ENSO-RELATED PHENOMENA AT LONG-TERM ECOLOGICAL RESEARCH SITES

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Abstract: I outline a framework for investigating and discussing climate variability and ecosystem response. The example of an El Niño–Southern Oscillation (ENSO) event is a relatively simple one for operationalizing this framework. I review some of the earlier findings related to El Niños and Long-Term Ecological Research (LTER) sites. Then I perform an analysis for the period 1957 to 1990 investigating the response of monthly mean temperature and monthly total precipitation standardized anomaly values to El Niño and La Niña events as indicated by the Southern Oscillation Index (SOI). Different LTER sites manifest strong, detectable, and weak or no climatic signals to El Niño and La Niña events. Some of the effects of the ENSO-related climate variability on selected ecosystems are discussed. A statistically significant climate signal at an LTER site does not necessarily mean there will be an ecologically significant response. El Niño signals in the temperature series at the Andrews Forest, Oregon, the Luquillo Rain Forest, Puerto Rico, and the Palmer, Antarctic (PAL), sites are found to be statistically the strongest. Of these, only the signal at the PAL site has an important ecological effect. Somewhat less statistically strong ENSO signals at the Northern Temperate Lakes, Wisconsin, and the Sevilleta, New Mexico, sites have important ecological effects. An analysis of the climatic response to the 1982/1983 "super El Niño" compared to more normal size warm events is equivocal. The results of the correlation analysis are discussed within the climate variability/ecosystem response framework previously outlined. The timing of the ENSO event and the identification of an ecosystem coupling mechanism are critical for this particular form of climate variability to have an effect. [Key words: Long-Term Ecological Research (LTER), ecosystem, El Niño–Southern Oscillation (ENSO), El Niño, La Niña, climate variability.]

INTRODUCTION

The significance of the El Niño–Southern Oscillation (ENSO) phenomenon lies in its influence on natural and human ecosystems. This paper focuses on the responses of the climates, and to a lesser extent, the responses of the ecosystems of the Long-Term Ecological Research (LTER) sites to El Niños and La Niñas occurring during the period 1957 to 1990. The LTER program conducts and facilitates ecological research at 18 nonurban sites in the United States and the Antarctic (LTER, 1989; Greenland and Swift, 1991) (Fig. 1; Table 1). Two urban LTER sites were added to the program in the Fall of 1997 and one coastal site was added in the Spring of 1998 but they are not considered in this analysis, which was performed before the initiation of these sites. Climate variability occurs at the LTER sites on a variety of different time scales but this paper concentrates on the quasi-quintennial time scale dominated by the ENSO phenomenon. The general climatology of the

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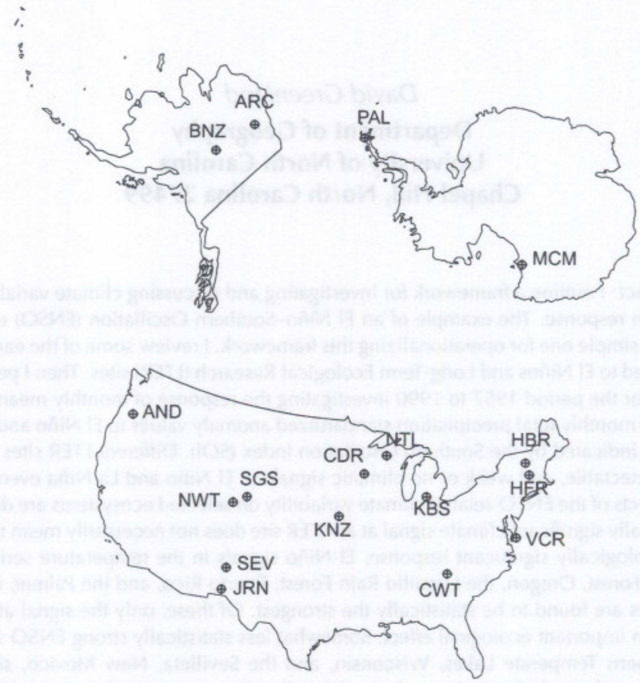

Fig. 1. The location of the Long-Term Ecological Research sites used in this study in the coterminous United States, Alaska, and the Antarctic.

effects of El Niños worldwide has been well established. El Niños in North America generally are associated with higher than average precipitation in the southwest and southeast of the country and lower than average precipitation in the Pacific Northwest (Ropelewski and Halpert, 1986; Kiladis and Diaz, 1989, 1992). However, these general patterns may mask the detailed responses that occur at individual locations.

I first provide some thoughts on a framework for investigating climate variability and ecosystem response. The idea of simple forcing event and direct response needs to be extended when considering ecosystems. The example of an El Niño and La Niña event is a useful one for operationalizing this framework. I then discuss some of the earlier findings related to El Niños and LTER sites. Then I perform an analysis for the period 1957 to 1990 investigating the response of monthly mean temperature and monthly total precipitation standardized anomaly values to El Niño and La Niña events as indicated by the Southern Oscillation Index (SOI). The 1957 to 1990 period is selected because it is a period when climatic data are available for almost all the LTER sites. Data for the 1997/1998 El Niño were not available from all LTER sites when this analysis was performed. The results of the analysis will be discussed within the climate variability/ecosystem response framework previously outlined.

