Forest (Greenland 1993).

It was concluded that there is evidence in the HJA Forest record for the 1976 step but not for the PNA-related 1957 step. However, when we interpret the Andrews record in terms of pre- and post-1976 values, it is clear that the year 1976 was a marked turning point at the HJA for both temperature and precipitation. For approximately 15 years prior to 1976 the annual temperature trend had been downward. Since that time the annual temperature trend has been upward. In absolute terms, the 1977 water year (which includes the winter of 1976-77) had the lowest precipitation values in the entire record with generally higher values both before 1977 and after it (1976 was an El Niño year). The five-year running mean of these data places the turning point two years later. Clearly the atmosphere changed to a different mode of operation in the mid-1970s; this change is well represented in the HJA data, as well as that of many other parts of the PNW.

THE REGIONAL CONTEXT

PNA & CNP Indices

Correlations were made between the HJA data and the PNA and the CNP indices for the period 1948 to 1987. The results (Table 1), in the context of this kind of synoptic climatological analysis, indicate quite high correlations between HJA winter water year precipitation and both indices. Precipitation at the HJA for January, representing the winter months, also displays a weak but significant correlation with both indices. No relationships are seen for July, representing the summer months, or for the calendar year totals of precipitation. Annual and January mean values of temperature exhibit a very strong correlation with the CNP index. The relationship of January mean temperatures to the PNA index is also very strong, while the relationships for the year and for July are not so strong but are nevertheless significant.

Table 1. Correlation coefficient values between Annual, January and July mean temperature and precipitation totals at the HJA and selected general circulation indices for the period 1948-1987.

Precipitation		Annual or Winter Water Yr.		Jan		July	
Variable Regressed Against		r^2	Sig Level %	r^2	Sig Level %	r^2	Sig Level %
PNA	Annual	0.08	<95				
	Winter Water Yr.	0.25	99				
PNA				0.16	95	0.00	<95
CNP	Annual	0.04	<95				
	Winter Water Yr.	0.17	99				
CNP				0.10	95	0.06	<95
CNP	Annual (1914-1990)	0.03	<95				
	Winter Water Yr. (1914-90)	0.21	99				
CNP	(1914-1990)			0.11	99	0.03	<95
Temperature		Annual		Jan		July	
Variable Regressed Against		r^2	Sig Level %	r^2	Sig Level %	r^2	Sig Level %
PNA		0.12	95	0.40	99	0.11	95
CNP		0.45	99	0.40	99	0.04	<95
CNP (1910-1990)		0.44	99	0.31	99	0.05	95

Physically, when the PNA index is positive and high, a meridional circulation in the westerlies with a ridge of high pressure shunts storms to the north of Oregon (and the HJA) giving rise to relatively dry weather. This situation also brings in warm air with relatively high temperatures from the southwest. When the PNA index is negative, the zonal circulation in the westerlies brings in storms from the Pacific Ocean giving rise to wetter weather and rather lower air temperatures. These interpretations are also consistent with the CNP values which, when low, indicate that a well-developed Aleutian low-pressure zone will guide storms northward to British Columbia but, when high, will allow storms to travel more directly eastward into Washington and Oregon.

CNP values, when low, indicate that a well-developed Aleutian low-pressure zone will guide storms northward to British Columbia but, when high, will allow storms to travel more directly eastward into Washington and Oregon

SOI Index

A direct comparison of winter water year HJA values and SOI values suggests a relationship in which low SOI values (warm event, El Niño years) tend to be associated with low precipitation values and high SOI values (cold event, La Niña years) tend to be associated with high precipitation values at the HJA. The relationship is clear, although it is not very strong statistically (r^2=0.14, significant at 99%). The 1983 year, which had an extraordinary strong low SOI value, is a noteworthy outlier on the scattergram. Without the 1983 value the relationship is stronger (r^2= 0.23 significant at 99%). A similar, though stronger and reversed, relationship exists on an annual time scale between the SOI values and the annual mean temperature at the HJA Forest (with the inclusion of the 1983 data point r^2=0.24, significant at 99%).

An examination of HJA climate values for extreme SOI years sheds further light on this issue. Yarnal and Diaz identified a number of warm (El Niño) and cold (La Niña) event winters (December, January and February). During warm- event winters, HJA precipitation is near average at 0.03 SD of the long-term (1914-1991) mean and the temperature is well above (0.77 SD) the long-term (1890-1991) mean. During cold event winters, HJA precipitation is well above (0.69 SD) the long-term mean and temperature is below it (-0.33 SD). Halpert and Ropelewski (1992) defined warm event years as those in which the SOI index value remained in the lower 25% of the distribution for five months or longer and similarly defined cold events years by using the upper 25% of the distribution. By these definitions, at the HJA during warm event years, the annual precipitation is near the long-term mean (-0.02 SD), and the winter water year precipitation is slightly above the long-term mean (0.15 SD), but the following winter water year is markedly below the long-term mean (-0.32 SD). Also during warm event years, HJA temperatures are well above the long-term mean (0.45 SD). During cold event years, HJA annual precipitation is well above the long-term mean (0.48 SD), although the winter water year precipitation is near the long-term mean (-0.05 SD). Most striking, however, is that during cold event years the following winter water year is 0.88 SD above the long-term mean. Also, during the cold event years the annual mean temperature is notably below (-0.37 SD) the long-term mean.

Thus, it seems there are definite relationships such that during many warm events (El Niño years) the winter water year precipitation at the HJA Forest is relatively low and the annual mean temperatures are relatively high. During cold events (La Niña years), the winter water year precipitation at the HJA Forest is relatively high, especially in the winter water year following a calendar year with a cold event, and the annual mean temperatures are relatively low. These findings are consistent with those of Yarnal and Diaz (1986) and Redmond and Koch (1991). The latter noted for the PNW as a whole that precipitation is low and temperature is high during low SOI values with the opposite also being true. Interestingly, they found that the relationship tended to be strongest in the mountainous climate divisions. They point out that a combination of low precipitation and high temperature values implies a smaller than average snowpack during El Niño years.

With one exception, there were no significant correlations in either precipitation or temperature when the data were lagged at monthly intervals. The exception was a weak relationship between HJA January precipitation and the SOI value of the previous March ($r^2 = 0.10$ significant at 95%). The relationship is interesting enough to pursue at a later time using seasonal as opposed to monthly data.

SALMON POPULATION

While salmon population sizes are affected by many non-climatic influences, they also seem to be affected by climate on at least two times scales

Salmon population sizes are affected by climate on at least two times scales. The decadal time scale exhibits a relationship between the size of salmon catch and air and water temperature. The interannual scale shows the effects of El Niño events such that salmon catch is often relatively low during and after the events. Occurrences on the shorter scale are superimposed on those of the larger scale and events on the two scales are probably interrelated. In addition, salmon population sizes are affected by many non-climatic influences such as those related to human activity.

