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Cover photo: Hurricane Hugo, which snapped trees and dumped salt water on South Carolina forests in September 1989, suddenly and dramatically altered a pine ecosystem. W.T. Swank photo was taken in the vicinity of the North Inlet LTER Site.

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OVERVIEW OF CLIMATE VARIABILITY AND ECOSYSTEM RESPONSE[1]

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Abstract.— Unusual ecosystem responses are frequently driven by meteorological events. The frequency and magnitude of these events and responses can be characterized through Long-Term Ecological Research. The LTER Climate Committee identifies four issues to be considered in future investigations: (1) the need to clarify terms and definitions used in discussing climate variability, (2) the importance of recognizing the various time and space scales of climate variability and ecosystem response, (3) the need to expand data beyond dependence on traditional summaries of temperature and precipitation, and (4) the value of insights gained from examining similarities and dissimilarities among climate episodes and ecosystem responses across LTER sites.

Keywords: LTER, scale, climate change, air mass.

INTRODUCTION

An important contribution of long-term ecological research is the ability to place unusual ecological events in perspective. In a study of 380 ecology papers, Weatherhead (1986) concludes that "the danger of short-term studies may be that they experience too many unusual events. The reason for this unexpected conclusion may be that we tend to overestimate the importance of some unusual events when we lack the perspective provided by a longer study." He also notes that abiotic atmospheric factors, particularly precipitation and/or temperature, cause the great majority of unusual ecosystem events. In their report on long-term research, Strayer and others (1986) find that long-term studies are necessary to explore four major classes of ecological phenomena. They identify these phenomena as (1) slow processes, (2) rare events, (3) subtle changes in systems, and (4) complex processes requiring long-term multivariate studies to detect change. Note that the static or no change situation was not listed as an ecological phenomenon. The first three of these classes of change may be closely correlated with climate data while climate data may be a significant variant in the fourth. Furthermore, according to Strayer and others, the measurement variables eventually selected in long-term research could be classified either as structural variables, such as species composition, or as functional variables such as primary productivity. Climate might be classified best as a set of functional variables, even though some of the functional relationships are not yet known.

Following presentation of the papers in this volume, the LTER Climate Committee discussed the application of long-term studies to research on climate variability and ecosystem response. We focused on four main areas: (1) clarifying our terminology, (2) recognizing the importance of time and space scale in all aspects of such work, (3) developing and promoting climatic indices, other than standard expressions of temperature and precipitation, that may be useful in ecosystem studies, and (4) utilizing the similarities and dissimilarities between sites.

TERMINOLOGY

Even before the Workshop began, Committee members began debating the meaning of the term "climatic variability". The view was that the term, as used in the Workshop title, implies abnormality whereas climate variability (or any other kind of ecosystem variability) is the normal condition. Climate variability was described as consisting of a pattern of "episodes" and "events". The time scale of the episode or event

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is **significant.** The following points led the group into the concept of episodes **versus** events as it applies to **Long-Term** Ecological Research **(LTER).**

We defined weather as a real-time **event,** whereas **climate** is a synthesis or time integration of weather element values or weather systems. Climate has the component of expectation that a characteristic will occur.

Clear terminology is necessary because weather events and climatic episodes have political ramifications when reported to the public by popular media. Reports must clearly state whether a particular heat wave or drought is a significant event or part of the variability that is an integral part of routine weather. Unfortunately, terms such as **"climatic** normal" and "normal climate" detract from the reality that variability is the normal characteristic of a climate system.

Because of their long-term emphasis and extensive spread over diverse **ecosystems,** LTER sites are key elements in the national effort to detect changes in the climate system. Without data, the detection of change is strongly molded by human bias toward a time scale which corresponds to the human **lifespan.** Extreme weather events are ranked in severity against those events within the **observer's** memory. The "Great Southeastern Drought of **1986-88"** is most **significant** to those who cannot recall the drought of the **mid-1920's.** A mature forest or natural grassland may be described as unchanging until someone obtains measurements of its characteristics over a period long enough to detect change. Investigators must be able to evaluate the state variables of an ecosystem before they can begin to relate change to climate variation. Consistently collected, long-term climatic data is a most valuable and necessary tool to categorize weather events and climate episodes. The LTER network provides opportunities to test for climate change and to relate it to ecosystem response without an **anthropocentric** time scale bias. This bias limits the ability to detect real changes between one episode and another. A corollary question might be, what other biases do we impose on the LTER ecosystems we study? For example, how do the sizes or sampling intensities of the LTER sites affect understanding of spatial scales?