Table 1. Long-Term Ecological Research Sites 1996

Site	Abbreviation	Ecosystem	Climate
H. J. Andrews Experimental Forest (Oregon)	AND	Coniferous forest	Marine West Coast
Arctic Tundra (Alaska)	ARC	Arctic tundra	Arctic tundra
Bonanza Creek Experimental Forest (Alaska)	BNZ	Boreal forest	Subarctic
Cedar Creek Natural History Area (Minnesota)	CDR	Hardwood forest/ Tallgrass prairie	Humid continental
Coweeta Hydrological Laboratory (North Carolina)	CWT	Deciduous forest	Humid continental
Hubbard Brook Experimental Forest (New Hampshire)	HBR	Northern hardwood	Humid continental
Harvard Forest (Massachusetts)	HFR	Hardwood/white pine/ hemlock transition	Humid continental
Jornada (New Mexico)	JRN	Desert	Subtropical desert
Kellogg Biological Station (Michigan)	KBS	Agricultural	Humid continental
Luquillo Experimental Forest (Puerto Rico)	LUQ	Tropical rainforest	Tropical rainforest
Konza Prairie (Kansas)	KNZ	Tallgrass prairie	Mid-latitude steppe
North Temperate Lakes (Wisconsin)	NTL	N temperate lake mixed forest	Humid continental
Niwot Ridge/Green Lakes Valley (Colorado)	NWT	Alpine tundra	Highland
Palmer Station (Antarctica)	PAL	Pelagic marine	Polar tundra
Sevilleta (New Mexico)	SEV	Desert/grassland/ forest transition	Low-latitude desert
Shortgrass Steppe formerly Central Plains Experimental Range (Colorado)	SGS/CPR	High plains grassland	Mid-latitude steppe
Virginia Coast Reserve (Virginia)	VCR	Barrier island	Humid subtropical

FRAMEWORK FOR INVESTIGATING CLIMATE VARIABILITY AND ECOSYSTEM RESPONSE

We must first recognize that there are several types of climate variability. The principal types according to Karl (1985) are as follows: (1) a trend is a smooth monotonic increase or decrease; (2) a fluctuation is two changes of mean whereby two maxima (minima) and one minimum (maximum) are evident; (3) a discontinuity is a single abrupt change in the mean; (4) a vacillation is a series of climate fluctuations but with mean values drifting about two or more average values; (5) an oscillation is a gradual transition between a maximum and minimum value that tends to repeat itself in the time series/rhythm; (6) an oscillation in which the interval between maximum and minimum value is approximately equal is called a periodicity, particularly where the maximum and minimum value are more or less equal over the period of interest. The focus of the present paper is on oscillations since the ENSO phenomenon represents at least a pseudo-oscillation. LTER ecologists sometimes simplify the foregoing terminology by using the terms "event" and "episode" to denote, respectively, short and long-period atmospheric-derived influences on the ecosystem. The time scale of the periods in this terminology can vary according to the nature and functioning of the ecosystem in question. Within the ENSO context, this LTER-related terminology is not so clear because of the time scale involved. An El Niño occurrence could either be looked at as an event or an episode depending on what part of the ecosystem is being affected.

The next part of the framework consists of a series of questions. (1) We first ask are there any preexisting conditions that will affect the impact of the climatic event or episode? For example, the effect of an intense rainstorm will be different depending on whether the soil is already saturated. (2) We next ask is the climate effect direct or does it go into a cascade? Then if a cascade is entered, how many levels does it have and is the interaction between each level linear or nonlinear? A cascade system generally is regarded as one that exhibits flow of material, energy, or information (Chorley and Kennedy, 1971; Strahler, 1980; Thomas and Huggett, 1980). (3) Is the primary ecological effect completed by the time of the next climatic event or episode (or part thereof)? If the effect is complete consideration may move to the next part of the cascade (if any). If the primary ecological effect is not complete (i.e., reaches a new constant level), is it still of sufficient magnitude to have an effect on the rest of the ecosystem? If so, we should pass the effect along the cascade scaling it if necessary according to how much of the complete impact of the event or episode was attained. (4) Does the climatic event or episode have an identifiable upper or lower limit? If a limit exists we can stop the consideration if necessary at the limit but keep the cascade going until it reaches further limits that may exist in later parts of the cascade. (5) Does the climatic event or episode reverse back to some original state (e.g., is it periodic, homeostatic)? If so, what time scales are involved? Does the climate state go back to the original position or beyond? Do cascades reverse? Can we identify the timing of these events? (6) After the climatic event or episode, do the values of the climatic variables return along their outward path or is there hysteresis or some other trajectory in operation? If the latter, how does this affect the cascade?

All the above relates to a deterministic, nonchaotic system. Is the system chaotic or random? If the latter, no further explanation is possible except that, in some cases, it may be possible to proceed using probability theory. If the system is chaotic, we need to compute, or otherwise find, the parameters of the chaos such as its attractors and Lyapunov exponents.