General and Decadal Climatic Effects

Salmon are affected by climate both when they are in the river part of their life cycle and when they are in the ocean part. While salmon are young, colder river water temperature slows down growth and warmer water accelerates growth (Netboy 1991). However, a temperature increase in rivers generally reduces survival because it could increase disease and fungal attacks in adults. It could also retard spawning to the point that the juvenile salmon are unprepared for marine life when it is time for them to move to sea (Neitzel et al. 1991). In the ocean, survival of hatchery smolts is greater in years of strong upwelling (which tends to be related to colder water) compared to years of weak upwelling (Pearcy 1992). The latter type of years are more often associated with El Niño conditions. The inverse relationship of warmer climate and decreased salmonids may hold up on the long time scale of the Holocene. There is limited evidence suggesting that during the Hypsithermal period of the Holocene salmon were less plentiful in the PNW (Neitzel et al. 1991). Besides being affected by temperature, a lack of water in the rivers can negatively impact suitable habitat availability. Consequently, a time of long-term drought such as in the mid- and late 1980s also has the potential to decrease salmon population size on the decadal time scale. Sharp (1992) claims that local populations of salmon throughout the western continental United States have suffered from drought recently. He uses the period 1976 to 1991 to define "recently." We may note that 1976 was the year of the step function in biophysical data series from the PNW.

It is not necessarily the colder water that affects the ocean salmon, but the related availability or non-availability of food resources, particularly zooplankton

It is not necessarily the colder water that affects the ocean salmon, but the related availability or non-availability of food resources, particularly zooplankton. The food resources, in turn, are affected by changes in ocean current location and areas of up- and downwelling. Such changes on the decadal time scale have been shown to be vitally important by Francis and Sibley (1991). Using data from 1925 to 1985, they clearly demonstrate a long-term direct association between air and water temperature and Alaskan Pink Salmon catches in the Gulf of Alaska. They also show an inverse relation between Pink Salmon catches in Alaska and Coho salmon catches off the coast of Washington and Oregon. The latter relation might be due to competition but it can also be explained by the north or south movement of the divergence (or bifurcation) zone between the Alaskan and California current and the greater or lesser affect of the currents related to that north-south movement. Hollowed and Wooster (1991) and Francis (1993) suggested an atmospheric model (symbolized here after the authors as HWF) in order to explain these conditions. The model is bimodal. That is to say, when the divergence zone (or bifurcation) is more to the north (HWF Type A) more cold subarctic current water can be brought into the Californian current and upwelling of nutrient-rich water is enhanced. But when the divergence point (or bifurcation) is further to the south (HWF Type B), more subarctic current water is taken into the Alaskan current and water off the Washington and Oregon coasts will be warmer. Type A is associated with a high CNP value, while Type B is associated with a low CNP value.

The model, if true, because of its foundation on air flow implicit with PNA and CNP indices, also explains the strong inverse relation found between annual temperatures at the HJA and the catch of Coho salmon off the coast of Washington and Oregon (Figure 2). There are also links between the interannual and the interdecadal time scales. Francis (1993) notes, for example, that Hollowed and Wooster have pointed out that the switch from the type A to the type B state has always occurred at the time of significant EN events.

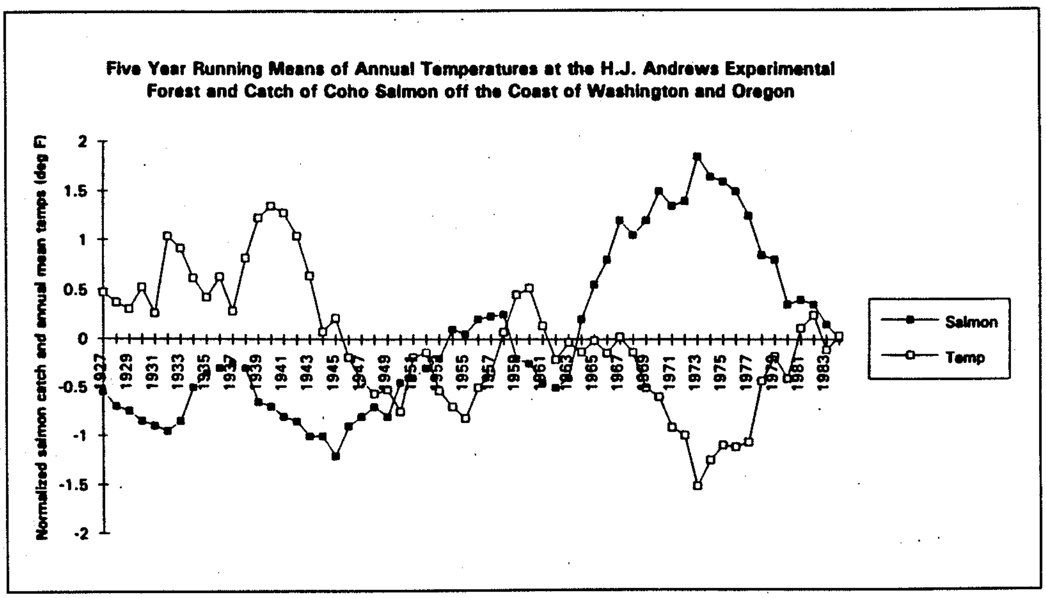


Figure 2. Five-year running means of annual temperatures at the Andrews Forest and the catch of Coho salmon off the coast of Oregon and Washington.

The Interannual Scale-El Niño Events

El Niño occurrences can impact salmon populations by providing anomalously warmer water and suppressing the upwelling which can provide nutrients. It should be noted, however, that no two EN events are identical and some are more pronounced than others. The 1982-83 EN event was a particularly strong one.

During the 1982-83 EN, salmon in the PNW appeared to be stalled in the estuaries because of the warmer water in the ocean (Rosemary 1993). The salmon in the estuaries were subject to disease and predation, which decreased the population. Also, reduced primary productivity off the coast impacted both juvenile and adult coho salmon (Pearcy 1992). During this EN event, 58% of the number of adults predicted to return actually died in the ocean. The same EN markedly decreased growth and fecundity of the salmon of that year. Warm ocean temperatures off the Oregon coast shifted the center of distribution of juvenile coho northwards to the coast of Washington.

There is evidence that the 1957-58 northern El Niño negatively affected salmon, giving rise in 1960 to the lowest ocean landings of adults since 1917

There is evidence that the 1957-58 northern EN also negatively affected salmon, giving rise in 1960 to the lowest ocean landings of adults since 1917 (Pearcy 1992). In addition, the lingering 1991-92 EN has also negatively affected salmon catch (Finley 1993). Indeed, it has been established that years just following EN event years generally tend to be years of low coho catches (Miller and Fluharty 1992).