Both the cyclic nature of and rapid changes in climatic values have been noted in earlier chapters of this volume. Examples include data from **Hubbard** Brook (accumulated daily precipitation and temperature **records),** Northern Lakes (dates of lake **freezing),** and Niwot Ridge (recent annual temperature **values).** Step functions might be more common than smooth trends or cycles, even on an **intra-annual** scale and for all elements. On a seasonal scale, **phenological** changes may force **step-function** shifts in microclimate values. Albedo, light transmission, and litter temperature, for example, change rapidly with leaf development or leaf fall. Other discontinuities in time series of climate variables are common at many LTER sites. These discontinuities may be more important than regular trends because they "reset" the ecosystem. For example, every storm establishes a new state for soils, vegetation, and associated drainage systems. Rapid change is a prime characteristic of the interval (event) between **episodes.**

For research on climatic cycles or step functions, members of the Committee cautioned against using methodology such as spectral analysis which looks for cyclic forms irrespective of the realities of the ecosystem. Such techniques should simply be used to search for an explanation of variance. Spectral analysis was applied to the **Niwot-Green** Lakes system and limited power was found to explain actual ecosystem operation. Other, more appropriate, methodologies may be available for investigating value discontinuities in ecosystem and abiotic variables. An example is the work of Walsh and **Richman** (1981) on the rotation of orthogonal principal **components.** By examining the sizes of anomaly fields, they were able to identify sister stations in both time and space and define discontinuities in the record. This technique could be very useful for extrapolating out from LTER sites.

As a result of the above **considerations,** the Committee found that LTER scientists, and others working in the field of climatic variability, should be more specific than the term "climatic change" allows. For clarity, we should apply a distinction between "episodes" and "events". An "event" was defined as a single occurrence, such as a large **rainstorm,** often embedded in the functioning of the synoptic climatic scale. An "episode" was taken as a string of events and its duration is probably related to the time constant of the system. Some events and most episodes reset the time clock of the system. They result in a large change in the ecosystem at the time of occurrence followed by a long tail of less obvious **adjustments.**

The Committee recognized at least three versions of climate episode. First, climate episodes are defined by the data of the climatic time series bounded by their indications of changes of state. Second, the perceived climatic episode is often described by means of climatic data but is actually bounded by a time scale of human memory lasting between 40 and 80 years. Third, a climate episode may be best defined by responses of the components of the ecosystem. All are especially dependent on spatial scale and the latter is specifically apropos for Long-Term Ecological Research.

SCALE

In discussion, the Committee continually returned to questions about time and space scales in which episodes occur. Scale is an important consideration because it determines what kinds of questions can be asked about the operation of the ecosystem. Researchers must relate the **scales** on which climate systems operate to those scales on which the biotic parts of the ecosystems operate.

Actually, some of the difficulty in **defining "climate"** and "climatic variability" arose because of difficulty in **defining** the time scale of climate. The 30-year period over which "climatic **normals"** are calculated is an artificial human construct championed by the National Weather Service (NWS) of the United States and may have little relevance to ecosystem realities. Other averaging periods for climate data might be more meaningful **(Kunkel** and Court **1990).** The averaging period will have a very large role in defining an "episode" and its importance.

The definition of **climate,** as perceived by an individual component of the ecosystem, is directly related to scale. A soil **micro-organism** might regard an individual rainstorm as a significant climatic event whereas a tree at the Andrews site in Oregon would be acclimated to a climate range far exceeding that found in any 30-year climatic normal of the NWS. Each ecosystem responder defines its own climate scale. Each organism has a condition where it is most successful and a band of tolerance where it can exist. Species with narrow tolerances may become endangered by a new episode.

Partly because scale has been ignored, we do not have a good understanding of many ecosystems. Ecosystems are often described as complex, and may appear unnecessarily so because we have not considered the various time scales relating the functioning of systems to their elements. **Thus,** complexity may be a function of the **way** we study the system and not necessarily a characteristic of the ecosystem **itself.**

Definition of appropriate time and space scales can be a major contribution of the **LTER** network. **LTER scientists,** and especially the **climatologists,** are well positioned to attack this problem. Sites should equip themselves with the tools to put events such as droughts and storms into perspective. An example of such tools is the Z-T methodology applied at the Coweeta site. The importance of developing such tools is demonstrated by the Midwest drought of 1988. Even in retrospect it is difficult to specify a tool to answer the question: when did the drought begin? **Agroclimatic** indices like the Palmer index suggested that this drought started in April. But the media only began asking questions about the drought in June - at least two months later. Part of the function of LTER is to answer questions from the public. Thus, we could adopt a goal of developing procedures that relate climate to the ecosystem **and** yet are understood by the public and the media. A major challenge would be to foster public understanding of research results at LTER sites where plant succession **is** a long **time-scale** process, such as Cedar Creek **MN** and Bonanza Creek **AK.** Another important LTER project might be to develop an index of drought (or any other abiotic variable) **that** would detect and define the short-term phenomenon that is superimposed and acting on a longer term process.