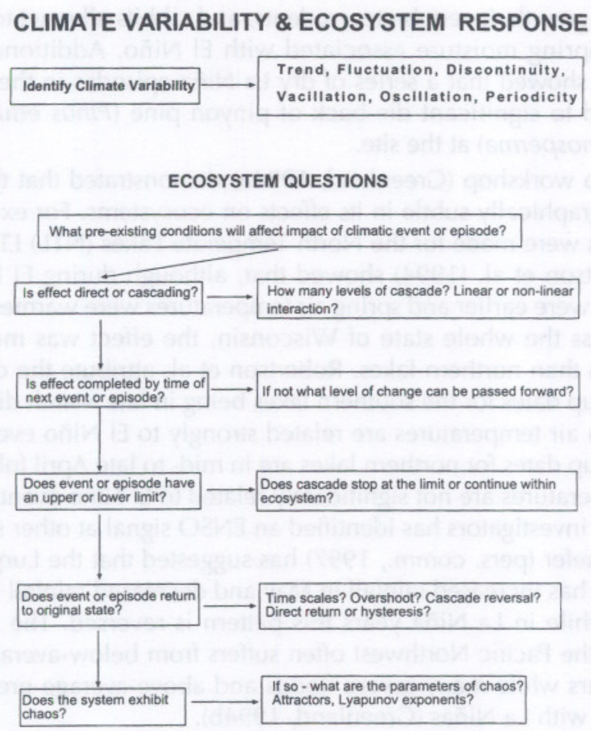

Fig. 2. A schematic outline of the proposed framework for investigating climate variability and ecosystem response.

A schematic outline of this framework is given in Figure 2. I will examine some of these considerations with respect to ENSO-related climate variability and ecosystem response at LTER sites.

PREVIOUS WORK AT LTER SITES

There has been an ongoing interest in the LTER Network in the El Niño phenomenon. A workshop, held in 1993, concentrated on the effect of El Niños and La Niñas at LTER sites (Greenland, 1994a). Since the LTER Network is spread across the North American and Antarctic continents (Fig. 1) it is natural that ENSO climatic signals should be stronger and more marked for some LTER sites than others. The line of LTER sites from the New Mexico, Southwest, through Colorado, to the Pacific Northwest follows the inverse influence of El Niño–related above-average precipitation in the Southwest to below-average precipitation in the Northwest. However, the intensity of ecological response differs. The effect of low stream flows on the ecosystems in the Northwest is less marked than the large hydrologic and ecological impact documented by workers at the Sevilletta (SEV) LTER site, in New Mexico (Molles and Dahm, 1990; Dahm and Molles, 1992). Wetter than usual winters during El Niños have large effects on the aquatic and terrestrial ecosystems at the Sevilleta site. Plant growth, invertebrates, rodents, and rabbits all react to the increase in autumn and spring moisture associated with El Niño. Additionally, Dahm and Moore (1994) showed that a series of dry La Niña episodes in the late 1940s and mid-1950s led to significant die-back of pinyon pine (*Pinus edulis*) and juniper (*Juniperus monosperma*) at the site.

The El Niño workshop (Greenland, 1994a) demonstrated that the ENSO signal could be geographically subtle in its effects on ecosystems. For example, sophisticated analyses were made for the North Temperate Lakes (NTL) LTER sites in Wisconsin. Robertson et al. (1994) showed that, although during El Niño events ice breakup dates were earlier and spring air temperatures were warmer than long-term averages across the whole state of Wisconsin, the effect was more extreme for southern lakes than northern lakes. Robertson et al. attribute the difference to the average breakup dates for the southern lakes being in late March directly following a period when air temperatures are related strongly to El Niño events. In contrast, average breakup dates for northern lakes are in mid- to late April following a period when air temperatures are not significantly related to El Niño events. Later work by individual site investigators has identified an ENSO signal at other sites. An investigation by Schaefer (pers. comm., 1997) has suggested that the Luquillo (LUQ) site in Puerto Rico has increased rainfall in May and decreased rainfall in October in El Niño years, while in La Niña years this pattern is reversed. The Andrews Forest (AND) site in the Pacific Northwest often suffers from below-average precipitation in El Niño years while many severe floods and above-average precipitation years are associated with La Niñas (Greenland, 1994b).

To date, the effect of ENSO phenomena on LTER sites has been investigated without a standardized methodology. This makes inter-site comparison difficult. Consequently, there follows here a systematic analysis on a common set of climatic data applicable to 17 of the LTER sites and designed to identify the relative strength of the El Niño and La Niña signal across the LTER network.

DATA ANALYSIS

The SOI was used for the analysis in this paper. Other indices may be more accurate but often do not extend throughout the period investigated in the current study. The SOI represents the standardized Tahiti-Darwin sea-level pressure (SLP) anomaly. SOI data were obtained from the web site of the Climatic Data Center (CDC) of the National Oceanic Atmospheric and Administration (NOAA) at http://nic.fb4.noaa.gov/cddb/cddb/soi. A list of ENSO years from 1950 (by three-month seasons) was obtained from NOAA at http://nic.fb4.noaa.gov/. Monthly average temperature and total precipitation values for 18 LTER sites for the period 1957 to 1990 were obtained from a previous study. These data are available through the LTER Network web site at http://lternet.edu under the path Committees/Climate/Climdes/. Data for the Antarctic site at McMurdo were not used because data for one of the years was found to be missing. There are no precipitation data for the other Antarctic site at Palmer. SOI data were already in standardized form. The remaining available LTER data were standardized by month. The standardized anomaly (z) is given by subtracting the sample mean of the batch from which the