Events on a decadal scale are comprised of events on shorter time scales. Thus, it is no surprise that the changing location of eastern North Pacific ocean current bifurcation is also seen on the interannual scale at the extremes of EN or LN. A northwards or southwards shift of the locus of bifurcation acts on salmon catch through the amount of zooplankton transported by the California current. Increased southward transport by the current is associated with increased zooplankton biomass. But during El Niño years the subarctic boundary may be shifted further to the south, and decreases in transport lead to low biomass and less food for juvenile salmon (Pearcy quoting Roesler and Chelton 1987). During such years, the divergence point between the California current and the Alaska current is to the south of its "usual" position and subarctic influence into the California current is decreased. In addition, the Aleutian low intensifies during the winter (presumably giving rise to low CNP and high PNA values) "producing a strong cyclonic circulation in the Gulf of Alaska that pushes warm water towards the coasts of Oregon and Washington" (Emery and Hamilton 1985). The reverse happens during LN years (Pearcy 1992).

CONCLUSION

The climate of the HJA is well coupled with hemispheric scale events in winter. This coupling has important implications for the climate of the HJA one or two, or possibly more, seasons ahead, thus allowing a new dimension in planning ecological experiments. An example of such coupling is manifested in the effect of climate on salmon numbers in the PNW. These numbers seem to be strongly controlled by EN events on the interannual scale and by air and ocean temperature on the decadal scale. The salmon population variation and its relation to climate is complex and deserves considerably more attention.

Acknowledgments

This study has been greatly benefited by the help and encouragement of Dr. Fred Swanson. Funding was provided in part by the U.S.D.A. Forest Service, Pacific Northwest Research Station, Cooperative Agreement No. PNW 92-0221. Data sets for the H.J. Andrews Forest were provided by the Forest Science Data Bank, a partnership between the Department of Forest Science, Oregon State University, and the U.S. Forest Service Pacific Northwest Research Station, Corvallis, Oregon. Funding for these data was provided by the Long-Term Ecological Research (LTER) Program and other National Science Foundation (NSF) programs (DEB-7611978, BSR-9011663), Oregon State University, and the U.S. Forest Service Pacific Northwest Research Station. The aid of Mr. Don Henshaw is appreciated in the provision of these data sets. Data sets for NWS stations in Oregon were provided by the Oregon Climate Service through the courtesy of the State Climatologist, Mr. George Taylor. Assistance or data were also provided by Dr. D. Leathers, Dr. R. Cerveny, Mr. Brian May and Mr. J.B. Fisher. I am grateful to Dr. Stanley Gregory for initially bringing to my attention the relation between the climate of the HJA and salmon populations.

REFERENCES

FRANCIS, R.C. 1993. Climate change and salmonid production in the North Pacific Ocean. *In:* Proceedings of the Ninth Annual Pacific Climate (PACLIM) Workshop. California Department of Water Resources, Interagency Ecological Studies Program, Tech. Rept. No. 34.

FRANCIS, R.C. and T.H. SIBLEY. 1991. Climate change and fisheries: What are the real issues? *The Northwest Environmental Journal* 7:295-307.

FINLEY, C. 1993. Low coho return may halt '94 ocean season. *The Oregonian,* November 18.

FRANKLIN, J.F., C.S. BLEDSOE and J.T. CALLAHAN. 1990. Contributions of the Long-Term Ecological Research Program. *BioScience* 40(7):509-523.

GREENLAND, D. 1993. Regional context of the climate of the H.J. Andrews Experimental Forest, Oregon. Pages 1-17 *in:* K.T. Redmond and V.L. Tharp (eds). *Proceedings of the Tenth Annual Pacific Climate (PACLIM) Workshop, April 4-7, 1993.* California Department of Water Resources, Interagency Ecological Studies Program, Tech. Rept. No. 36.

HALPERT, M.S. and C.F. ROPELEWSKI. 1992. Surface temperature patterns associated with the Southern Oscillation. *Journal of Climate* 5:577-593.

HOLLOWED, A.B. and W.S. WOOSTER. 1991. Year class variability of marine fishes and winter ocean conditions in the Northeast Pacific Ocean. ICES Variability Symposium. Paper No. 33. Session 3.

JOHNSON, D.M. and J.O. DART. 1982. *Variability of Precipitation in the Pacific Northwest: Spatial and Temporal Characteristics.* Water Resources Research Institute:Oregon State University, Corvallis, OR, USA. WRRI-77. 181 pp.

LEATHERS, D.J., B. YARNAL and M.A. PALECKI. 1991. The Pacific/North American teleconnection pattern and United States climate. Part I: Regional temperature and precipitation associations. *Journal of Climate* 4(5):517-528.

LEATHERS, D.J. and M.A. PALECKI. 1992. The Pacific/North American teleconnection pattern and the United States climate. Part II: Temporal Characteristics and index specification. *Journal of Climate* 5:707-716.

LOY, W.G., S. ALLAN and C.P. PATTON. 1976. *Atlas of Oregon.* University of Oregon Press: Eugene, OR, USA. 215 pp.

MCKEE, A. and F. BIERLMAIER. 1987. H.J. Andrews Experimental Forest, Oregon. Pages 11-17 *in: D. Greenland (ed). The Climates of the Long-Term Ecological Research Sites.* Institute of Arctic and Alpine Research. University of Colorado. Occasional Paper No 44.

MCKEE, A., G.M. STONEDAHL, J.F. FRANKLIN and F.J. SWANSON. 1987. *Research Publications of the H.J. Andrews Experimental Forest, Cascade Range, Oregon, 1948 to 1986.* General Technical Report. PNW-GWT-201. U.S. Department of Agriculture Forest Service, Pacific Northwest Research Station, Portland, OR, USA. 74 pp.

MILLER, K.A. and D.L. FLUHARTY. 1992. El Niño and Variability in the Northeaster Pacific Salmon industry: implications for coping with climate change. Pages 49-88 *in:* M.H. Glantz (ed.). *Climate Variability, Climate Change and Fisheries.* Cambridge University Press:Cambridge, U.K. and New York, NY. 450 pp.

NAMIAS, J. 1969. Seasonal interactions between the North Pacific Ocean and the atmosphere during the 1960s. *Monthly Weather Review* 97(3):173-192.

NETBOY, A. 1980. *The Columbia River Salmon and Steelhead Trout: Their Fight for Survival.* University of Washington Press:Seattle, WA, USA.

NEITZEL, D.A., M.J. SCOTT, S.A. SHANKLE and J.C. CHATTERS. 1991. The effect of climatic change on stream environments: The salmonid resource of the Columbia river basin. *The Northwest Environmental Journal* 7:271-293.

PACIFIC NORTHWEST RIVERS COMMISSION. 1969. *Climatological Handbook of the Columbia Basin States.* 3 vols. Private publication by the Pacific Northwest Rivers Commission.

PEARCY, W.G. 1992. *Ocean Ecology of North Pacific Salmonids.* University of Washington Press: Seattle, WA, USA.

PHILLIPS, E.L. 1960. Climates of the States No. 60-45: Washington. Pages 1042-1049 *in: Climates of the States.* Vol 2. Gale Research Company:Detroit, MI, USA.

REDMOND, K.T. 1985. An inventory of climate data for the state of Oregon. Report SCP-3. Office of the State Climatologist. Climatic Research Institute:Oregon State University, Corvallis, OR, USA. 160 pp.