We may not have been characterizing the most relevant and comparable time and space scales between ecosystems and climatic events. Discussion suggested that hierarchy theory can be helpful, and that the functional factors of ecosystems should be used to select those climatic events that may be most important. The reverse process was also recognized. Ecologists are now asked to estimate ecosystem responses for the multitude of climate projections. In some cases, the rate of the projected climatic or environmental change exceeds the capacity of an ecosystem to respond gradually. What is that limit, and what alternate response can be predicted from research?

Various examples of environmental change exceeding the response capacity of the ecosystem are available in the LTER Network. A **short-time-scale** example is the inability of root growth in the Midwest to keep up with lowering water table during the 1988 drought. On a longer time scale, marsh growth on the Virginia Barrier Islands was unable to keep up with a relatively high rate of rise in sea level.

Our current climatic data impose several **time- and space-scale** limitations. The time limitation is that the length of the reliable observed climatic record in most parts of the U.S. is on the order of a hundred years. This affects the results in several papers in this volume. A scale limitation is that most modeling studies based on current General Circulation Models **(GCMs)** employed to investigate potential effects of increase in greenhouse gasses are on a scale so large that a State the size of Colorado might contain only one grid point.

Furthermore, each ecosystem has a significant spatial scale, yet each LTER site can study only a portion of its ecosystem. **Tansley's** (1935) original definition recognized scale as an element of the ecosystem. He said (p. 299), "These **ecosystems,** as we may call them, are of the most various kinds and **sizes."** Ecosystems are perceived and identified because they have a degree of resilience and resistance to episodic change and thus are able to transcend smaller **time-** and **space-scale** changes.

If we recognize that varying **time-** and **space-scales** are important in the structure of ecosystems, then how should this fact be included in research plans? One approach, based on hierarchy theory as noted above, can use elements of the ecosystem to identify important scales. A second method is to identify important scales in descriptive data.

Such an identification has been attempted elsewhere, and the Committee suggested that climatologists and ecologists refer to earlier attempts by Clark **(1985), Delcourt** and others (1983), Di Castri (1988), and Mason (1970). For example, Delcourt used log-log axes in diagrams that related ecosystem **events** to time scales and/or ecosystem events to space scales. **Thus,** we would display at one end of the scale the activities of soil microbes and, further up the scale, plants and trees in a successional system.

In making these time and space distinctions, we will be addressing the problems of complexity in the same sense as in the concepts of hierarchy theory. Those concepts were applied to ecology by such seminal works as Allen and Starr (1982) and O'Neill and others (1986). In organizing our ideas around specific time and space scales we will be dealing with an organized complexity instead of disorganized complexity. We will find that all parts of the system do not interact at the same time because of the very existence of different time and space scales. For instance, microbial respiration rates are more related to individual rain events than to gap/phase succession events in forests that have been subject to long-lasting droughts. This approach for simplifying organized complexity will enable us to structure our view of systems, but we may need to upgrade our key skills for sampling our systems. In all of these considerations, the functional ecosystem variables assume greater importance than the structural variables. Therefore, the climate variables that relate to ecosystem function rather than to structure should be emphasized.

Thus, we conclude that understanding climate variability and ecosystem response demands that we pay particular attention to space and time scales. We must beware of arbitrarily imposed, human-derived scales and concentrate on those scales that emerge from the functioning of the ecosystem and climate systems. Research should specifically identify those functions and processes of the ecosystem that cannot keep up with potential rates of abiotic change such as postulated global wanning rates.

INDICES FOR INTERSITE COMPARISON

The LTER Climate Committee recognized a continuing need for consistency in obtaining and handling data across the Network. A set of time series analyses across all sites would be useful. Also useful would be new indices, not directly dependent on monthly and annual mean temperature and precipitation values, to extend the information base beyond our earlier work (Greenland 1987). One such index, the date of lake freezing, is ably demonstrated in this volume for the Northern Lakes site. However, this and another index related to storm surge data are specific for the LTER sites and ecosystems they represent.

Other data sets exist that could provide useful and general climatic indices. For example, the Department of Environmental Sciences at the University of Virginia has records of cyclone frequencies since 1885 and 500 to 1000 mb thickness levels for all LTER sites.