Table 2. Correlation Coefficients between Monthly Southern Oscillation Index Values Long-Term Ecological Research Site Temperatures[a]

Lag	0	1	2	3	4	5	6	7	8	9	10	11
AND	–.196	–.226	–.193	–.187	–.15	–.089	–.088	–.085	–.065	–.041	–.014	.005
ARC	–.082	–.046	–.07	–.073	–.077	–.043	.057	.014	.028	.011	–.028	–.002
BNZ	–.081	–.098	–.108	–.105	–.104	–.096	–.014	–.042	–.024	.011	–.025	–.03
CDR	–.09	–.011	.025	–.028	–.041	–.023	–.095	–.064	–.075	–.066	–.078	–.064
CWT	.019	.093	.142	.037	.003	–.028	–.005	–.037	–.062	–.047	.005	–.062
HBR	.004	–.055	–.006	–.013	–.022	–.018	–.073	–.103	–.093	–.035	–.07	–.049
HRF	.007	–.03	–.025	–.027	–.052	–.056	–.106	–.137	–.11	–.05	–.093	–.081
JRN	–.059	–.089	–.079	–.093	–.131	–.136	–.095	–.088	–.045	–.061	–.022	.011
KBS	–.127	–.103	–.063	–.046	–.017	–.001	–.041	–.029	–.049	–.075	.045	.083
KNZ	–.007	.065	.116	.091	.037	.044	.009	–.08	–.043	–.017	–.002	.014
LUQ	–.157	–.199	–.279	–.238	–.223	–.267	–.252	–.234	–.152	–.157	–.15	–.141
NTL	–.092	–.087	–.023	–.049	–.082	–.128	–.142	–.178	–.156	–.069	–.068	–.066
NWT	.005	.054	.093	.023	.032	.083	.019	–.01	.03	.03	–.015	.036
PAL	.166	.208	.202	.217	.185	.169	.156	.164	.121	.154	.135	.133
SEV	–.005	.026	.05	.032	.036	.031	–.002	–.062	–.085	–.132	–.165	–.117
SGS	–.096	–.029	.012	–.01	–.014	–.004	–.022	–.072	–.051	–.03	–.011	.0
VCR	.059	.065	.096	.062	.011	.013	–.022	–.067	–.1	–.023	–.008	–.048

[a]Trailing numbers represent lags be month of correlation—that is, 0 = no lag, 1 = Southern Oscillation Index value correlated against the temps of the following month.

data are drawn and dividing by the sample standard deviation (s_x): so $z = (x - mean_x)/s_x$, where x is an individual observation (Wilks, 1995). The data were manipulated so that correlation coefficients were computed between the SOI value for a given month and the standardized temperature or precipitation anomaly for each of 17 LTER sites for the same month and for successive 11 months lagged 1 month at a time (Tables 2 and 3). A second analysis was performed on the LTER sites that showed the highest correlation coefficients with the SOI data to see if there was a difference in climatic response to the 1982/1983 "super El Niño" compared to "normal El Niños."

RESULTS AND DISCUSSION

The Pearson product moment correlation coefficients between the SOI value for a given month and the standardized temperature or precipitation anomalies do not show very high values (Tables 2 and 3) because the data are inherently noisy. However, most of the values shown are statistically significant partly owing to the large number of pairs of observations (397 to 408) in the analyses. Another reason that the correlation coefficients are low is that all SOI values during the period are used and thus both El Niño (extreme negative SOI values) and La Niña (extreme positive

Table 3. Correlation Coefficients between Monthly Southern Oscillation Index Values Long-Term Ecological Research Site Precipitation[a]

Lag	0	1	2	3	4	5	6	7	8	9	10	11
AND	.024	.086	.069	.139	.072	.02	.068	.01	–.024	–.024	.013	–.027
ARC	.02	.019	.019	.004	–.056	–.027	.006	–.011	–.006	.003	–.011	.022
BNZ	.097	.1	.1	.051	.013	.029	.013	.063	–.021	–.027	–.002	.008
CDR	.037	.079	–.006	–.087	–.034	–.055	–.051	–.069	–.027	–.052	–.058	–.051
CWT	.075	.005	.057	.002	.074	.081	.067	.061	.036	.059	.04	.045
HBR	.05	.023	–.01	.017	–.009	.036	–.015	.033	.032	.034	.018	–.015
HRF	.008	.001	–.007	.021	.036	.081	.046	.016	.014	.051	.01	–.038
JRN	.003	–.031	.058	.081	.0	–.028	.027	–.011	–.043	–.091	–.049	–.111
KBS	.094	.069	.07	.032	–.005	.057	.002	.014	–.024	–.02	–.032	.001
KNZ	–.069	–.05	–.037	–.042	.017	–.007	–.028	–.015	–.041	–.038	.001	–.027
LUQ	.012	.022	–.042	–.037	–.089	–.025	–.041	–.079	–.073	–.019	–.035	–.048
NTL	.034	.036	–.032	–.012	–.008	–.059	–.071	–.108	–.1	–.111	–.1	–.086
NWT	–.028	–.019	–.061	–.008	–.026	–.033	–.025	–.039	–.055	–.06	.012	–.025
SEV	–.106	–.093	–.159	–.172	–.124	–.094	–.088	–.043	–.068	–.015	.015	.051
SGS	–.082	–.062	–.084	–.085	.006	.019	.007	.005	–.04	–.046	–.042	–.044
VCR	–.024	–.083	–.105	–.104	–.05	–.028	.028	–.005	.0	–.054	.017	–.017

[a]Trailing numbers represent lags be month of correlation—that is, 0 = no lag, 1 = Southern Oscillation Index value correlated against the precipitation of the following month.