REDMOND, K.T. and R.W. KOCH. 1991. Climate and streamflow variability in the western United States and their relationship to large-scale circulation indices. *Water Resources Research* 27(9):2381-2399.

ROPELEWSKI, C.F. and M.S. HALPERT. 1986. North American precipitation and temperature patterns associated with the El Niño/Southern Oscillation (ENSO). *Monthly Weather Review* 114:2352-2362.

ROSEMARY, K. 1993. El Niño's action may be portent of wetter, colder '93/'94 winter. *The Oregonian.* Feb 18, Section D8.

SHARP, G. 1992. Fishery catch records, El Niño/Southern Oscillation, and longer term climate change as inferred from fish remains in marine sediments. Pages 379-417 *in*: H.F. Diaz and V. Markgraf (eds). *El Niño: Historical and Paleoclimate Aspects of the Southern Oscillation.* Cambridge University Press: Cambridge, U.K. and New York, NY. 472 pp.

STERNES, G.L. 1960. Climates of the States No. 60-35: Oregon. Pages 806-811 *in: Climates of the States.* Vol 2. Gale Research Company:Detroit, MI, USA.

WARING, R.H., H.R. HOLBO, R.P. BUEB and R.L. FREDRIKSEN. 1978. Documentation of meteorological data from the Coniferous Forest Biome primary station in Oregon. General Technical Report. PNW-73. U.S. Department of Agriculture Forest Service, Pacific Northwest Research Station, Portland, OR, USA. 23 pp.

WIGLEY, T.M.L., P.D. JONES, K.R. BIFFRA and G. SMITH. 1990. Obtaining sub-grid scale information from coarse-resolution General Circulation Model output. *Journal of Geophysical Research* 95(D2):1943-1953.

YARNAL, B. and H.F. DIAZ. 1986. Relationships between extremes of the Southern Oscillation and the winter climate of the Anglo-American Pacific Coast. *Journal of Climatology* 6:197-219.

IMPACT OF EL NIÑO ON KONZA PRAIRIE RESEARCH NATURAL AREA

John M. Briggs

Historical records have revealed little impact of El Niño on climate in the midwestern United States. D'Arrigo and Jacoby (1992) correlated winter Southern Oscillation Index (SOI) and tree-ring chronologies in Mexico and the southern United States from the period of 1866 to 1900 to examine the nature of El Niño Southern Oscillation (ENSO) influence on tree growth. Three of their sites were in southeast Kansas, about 200 km from the Konza Prairie Research Natural Area (RNA). Their analysis revealed a weak, negative relationship between winter SOI and tree growth in southeast Kansas.

To examine the relationship between SOI and precipitation at Konza Prairie, we used Spearman correlation analysis. Precipitation records from 1858 are available from Manhattan, Kansas (about12 km from Konza Prairie RNA). On a monthly basis, only February precipitation and February SOI were significantly correlated ($rs = -0.31$; $p = 0.0019$). On a growing season basis, (April to September) no relationship was detected ($rs = 0.25$; $p = 0.19$), nor was there any significant relationship found using yearly time steps ($rs = 0.02$; $p = 0.83$).

Finally, we conducted a Time Series Analysis (ARIMA) at monthly, growing season and yearly intervals. At best, there appeared to be a weak and non-significant ($p=0.42$) four- to five-year time lag in the growing season precipitation and SOI values.

Thus, based upon this analyses, we conclude that El Niño events have little impact on our weather or biotic systems.

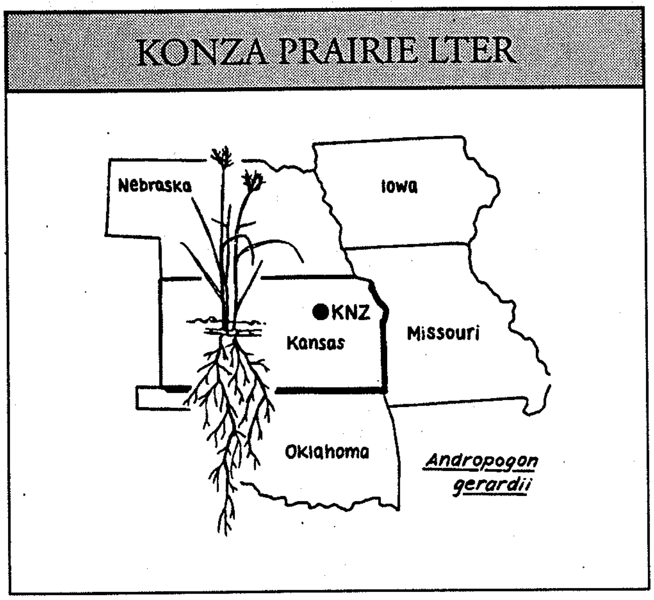


Figure 1. Location of the Konza Prairie, Kansas LTER site.

REFERENCE

D'ARRIGO, R.D. and G.C. JACOBY. 1992. A tree-ring reconstruction of New Mexico winter precipitation and its relation to El Niño/Southern Oscillation events. Pages 243-257 *in:* H.F. Diaz and V. Markgraf (eds). *El Niño: Historical and Paleoclimatic Aspects of the Southern Oscillation.* Cambridge University Press: Cambridge, U.K. and New York, NY. 472 pp.

RELATIONS BETWEEN EL NIÑO/SOUTHERN OSCILLATION EVENTS & THE CLIMATE AND ICE COVER OF LAKES IN WISCONSIN

Dale M. Robertson, Wendy Anderson & John J. Magnuson

INTRODUCTION

The term El Niño refers to the anomalous warming of the surface water of the equatorial Pacific Ocean, which occurs every two to seven years (Mysak 1986). Closely connected with the phenomenon is the Southern Oscillation, which refers to the seesawing of atmospheric pressure between the southeastern and western tropical Pacific Ocean (Rasmusson and Carpenter 1982). El Niño events have been shown to consistently occur when atmospheric pressure is unusually high over the western Pacific and unusually low over the southeastern Pacific. Collectively, these two phenomena have been referred to as *ENSO events*.Unusual climatic conditions near the tropics have been shown to be directly associated with ENSO events: warmer and wetter than normal in Peru and Ecuador and drier than normal in Australia and Indonesia (Quinn et al. 1978, Mysak 1986). Climatic anomalies in North America include unusually warm winters in southwestern Canada (Rasmusson and Wallace 1983) and usually cool and wet conditions in the southeastern United States (Mysak 1986), especially in the winter (Barnett 1981). Little or no correlation was found between ENSO events and unusual climatic conditions in the central region of the United States (Barnett 1981, Ramage 1986). Most of the climatic anomalies, especially in North America, have been found in the mature phase of the ENSO event (Year 1 used later), when sea-surface temperatures in the Pacific are most unusually warm and when the ocean is providing energy into the atmosphere (Barnett 1981).