An index that seemed to have wide application for intersite comparisons emanated from air mass climatology. Climate at a place is dependent on exposure to a characteristic pattern of air mass types which integrate many climatic elements such as temperature, precipitation, and humidity. Wendland and Bryson (1981) refined the concept of frequency of air mass climatology by using streamline analysis to map airstream regions. The regions are defined by the boundaries between airstreams from different global source areas. Wendland and Bryson traced the source of these air streams by mapping monthly surface level streamlines (*i.e.,* lines of resultant winds along which air actually flows at any given moment). Every LTER site experiences periods during the year when there is a shift between being in the region of one airstream and being under the influence of air from another. An index for comparing LTER sites might be the number of months duration in different airstream regions. The time pattern of airstream regions could also explain the seasonal distribution of precipitation and strong site contrasts such as the extreme between Jornada and Andrews. Variation might increase with distance of a site from the source of the airstream.

Wendland, who pioneered this work, has since examined air mass frequency data for all LTER sites (Table 1). These frequencies can be refined to ensure that the boundaries for the air mass regions are based on data representative for each LTER site. For example, the elevated Niwot site is not expected to be in the same air mass as the Plains site, both based here on Denver data. Table 1 indicates the duration of each air mass from various source regions and suggests the climate for the 1948-1963 period. In another time period, the air mass frequencies might change, especially at sites near the confluences of airstreams. Thus, this data form may provide evidence of moves from one climatic episode to another.

The Committee thus recommends that sites, singly and as a network, investigate new and non-standard climatic indices to supplement the information obtained from standard climatic observations and summaries. Our goal is to define and refine relationships between climatic variation and ecosystem response.

SIMILARITY AND DISSIMILARITY

Outwardly, LTER sites appear so different that useful comparisons are either obvious or else impossible. A benefit of having LTER sites in very different biomes is that broad-scale comparisons, not often available to ecologists, can be made which should give valuable insights into ecosystem function and processes. This was demonstrated during the Workshop when similarities and dissimilarities between sites were examined.

Many sites have not yet identified clear or obvious ecosystem responses to slow climate trends or even to events of mid-scale severity. But most sites have experienced major responses to a severe weather event. The Hubbard Brook ecosystem, for example, was not markedly disturbed by the droughts of the 1960s but still shows the effect of a single hurricane in 1938. This may be yet another example of our inability to perceive long-term changes. Tree blowdown has been a repeated catastrophic wind event at several LTER sites and,

Table 1.—Mean number of months per year of domination by five air mass types for LTER sites, 1948-1963.

Site	North Pacific	North Atlantic and Gulf	Ohio Valley	Arctic	High Plains
Andrews, OR	12				
Sevilleta, NM	11	1			
Konza Prairie, KS	5	5	2		
Hubbard Brook, NH	3	6	3		
Bonanza Creek, AK	2	7	3		
Jornada, NH	2	7	3		
Virginia Coast, VA	1	8	3		
Niwot Ridge, CO	3	5	2		2
Central Plains, CO	3	5	2		2
Okefenokee, 6A		9	3		
North Inlet, SC		9	3		
Coweeta Lab, NC	1	7	4		
Luquillo For., PR		12			
Cedar Creek, MN	3	3	2	3	1
Illinois Rivers, IL	3	4	2	1	2
Northern Lakes, HI	3	4	1	2	2
Kellogg Sta., HI	2	4	2	2	2
Harvard For., HA	1	5	4	1	1
Arctic Tundra, AK	4			8	

since the Workshop, hurricane damage has significantly altered both the North Inlet and Luquillo sites. Many ecological responses are due to secondary effects of atmospheric events, such as flooding or landslides. For example, the redistribution of sediment by an intense rainstorm on the otherwise dry Jornada site has marked consequences on the biota either by burying them or by providing new microhabitats.

Several sites reported possible time coincidence for deviations in climate variables. The years of climatic change suggested by shifts in freezing dates of Lake Mendota, WI, in 1880, 1940, and possibly 1980, were noted as times of change at some other sites and also in general climate data. LTER sites may benefit from examining their own records for common break points in data sets. Data at most sites, as well demonstrated by the Central Plains Experimental Range, follow hemispheric, or at least regional, trends in temperature and precipitation. This augurs well for the extrapolation of results from the LTER network to larger areas. Yet, unique or isolated sites such as Niwot will not display the same spatial and temporal trends as adjacent dissimilar areas.