SOI values) events occur in the series. This approach differs from one where correlations are found between one or more climate variables of El Niño years only and some other ecosystem variable. The higher correlation coefficients in this analysis therefore indicate sites where the climatic variable relates to both El Niño and La Niña events. Unless otherwise specified, I use the term ENSO in the discussion below to refer to both of these extremes. Although there are a few exceptions, the results of the current study are consistent with the expected patterns based on our general knowledge of the geography of ENSO effects on the climate. Given these facts, it is appropriate to classify the LTER sites in terms of their ENSO responses into three categories (Table 4). The first category is of three data series (ANDt, LUQt, and PALt) where a strong response is seen ($r > .2$). Here, and in the following, I use the abbreviation letters of the LTER sites (Table 1) and a lowercase t or p to indicate temperature and precipitation, respectively. The second category is of data series that display a detectable signal ($r = .1$ to $.2$). There are 15 data series in this group. The third category is where there is no signal according to the definition ($r < .1$). Some of the data series in this category do come close to the cutoff r value and might well have an ENSO signal by other definitions. The duration in months of the ENSO signal is shown in Table 4, where it can be seen that in some data series the signal lasts for up to six months whereas in other series the signal occurs only in a single

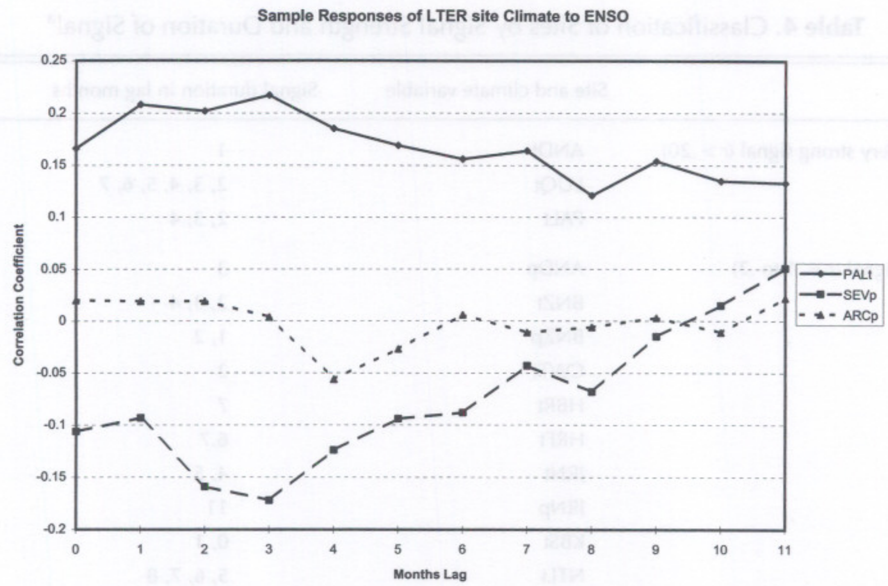

Fig. 3. Sample responses of climate to ENSO events at selected LTER sites. The graph shows the value of the correlation coefficient between the SOI value and the value of the identified climate variable at the site for the same month and up to 11 lagged months following the SOI value of a given month.

month. The general types of patterns in the data are represented by the data series for PALt, SEVp, and ARCp (Fig. 3). The ENSO signal at the Palmer site in the Antarctic is strong and actually lasts in some form for the whole 12 months. Although the analysis does not extend so far, it is possible that the signal may be found before the beginning and after the end of the 12 months considered here. The SEVp ENSO signal is seen to be strongest in the second and third month after the strongest SOI value and then to gradually decrease in strength becoming insignificant after the seventh month. The ARCp series is an example of a data series with no ENSO signal.

There are some interesting details and implications that arise from these results. First, as expected, the LUQ, Puerto Rico, site shows strong and long lasting higher than normal temperatures associated with El Niño occurrence and lower than normal temperatures with a La Niña. The site also shows drier than normal conditions associated with El Niño occurrence but these do not fall within the detectable limit assigned in this study. The drier than normal conditions that are consistent with Schaefer's earlier findings actually have more effect on the ecosystem than do the warmer than average conditions. Statistically, this is because the temperatures are usually high and a little increase will not make much difference. However, the precipitation at this site is the highest of all LTER sites (2470 mm annually) and the variability around this value can be very large. Between 1961 and 1990 the wettest year (1979) had 3955 mm of precipitation, while the driest year (1967 following the 1966 El Niño) had 1540 mm. Ecologically the decrease of precipitation, according to Schaefer, has a large impact on the stream flows and their water chemistry. This