The anomalous atmospheric conditions in the Pacific Ocean during ENSO events propagate unusual atmospheric conditions into extra-tropical areas which, in turn, lead to the unusual climatic conditions described above for North America (Barnett 1981, Rogers 1984, Mysak 1986). This indirect influence on downstream climatic patterns has been referred to as the Pacific/North American (PNA) teleconnection pattern (Horel and Wallace 1981).

Ice-cover records represent an integration of winter weather conditions—the period during which teleconnections have been hypothesized and found to be strongest (Robertson 1989). Consistent climatic anomalies have been demonstrated by unusual ice durations in Lake Mendota, Wisconsin during ENSO events from 1940 to 1988, primarily caused by unusually early ice breakup associated with usually warm late-winter air temperatures (Robertson 1989). However, winter air temperatures (from 1900 to 1983) in Illinois, just south of Lake Mendota, revealed no relationship with ENSO events. Barnett (1981) has suggested teleconnectic patterns which would result in the differences found by Robertson (1989), finding relationships between ENSO events and climatic anomalies along the west coast, the southeastern United States, the northern tier states and southern Canada, but no relationship in the central part of the United States. However, other studies have suggested little or no relationship should be found for areas near Wisconsin (Rogers 1984).

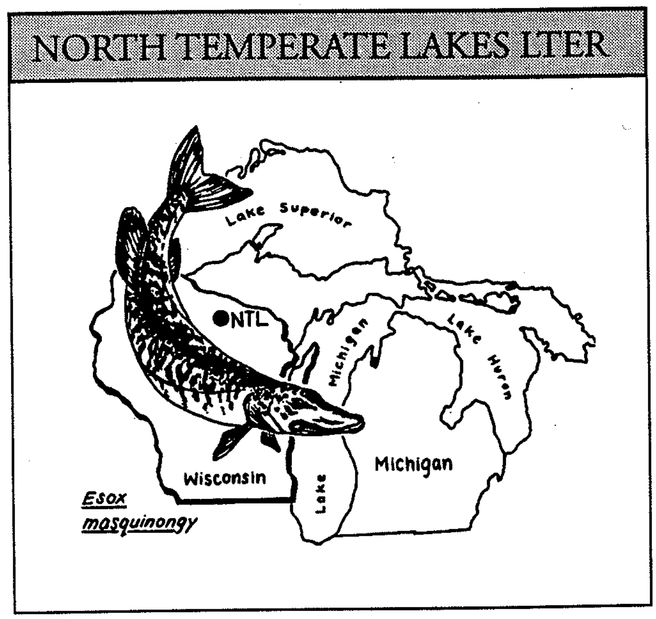


Figure 1. Map showing location of the North Temperate Lakes, Wisconsin LTER site.

In this paper, we examine ice breakup and air temperature data from lakes across Wisconsin, from 1968 to 1988, to determine if the climatic anomalies demonstrated by the ice cover and air temperature data for Lake Mendota are indicative of a consistent regional response to ENSO events. Monthly air temperature data are then examined in detail to describe why a difference in ice breakup occurs in lakes throughout Wisconsin in response to ENSO events. Some of the potential ecological effects of an earlier than usual break up of ice are also discussed.

STUDY AREA & METHODS

Breakup dates from 1968 to 1988 for 20 lakes located throughout Wisconsin were obtained from the Wisconsin State Climatologist, Northeast Wisconsin Audubon Society, Devils Lake State Park, Wisconsin Phenological Society, and from various local newspapers. These lakes were primarily located in the northern and southern thirds of the state, and therefore referred to as northern and southern lakes. All of the breakup data (for each lake, for each ENSO) were standardized by subtracting the mean breakup date for the five years surrounding the specified ENSO event. This allowed the comparison of the annual differences that occur among lakes with

Table 1. Three-way Analysis of Variance between breakup dates and inter-year, region, and inter-ENSO factors for five El Niños between 1968 and 1988.

Factor	Degrees of Freedom Error	Mean Square	F-Value	P-value
Inter-year	4	2313.8	125.6	0.0001
Region	1	0.3	0.0	0.8990
Inter-ENSO	4	1.2	0.0	0.9926
Inter-year * Inter-ENSO	16	629.7	34.2	0.0001
Inter-year * Region	4	479.1	26.0	0.0001
Region * Inter-ENSO	4	1.0	0.1	0.9947
Inter-year * Inter-ENSO * Region	16	203.0	11.0	0.0001

Table 2. Two-way Analysis of Variance between ENSO year and breakup dates, March air temperatures, April air temperatures, and total winter snowfall for northern and southern lakes for five El Niños between 1968 and 1988.

Factor	P-value North	P-value South
Breakup Date	0.0001	0.0001
March Air Temperature	0.0015	0.0941
April Air Temperature	0.8649	0.8500
Winter Snow	0.8740	0.8893

different average breakup dates and during a period with possible climatic changes (Robertson 1989). During the period from 1968 to 1988, five moderate to strong El Niños occurred with onset years of 1965, 1972, 1976, 1982, and 1986 (Quinn et al. 1978, Robertson 1989).

Air temperature data were obtained for two cities in Wisconsin: Madison and Minocqua (the latter being represented by the Minocqua Dam observing station). Data from Madison, located in south-central Wisconsin, were used to represent the southern lakes and data from Minocqua Dam, located in north-central Wisconsin, were used to represent the northern lakes. Minocqua Dam is located approximately 20 km south of Trout Lake, the site of the North Temperate Lakes Long-Term Ecological Research site.

A three-way analysis of variance (ANOVA) was used to test whether statistically significant differences in ice breakup occurred in any year within an ENSO cycle (inter-year effect), among ENSO events (inter-ENSO effect), and/or within the state, i.e., northern versus southern lakes (regional effect). A two-way ANOVA was performed to determine whether statistically significant differences in monthly air temperatures occurred in any year within an

ENSO cycle (inter-year effect). If the inter-year effect was significant, a Fisher's protected LSD student t-test was used to determine which of the years were significantly different. Composite-event graphs, created by averaging the standardized breakup dates for each five-year sequence immediately surrounding the onset year of the El Niño (Year 0), are used to demonstrate the average conditions that occur just prior to, during, and following the onset of the El Niño (i.e., a superposed epoch analysis).