At first the Kellogg Biological site was believed to be functionally different from other sites because of its emphasis on monoculture of agricultural crops and the attention given to short time-scale investigations emphasizing specific times of the year. These seasonal studies include winter impact on the life cycle of insect pests, spring weather affecting germination, and climatic influences on pollination and seed set. The lesson is that weather events are marked by phenological events, a phenomenon equally true at other LTER sites. The fact that the Kellogg ecosystem defines shorter time scales is another demonstration of the importance of recognizing all time scales as was discussed earlier.

Discussion revealed that many LTER sites had considerably more data than simply monthly means and totals of temperature and precipitation values. In many cases, high-quality data for climate and ecosystem variables coexist. Opportunities were recognized for episodic studies on daily and other time scales in intersite LTER studies.

In summary, several fertile areas for further research can capitalize on the similarities and dissimilarities of climate variability and ecosystem response across LTER sites. These include an investigation of (1) the importance of catastrophic events in relation to slower trends and cycles, (2) the time coincidence of certain major climatic breakpoints which appear to exist at several sites and the effects on ecosystems as they shift from one episode to another, (3) the relationship of climate to phenological studies across the LTER network.

CONCLUSION

Climatic variability and ecosystem response is clearly a topic having all the intricacies of a Gordian knot. Deliberations of the LTER Climate Committee have indicated some important starting points at which the knot may be unravelled. First, we must be very conscious of our terminology. Loose usage of terms may well hinder our conceptualization of reality. Second, we must put considerations of scale at the beginning of our investigations instead of making *a priori* assumptions about them. There is a tendency, of which we must be cautious, to impose human-oriented concepts of scale on our real systems instead of letting the functions of the ecosystems themselves define our scale for us. Third, we have identified some exciting ways by which we can go beyond the use of simple temperature and precipitation values to relate to ecosystem functions or define breakpoints between climatic episodes. Finally, insights gained by comparing similarity and dissimilarity between the LTER sites will improve understanding of on-site ecosystems as well as explain intersite variation.

None of these ideas are new; but within the context of climate variability and ecosystem response at LTER sites, they take on a new significance. The highly disparate nature of LTER sites allows the Committee to search for indices like air mass frequency that go beyond information restrained to local observations alone. This opportunity can lead to a broader search for new concepts and techniques in ecosystem science as a whole. The LTER Climate Committee Workshop generated ideas and concepts that should facilitate notable progress in understanding climate variability and ecosystem response.

REFERENCES

Allen, T.F.H.; Starr, T.B. 1982. Hierarchy: perspectives for ecological complexity. Chicago: University of Chicago Press. 291 pp.

Clark, W.C. 1985. Scales of climate impacts. Climatic Change. 7:5-27.

Delcourt, H.R.; Delcourt, P.A.; Webb, T. 1983. Dynamic plant ecology: The spectrum of vegetation change in space and time. Quaternary Science Reviews. 1:153-175.

Di Castri, F. 1988. Enhancing the credibility of ecology: Interacting along and across hierarchical scales. GeoJournal 17(1):5-35.

Greenland, D., ed. 1987. The climates of the Long-Term Ecological Research sites. Occasional Paper 44. Boulder, CO: Institute of Arctic and Alpine Research. 81 pp.

Kunkel, Kenneth E.; Court, Arnold. 1990. Climatic means and normals — A statement of the American Association of State Climatologists (AASC). Bulletin American Meteorological Society. 71(2):201-204.

Mason, B.J. 1970. Future developments in meteorology; an outlook to the year 2,000. Quarterly Journal of the Royal Meteorological Society. 96:349-368.

O'Neill, R.V.; DeAngelis, D.L; Waide, J.B.; Allen, T.F.H. 1986. A hierarchical concept of the ecosystem. Princeton, NJ: Princeton University Press. 253 pp.

Strayer, D.; Glitzenstein, J.S.; Jones, C.G. [and others]. 1986. Long-term ecological studies: An illustrated account of their design, operation, and importance to ecology. Occasional Publication 2. Millbrook, NY: Institute of Ecosystem Studies. 38 pp.

Tansley, A.G. 1935. The use and abuse of vegetational concepts and terms. Ecology. 16:284-307.

Walsh, J.E.; Richman, M.B. 1981. Seasonality in the associations between surface temperature over the United States and the North Pacific Ocean. Monthly Weather Review. 109:767-783.

Weatherhead, P.J. 1986. How unusual are unusual events? American Naturalist. 128(1)150-154.

Wendland, W.M.; Bryson, R.A. 1981. Northern Hemisphere airstream regions. Monthly Weather Review. 109:255-270.