Table 4. Classification of Sites by Signal Strength and Duration of Signal[a]

	Site and climate variable		Signal duration in lag months
Very strong signal ($r > .20$)	ANDt		1
	LUQt		2, 3, 4, 5, 6, 7
	PALt		2, 3, 4
Signal ($r = .1$ to $.2$)	ANDp		3
	BNZt		2, 3, 4
	BNZp		1, 2
	CWTt		2
	HBRt		7
	HRFt		6.7
	JRNt		4, 5
	JRNp		11
	KBSt		0, 1
	NTLt		5, 6, 7, 8
	NTLp		7, 8, 9, 10
	SEVt		9, 10, 11
	SEVp		0, 2, 3, 4
	VCRt		8
	VCRp		2, 3
No signal ($r < .1$)	ARCt	ARCp	
	CDRt	CDRp	
	CWTp		
	HBRp		
	HRFp		
	KBSp		
	KNZt	KNZp	
	LUQp		
	SGSt	SGSp	
	NWTt	NWTp	

[a]The t and p after the site name represent temperature and precipitation, respectively.

can have an even greater ecological impact when the below-normal precipitation occurs in the dry season between January and March at this site.

El Niño occurrence is associated with higher than normal temperatures at the NTL site in Wisconsin and La Niña corresponds to lower than average temperatures. However, the greater effect is found in the following summer for a winter-time maximum or minimum SOI value. It is not known if this has effects on the ecosystem. I am not aware of any investigations on this point. The work of Robertson et al.

(1994) focused on the temperatures during the spring melt out of lake ice and this had obvious ecosystem effects. The ENSO effect for El Niños also is manifested in NTL precipitation values by increasing them in summer and into fall. This may affect the atmosphere/groundwater water input ratio to the lakes and have a cascading effect through the ecosystem.

The Colorado alpine site (NWT) had one of its highest precipitation years (1581 mm) in the "super El Niño" year of 1983. Although the El Niño–related precipitation signal at NWT is consistent with the El Niño occurrence, the signal is not strong. Most likely the high precipitation of this year cannot be explained by the 1982/1983 El Niño alone.

The Antarctic site, PAL, ENSO-related signal in temperature is extremely strong in the context of the present study. As mentioned, it is so strong that it probably continues to earlier and later lag months. Smith et al. (1996) has suggested the lag may extend out to 19 months. During El Niño events, temperatures at PAL tend to be colder than average. Smith et al. have noted that El Niño occurrence is associated with above-average ice extents in the Western Antarctic Peninsular area. Here the effect on the quasi-quintennial time scale somewhat offsets the strong warming trend that has been noted at this site over the last 40 to 50 years. An important ecological linkage is associated with penguins in this location. Optimum sea ice conditions no longer exist for Adélie penguins in the Western Antarctic Peninsular because of the lack of sea ice caused by long-term warming. In contrast, Chinstrap penguin populations are increasing because they do better in open water conditions (Fraser et al., 1992). Thus, on the longer time scale of five decades, the smaller time scale El Niños give a "momentary" respite to the Adélie penguins at the expense of the Chinstrap penguins while La Niñas may have the opposite effect.

At the SEV site in New Mexico, the ENSO-related temperature signal shows up very late, 9 to 11 months after the lowest or highest SOI value. It is difficult to think of a physical reason for this. There are probably few ecological events related to this. On the other hand, the ENSO-related precipitation increase is manifested shortly after the extreme SOI value occurrence. The effect of the increase in winter precipitation in the case of El Niños has been well documented (Molles and Dahm, 1990; Dahm and Molles, 1992). Following the forecast of the 1997/1998 El Niño event, workers at the SEV site issued a warning to New Mexican residents to be particularly careful not to allow the buildup of household and other waste. Such waste would add to the natural increased rainfall-derived accumulation of vegetative material upon which rats and other small mammals feed. It was hoped, by issuing the forecast, to decrease the possibility of rat-born hanta virus outbreaks. Such outbreaks did not occur during the months after the 1997/1998 El Niño, but it is not possible to assess the effectiveness of the warning (Parmenter, pers. comm., October 1998).

The analysis of the climatic response to the 1982/1983 "super El Niño" compared to more normal size warm events was not clear cut. The "normal" size events were selected on the basis of the data identified by Kiladis and Diaz and found on the NOAA web page (nic.fb4.noaa.gov). I investigated the LTER sites that had shown the highest response in the previous analysis to El Niños. The 1982/1983 El Niño was certainly larger in terms of its SOI value than those of 1958, 1965, 1972,