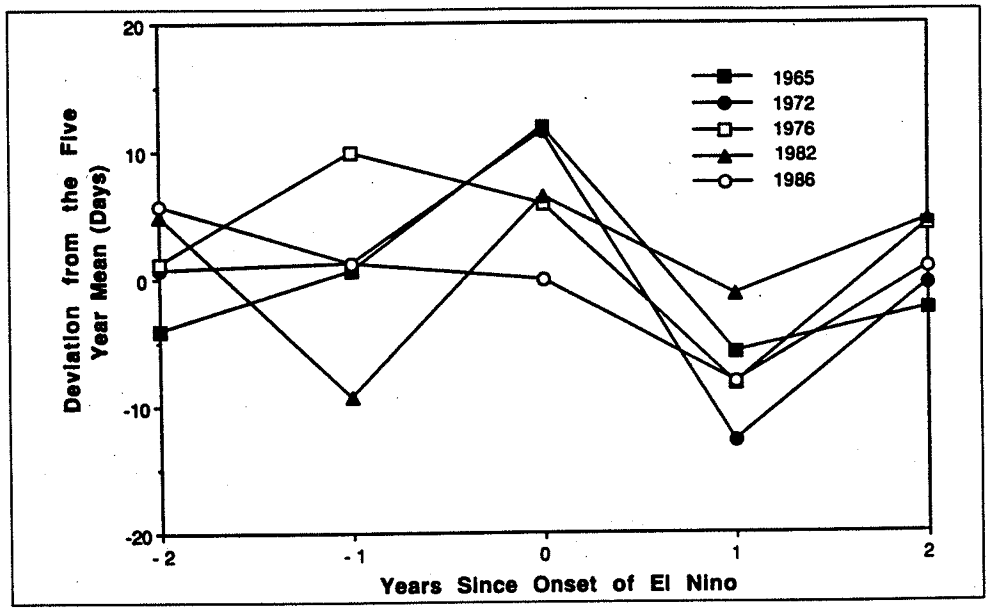


Figure 2. Variations in mean breakup dates for specific years in the ENSO sequence for specific ENSO events. The year noted for each curve represents the onset year (Year 0) of each El Niño.

RESULTS

Ice Breakup

The three-way ANOVA indicates that of the three factors examined to explain the variability in breakup dates, the single most important factor was the year within the ENSO cycle (inter-year effect) (Table 1). The other two factors by themselves were insignificant. In addition, the interactive effects of inter-year effect with both the inter-ENSO effect and the regional effect, and the three-way interaction between these three factors were all statistically significant. In the following, inter-year effect is examined in detail. Since the two-way interactions with the inter-year effect are statistically significant, we will examine the differences within the ENSO cycle for each El Niño event and for each region, separately. Although the three-way interaction was significant, its importance was small relative to the other significant factors (compare mean square errors) and, therefore, is not examined.

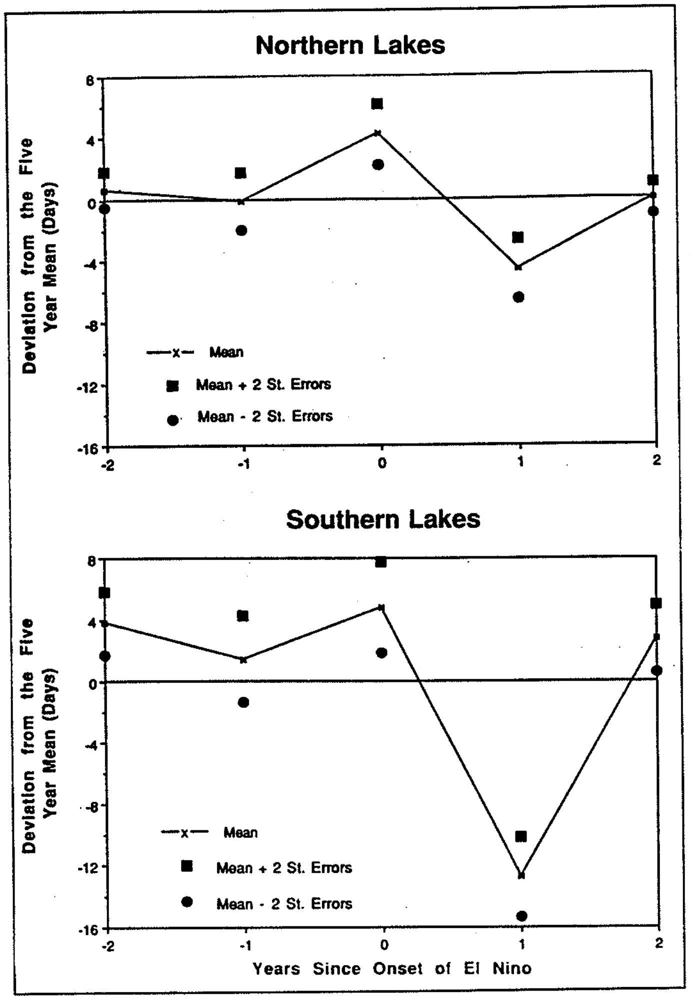


Figure 3. Variations in mean breakup dates for specific years in the ENSO sequence for the northern lakes (top) and the southern lakes (bottom). Year 0 represents the onset year of the El Niño. Plus and minus two standard errors are indicated on the graphs.

Variability in Breakup Among ENSO Events for Each Region

The statistical significance of the inter-year effects and the two-way interaction between the inter-year effects and the inter-ENSO effect indicate that there is a difference among years within a five-year ENSO sequence, and this varies among ENSO events (Figure 2). Breakup is usually earlier in Year 1 of the ENSO sequence (discussed in detail below). There are differences observed among ENSO events; however, we feel that the statistical significance of the two-way interaction was caused by the coherency in breakup dates among lakes. Within any specific year, the standardized breakup dates for the lakes were very similar, especially within a specific region.

Variability in Breakup By Region

The statistical significance of the inter-year effects and the two-way interaction between inter-year effects and the regional effects indicate that there is a difference in breakup dates among years within the five-year sequence and this varies between regions. The average standardized-breakup date (computed by averaging standardized-breakup dates for all lakes in the specified region, for all ENSO events) and plus and minus two standard errors are shown for each year within the five-year ENSO sequence for each region (Figure 3). The same pattern is observed for each region (significance shown in Table 2), with breakup dates being unusually early in Year 1 (the winter in which the waters in the Pacific Ocean are most unusually warm and when teleconnections have been hypothesized to be strongest)—all other years are relatively similar. Breakup dates for the northern lakes in Year 1 are 4.5 days earlier than in any other year of the sequence (significant at

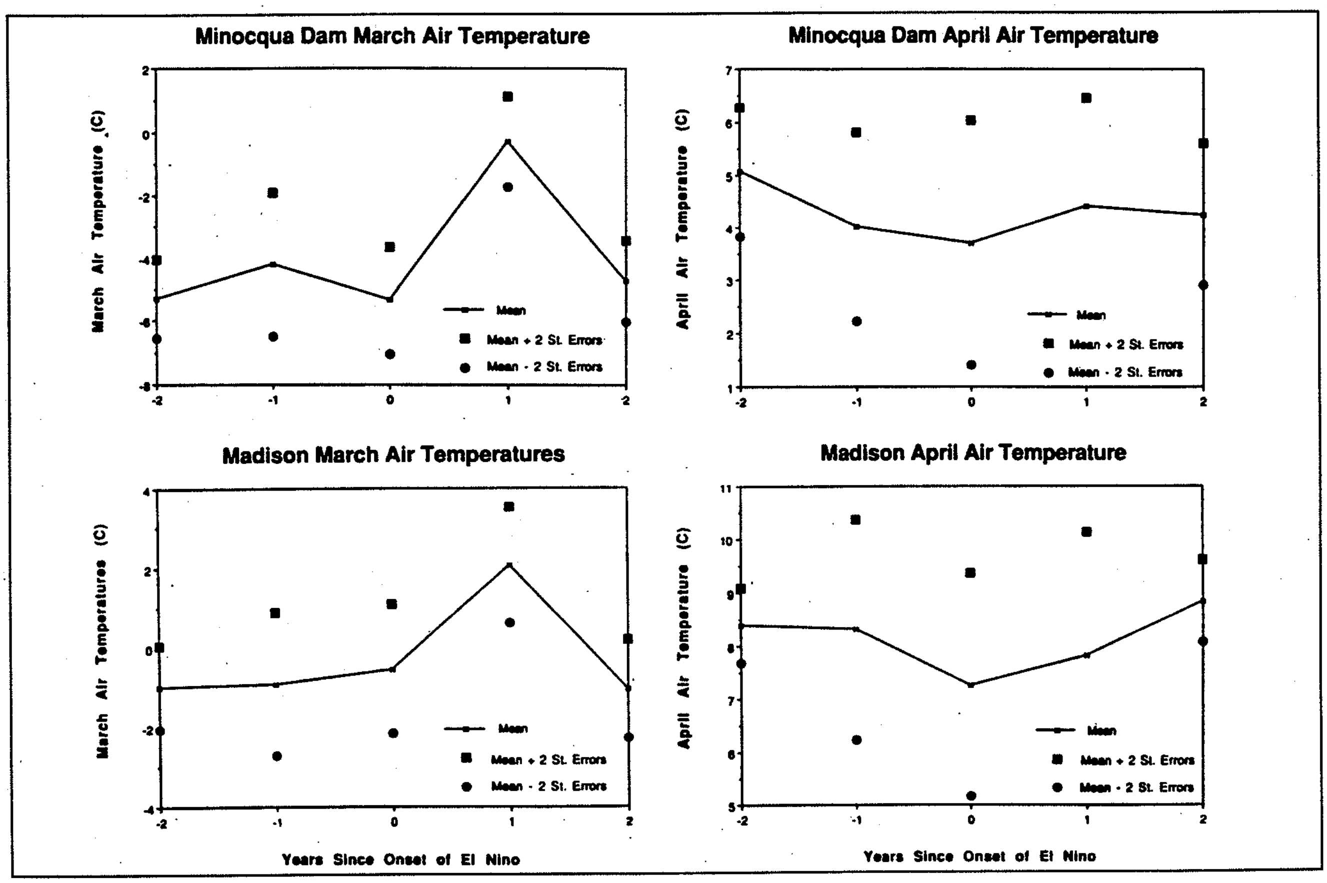


Figure 4. Variations in average March and April air temperatures for specific years in the ENSO sequence for Minocqua Dam (representative of the northern lakes—top) and Madison (representative of the southern lakes—bottom). Year 0 represents the onset year of the El Niño. Plus and minus two standard errors are indicated on the graphs.

$p<0.05$). Breakup dates in Year 0 are 3.5 days later than in any other year of the sequence and are also significant at $p<0.05$. Breakup dates for the southern lakes in Year 1 are 14.2 days earlier than in any other year of the sequence (significant at $p<0.05$)—all other years are relatively similar.

Variability in Air Temperature and Precipitation By Region

Ice-cover records (breakup dates) have been shown to primarily integrate the effects of local air temperatures leading up to the specified events (Robertson et al. 1992, and others); therefore, monthly air temperatures and winter snowfall were examined to see if and what unusual climatic conditions cause the unusually early breakup dates.

March air temperatures were strongly related to the year in the ENSO sequence; however, April air temperatures demonstrated little or no relationship (Table 2 and Figure 4). March air temperatures were 3.9°C warmer than in any other year in the ENSO sequence at Minocqua Dam (representative of the northern lakes) and 3.0°C warmer than any other year at Madison (representative of the southern lakes) (both significant at $p<0.05$). All other years within the ENSO sequence were relatively similar for both regions. Total winter snowfall demonstrated no significant relationship with the year in the ENSO sequence (Table 1).

DISCUSSION & ECOLOGICAL SIGNIFICANCE

If air temperatures are more related to ENSO events in the northern part of the state of Wisconsin than in the southern part, why then are breakup dates of the northern lakes only 3.5 days earlier during Year 1 than in any other year of the ENSO sequence?

The unusually early breakup dates for lakes across Wisconsin occurring during the mature phase of ENSO events indicate that the unusually early breakup dates and warmer than normal late-winter air temperatures found for Lake Mendota (Robertson 1989) are not only indicative of a local relationship, but also of a larger regional response associated with the five ENSO events occurring between 1968 and 1988. These unusual climatic conditions are consistent with the spatial locations and timing of the teleconnections found by Barnett (1981). Ramage (1986) did not find unusual winter air temperatures in Illinois to occur during ENSO events. This lack of a relationship may have been caused by either little or no relationship with ENSO events in the central areas of the United States as suggested by Rogers (1984) or that the wrong period was examined (i.e., monthly air temperatures should have been examined instead of average-winter air temperatures).

One question remains: if air temperatures are more related to ENSO events in the northern part of the state of Wisconsin than in the southern part (Figure 3), why then are breakup dates of the northern lakes only 3.5 days earlier during Year 1 than in any other year of the ENSO sequence compared to 14.2 days earlier than in other years for the southern lakes (Figure 3)? The explanation appears to come from the absolute values of the air temperatures effected and the timing of breakup for the lakes for these two different regions. Ice cover of lakes break up following a period with air temperatures exceeding 0°C (McFadden 1965, Robertson 1989). For the southern lakes, the unusual air temperatures in March reach almost 3°C and occur just prior to when the lakes typically break up (late March). Therefore, breakup for these lakes coincides perfectly for the unusual air temperatures to have their largest impact. However, for the northern lakes, the unusual March air temperatures do not exceed 0°C and therefore the lakes are not ready to break up. Typical breakup dates for the northern lakes range from mid- to late April following a month which was demonstrated to have little or no relationship with ENSO events. Therefore, the effects on breakup of the unusually warm March air temperatures in the northern part of the state are obscured or partially hidden by April air temperatures which demonstrate little relationship with ENSO events.

Earlier breakup of ice cover can positively and negatively affect some fish species. Many shallow lakes in the midwest go anoxic during the winter and suffer a winterkill of fishes. Lakes that winterkill have a special assemblage of fishes, including the central mudminnow, *Umbra limi*, that can withstand these severe conditions (Magnuson et al. 1989); however, game fishes cannot. The likelihood that a lake becomes anoxic in winter depends on the rate of oxygen depletion and the duration of ice cover. Winterkill would be less likely to occur in a winter with an earlier breakup. Ice cover provides a stable environment required for egg incubation of some fish species, such as whitefish. Freeburg et al. (1990) and Brown et al. (1993) found that strong year-classes of whitefish in the Great Lakes occurred in years with longer ice cover. Earlier breakup can also have indirect effects on the ecology of lakes by increasing the length of the open-water period—the period of generally higher productivity. If the longer open-water period is associated with warmer summer water temperatures, the overall productivity of the systems should increase (if food remains available) and stratification should last longer (Robertson et al. 1992). Longer stratification with increased productivity will increase the length of hypolimnetic isolation and increase the chances of hypolimnetic anoxia. Increased hypolimnetic anoxia would be detrimental to any cold-water species.