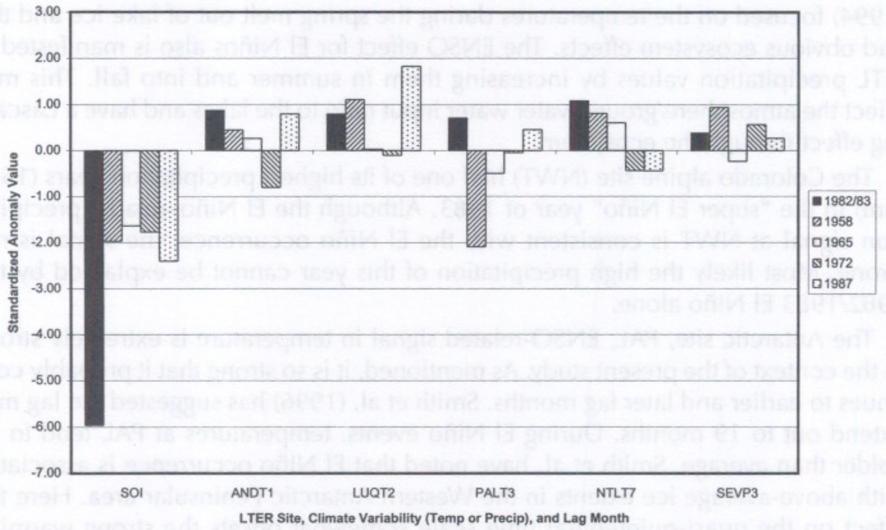

Fig. 4. The climate response of selected LTER sites to the 1982/1983 "super El Niño" compared to "normal" El Niños.

and 1987 (Fig. 4). However, the responses to these five ENSO events are not altogether consistent. At AND, in the Pacific Northwest, the 1982/1983 temperature anomaly was larger than for any of the other El Niño years as was also true for the NTL, Wisconsin, temperature anomaly of the following summer. But for LUQ, Puerto Rico, (temperature) and SEV, New Mexico, (precipitation), the 1982/1983 El Niño led to a smaller response than in some of the other El Niño years. The PAL temperatures in the Antarctic showed a larger positive anomaly for the 1982/1983 event than other years but the pattern is confounded by the large negative anomaly for the 1958 event. I conclude that super El Niños might give rise to larger climatic responses than normal El Niños at some of the LTER El Niño–sensitive sites but not necessarily all of them. The addition of data from 1997/1998 may help to clarify the pattern and add more consistency.

APPLICATION OF FRAMEWORK FOR INVESTIGATING CLIMATE VARIABILITY AND ECOSYSTEM RESPONSE

We have concentrated here only on an oscillatory forcing function of climatic variability—the ENSO. We have seen that, at any particular site, there may be a variety of responses ranging from long-lasting responses of several months, and short-lived responses of one month, to no response at all. Whereas it is not possible to go into the details of the framework for all LTER sites, some examples are appropriate. The questions of the framework only apply to those ecosystems that have shown some climatic response to the ENSO event. So, for example, although there is a strong "instantaneous" ENSO temperature signal at the Andrews site, it is not likely to have much effect on the ecology since it usually occurs in the mild winters of the Pacific Northwest.

As outlined previously, the next part of the framework consists of a series of questions.

(1) We first ask are there any preexisting conditions that will affect the impact of the climatic event or episode?

One of the benefits of asking this question is that it usually will stimulate new research questions. An example in the present case relates to the effect of ENSO events that are themselves superimposed on a longer warming/less ice trend at the Antarctic PAL site. Here the new question arises at what stage does the environmental condition pass a threshold that might lead to a fast decline or increase in the penguin populations? The issue of preexisting conditions further raises questions about the relationship between climatic events on one time scale and those on another. It is possible, for example, that La Niña years set the stage in the Pacific Northwest for increased, short-term, rain-on-snow flood events at the Andrews Rainforest.

(2) We next ask is the climate effect direct or does it go into a cascade? Then if a cascade is entered, how many levels does it have and is the interaction between each level linear or nonlinear?

A direct climatic effect on an ecosystem is exemplified by a windthrow event yet even this sets off a chain of ecosystem responses at a relatively small spatial scale. Climate effects on ecosystems however most often go into cascades. So, for example, the increased El Niño–related precipitation at SEV, increases the water in the aquatic systems, and also sets the stage for increased primary productivity on the terrestrial systems. The latter, in turn, provides increased forage for small mammals, which, in their turn, provide transportation for the Hanta virus. This terrestrial ecosystem example simplistically identifies a three-level system. Quantification of this system would help determine the degree to which the various stages were linear or nonlinear.

(3) Is the primary ecological effect completed by the time of the next climatic event or episode (or part thereof)? If the effect is complete, consideration may move to the next part of the cascade (if any). If the primary ecological effect is not complete (i.e., reaches a new constant level), is it still of sufficient magnitude to have an effect on the rest of the ecosystem? If so, we should pass the effect along the cascade scaling it if necessary according to how much of the complete impact of the event or episode was attained.

At NTL the ecological effect of early ice melt out during an El Niño is completed by the time of the next El Niño event. Where an early melt out occurs, primary productivity can have an early start and, at least in hypothesis, there can be more productivity during the growth season at all higher trophic levels. The higher trophic levels represent the next part of the cascade. Within the ENSO context, the ecological effect may not be complete for ecosystems, such as forests, acting on long time scales. In most of these kinds of cases, an individual El Niño will not have a measurable effect except possibly on the aquatic parts of the system as in the case of LUQ. There will be few, if any, examples for the El Niño time scale where the ecological effect is not complete by the time of the next event.

(4) Does the climatic event or episode have an identifiable upper or lower limit? If a limit exists, we can stop the consideration if necessary at the limit but keep the cascade going until it reaches further limits that may exist in later parts of the cascade.