CONCLUSION

During winters of the mature phase of ENSO events, ice breakup dates across the state of Wisconsin were earlier (ranging on average from 5 to 14 days) and spring air temperatures were warmer (primarily March air temperatures ranging from 3 to 4°C) than in other years. These climatic differences are consistent with that found by Robertson (1989) and consistent with the teleconnectic patterns suggested by Barnett (1981). The consistent anomalies across the state of Wisconsin indicate that this a regional climatic response to ENSO events. Differences in ice breakup, although being earlier across the state, are more extreme for southern lakes than for northern lakes. This difference is caused by the average breakup dates for southern lakes being in late March directly following the period when air temperatures are strongly related to ENSO events, whereas average breakup dates for northern lakes are in mid to late April following a period when air temperatures are not significantly related to ENSO events.

Earlier than normal breakup of ice cover associated with ENSO events may decrease the length of winter anoxia and the potential for winterkill in shallow lakes; however, it may also decrease the length of the period with stable conditions during winter that is required for egg incubation of some fish species. Earlier breakup will increase the length of the open-water season, which may lead to an increase in overall productivity and a longer summer stratification period—both leading to an increased chance of hypolimnetic anoxia during summer.

REFERENCES

BARNETT, T.P. 1981. Statistical prediction of North American air temperatures from Pacific predictors. *Monthly Weather Review* 109:1021-1041.

BROWN, R.W., W.W. TAYLOR and R.A. ASSEL. 1993. Factors affecting the recruitment of lake whitefish in two areas of northern Lake Michigan. *J. Great Lakes Res.* 19:418-428.

FREEBURG, M.H., W.W. TAYLOR and R.W. BROWN. 1990. Effect of egg and larval survival on the year-class strength of lake whitefish in Grand Traverse Bay, Lake Michigan. *Trans. Am. Fish. Soc.* 119:92-100.

HOREL, J.D. and J.M. WALLACE. 1981. Planetary-scale atmospheric phenomena associated with the Southern Oscillation. *Monthly Weather Review* 109:813-829.

KILADIS, G.N. and H.F. DIAZ. 1989. Global climatic anomalies associated with extremes in the Southern Oscillation. *Journal of Climate* 2:1069-1090.

MAGNUSON, J.J., C.A. PASZKOWSKI, F.J. RAHE, and W.M. TONN. 1989. Fish ecology in severe environments of small isolated lakes in northern Wisconsin. Pages 487-515 *in:* R.R. Sharitz and J.W. Gibbons (eds.). *Freshwater Wetlands, and Wildlife.* Conference-8603101, DOE Symposium Series No. 61. USDOE Office of Scientific and Technical Information, Oak Ridge, Tennessee.

MCFADDEN, J.D. 1965. The interrelationship of lake ice and climate in central Canada. Tech. Report No. 20. Dept. of Meteorology. University of Wisconsin-Madison.

MYSAK, L.A. 1986. El Niño interannual variability and fisheries in the Northeast Pacific Ocean. *Canadian Journal of Fisheries and Aquatic Sciences* 43:464-497.

QUINN, W.H., D.O. ZOPH, K.S. SHORT and R. YANG. 1978. Historical trends and statistics of the Southern Oscillation, El Niño, and Indonesian droughts. *Fisheries Bulletin* 76:663-677.

RAMAGE, C.S. 1986. El Niño. *Scientific American* 254:77-83.

RASMUSSON, E.M. and T.M. CARPENTER. 1982. Variations in tropical sea surface temperature and surface wind fields associated with the Southern Oscillation/El Niño. *Monthly Weather Review* 110:354-384.

Robertson, D.M. 1989. *The Use of Lake Water Temperature and Ice Cover as Climatic Indicators.* Ph.D. Thesis. Oceanography and Limnology Graduate Program, University of Wisconsin-Madison.

ROBERTSON, D.M., R.A. RAGOTZKIE and J.J. MAGNUSON. 1992. Lake ice records used to detect historical and future climatic changes. *Climatic Change* 21:407-427.

ROGERS, J.C. 1984. The association between the North American Oscillation and the Southern Oscillation in the Northern Hemisphere. *Monthly Weather Review* 1999-2015.

LTER NETWORK OFFICE PUBLICATIONS

1: Long-Term Ecological Research. *BioScience.* 1984.

2: *The Climates of the Long-Term Ecological Research Sites.* 1987.

3: Standardized Meteorological Measurements for Long-Term Ecological Research Sites. *Bulletin of the Ecological Society of America.* 1987.

4: *1990s Global Change Action Plan.* 1990.

5: *Long-Term Ecological Research Network Core Data Set Catalog.* 1990. (Out of print. Available on-line)

6: *Climate Variability and Ecosystem Response.* 1990.

7: *Internet Connectivity in the Long-Term Ecological Research Network.* 1990.

8: Contributions of the Long-Term Ecological Research Network. *BioScience.* 1990.

9: Long-Term Ecological Research and the Invisible Present, and Long-Term Ecological Research and the Invisible Place. *BioScience.* (Three articles, including Publication No. 8, above). 1990.

10: *Proceedings, LTER Data Management Workshop, Snowbird, UT.* 1990.

11: *Long-Term Ecological Research in the United States: A Network of Research Sites* (6th edition, revised). 1991.

12: *Technology Development in the Long-Term Ecological Research Network: Status of Geographic Information Systems, Remote Sensing, Internet Connectivity, Archival Storage & Global Positioning Systems.* 1991.

13: *Proceedings, LTER Data Management Workshop, San Antonio, TX.* 1991.

14: *Guidelines and Sample Protocol for Sampling Forest Gaps.* 1992.

15: *Stream Research in the LTER Network.* 1993.

16: *Long-Term Ecological Research and Regional Prediction.* 1993. (Available from Elsevier Science Publishers, The Netherlands)

17: *International Networking in Long-Term Ecological Research.* 1994.

18: *El Niño and Long-Term Ecological Research (LTER) Sites* (this volume). 1994.

LTER

PUBLICATIONS
LTER Network Office
University of Washington
College of Forest Resources, AR-10
Seattle, Washington 98195

PH: 206-543-6764 or 4853 / FAX: 206-685-7295
E-mail: *Office@LTERnet.edu* (Internet)

LTER

LTER NETWORK OFFICE
University of Washington
College of Forest Resources
AR-10
Seattle, WA 98195

LTER Publication No. 18