The ice melt at the NTL represents a more- or less-linear change. The change has a limit since there is always a finite amount of ice to melt out. After the melt out, the cascade of the energetics of the lake ecosystem will continue through the various trophic levels. Most changes will have limiting values. It will often be important to identify what these limiting values are for both the climatic system and the ecosystem. We might assume, in the case of the climate system, that the climatic effects of the "super El Niño" represents a set of limiting values. However, it was shown in the above analysis that this does not necessarily lead to the identification of unequivocal limiting values although this may simply represent a limitation of this particular analysis.

(5) Does the climatic event or episode reverse back to some original state (e.g., is it periodic, homeostatic)? If so, what time scales are involved? Does the climate state go back to the original position or beyond? Do cascades reverse? Can we identify the timing of these events?

The first of these five questions has a relatively easy answer as far as ENSO climatic phenomena are concerned. The climatic variation is quasi-periodic and returns more or less to its original position. Atmospheric cascades usually do not reverse. The timing of ENSO events is on a quintennial time scale in terms of the usual occurrence of the event yet when an ENSO event occurs it does so on a seasonal and monthly time scale. These answers also apply to many El Niño–influenced ecosystems. An increase in Adélie penguin populations during a greater than average ice year associated with an El Niño will be reversed by the occurrence of a La Niña if we assume La Niña has the opposite climatic effect at the Palmer site. Energy flow through trophic levels is not reversed. The timing of many events in the Palmer, Antarctic, ecosystem is well established.

(6) After the climatic event or episode, do the values of the climatic variables return along their outward path or is there hysteresis or some other trajectory in operation? If the latter, how does this affect the cascade?

Changes in the atmospheric part of the ENSO system tend to return along their outward path at least as far as the values of the climatic variables is concerned. This generally applies to atmospheric pressures in the Pacific Ocean source areas of the events and the values of temperature and precipitation in the affected climates of the world. The energy transfers related to the ENSO phenomenon in the Pacific Ocean do not return along the same path because of the operation of the second law of thermodynamics. El Niño–related ecosystem changes such as the increase of populations in the NTL lake ecosystem will often reverse themselves along the same or similar pathway after the El Niño event. El Niño–related changes such as the a loss of aquatic species in the temporally relative drought of a LUQ aquatic ecosystem conceivably may take some time to reverse and a hysteresis effect might come into play. An extreme example of this is the episode in the late 1940s and mid-1950s of a series of dry La Niña events that led to significant die-back of pinyon pine (*Pinus edulis*) and juniper at the SEV site.

All the above relates to a deterministic, nonchaotic system. A consideration of chaotic systems is beyond the scope of this paper. I recognize that many, if not most, of our atmospheric and ecosystems display some degree of chaos and that it will be essential to address this topic in the future.

The application of this framework to the ENSO case of climate variability has been very effective in raising further research questions and providing a manner in which they can be posed. The application also has identified at least one important insight. Although some of the answers to the framework questions yield nothing new and are sometimes even trivial, the realization that the climatic ENSO signal has to be specifically connected to some part of the ecosystem to be effective provides a great stimulus for further investigations. We have learned that the timing of the climate signal is critical for effectiveness. Also the particular climatic variable in which the ENSO signal is found has to be one with a direct link to the ecosystem. The existence of a coupling mechanism between the climate variability signal and an ecosystem driving function, therefore, is critically important. The same would also be true for climate variability relations with human systems.

CONCLUSIONS

I have provided a framework for classifying and discussing climate variability and ecosystem response. Clearly the idea of a simple forcing event and direct response needs to be extended when considering ecosystems. The example of an ENSO event has been a useful, and relatively simple, one for operationalizing this framework. I have reviewed some of the earlier findings related to El Niños and LTER sites. I have performed an analysis for the period 1957 to 1990 investigating the response of monthly mean temperature and monthly total precipitation standardized anomaly values to ENSO events as indicated by the SOI. The LTER sites that manifest strong, detectable, and weak or no climatic signals to ENSO events have been identified. Some of the effects of the ENSO-related climate variability on the ecosystem have been discussed. We have learned that the timing of the ENSO and the identification of an ecosystem coupling mechanism are critical for this particular form of climate variability to have an effect. A statistically significant climate signal at an LTER site does not necessarily mean there will be an ecologically significant response. ENSO signals in the temperature series at the AND, LUQ, and PAL sites are found to be the strongest statistically. Of these, only the signal at the PAL site has an important ecological effect. Somewhat less statistically strong ENSO signals at NTL and SEV have important ecological effects.

The results of the analysis of the climatic response to the 1982/1983 "super El Niño" compared to more normal size warm events were not clear cut although in some cases the effects of the super El Niño were more pronounced. The results of the overall analysis of this paper have been discussed within the climate variability/ecosystem response framework previously outlined. This has allowed us to at least begin a thorough consideration of ecosystem response to a climatic phenomenon. However, I have only skimmed the surface of this topic. The framework is very effective at raising and posing new research questions. The framework needs to be applied in detail to individual systems, or parts thereof, in the various LTER and other ecosystems. The framework needs to be applied in a quantitative fashion. It also needs to be applied to climatic forcing functions at other time scales ranging from an individual rainstorm to a major glacial period. Only after many such applications will we begin to see some of the important basic principles relating climate variability and ecosystem response.

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