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An Introduction to Climate Variability and Ecosystem Response

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The regularities of our planet's climate determine a large part of the form and function of Earth's ecosystems. The frequently nonlinear operation of the atmosphere gives rise to a rich complexity of variability superimposed on the fundamental regularities. A traditional definition of climate is "the long-term state of the atmosphere encompassing the aggregate effect of weather phenomena—the extremes as well as the mean values" (Barry and Chorley 1987). Ecosystems share some of the same properties as the climate system. At one level their operation is fairly straightforward. Ecologists, to a certain extent, understand the flows of energy and matter through these systems. A good deal of ecosystem operation over time is characterized by some degree of homeostasis. On the other hand, nonlinear change and multiple variables have placed uncertainty and surprise at the forefront of much ecological research. In both the climate and the ecosystem the only certainty often appears to be change. The task of this book is to focus on some of this change at the interface between the climate and the ecosystem and by doing so gain insights into the operation of both systems.

The Theme of the Book

Millennial-scale (1000-year) climate variability has driven large changes of vegetation and fauna at almost all of the Long-Term Ecological Research (LTER) sites. Decadal climate variability at some sites has seen dramatic changes in fish catches and has altered tree species composition. During the first two decades of study, LTER sites have been affected by two super El Niño events and several more "normal" El Niños and La Niñas. Major droughts have affected species diversity and killed some trees. Severe storms and floods have damaged stream restoration structures. Coastal sites have measured a rise in sea level. Antarctic sites have documented the decrease of some penguin populations and a rise in other populations as a result of climatic warming over 50 or more years. Climate variability has constantly been on investigators' minds. It is little wonder that ecologists clearly recognize climate as a driver of biotic systems. Parmesan and her coworkers describe how climate affects individual fitness, population dynamics, and the distribution and abundance of species, as well as ecosystem structure and function (Parmesan et al. 2000). They relate how regional variation in climatic regimes creates selective pressures for the evolution of locally adapted physiologies, and morphological and behavioral adaptations. They quote the curious fact that climate even determines gender in some species. Map turtles (*Graptemys*) produce only males if the incubation temperatures are below 28°C and only females if the incubation temperatures are above 30°C (Bull and Vogt 1979). The implications of a steep warming trend for this species are dire! The role of climate as a driver of ecosystems has important practical implications for ecology. For example, Swetnam and Betancourt (1998) make clear that regional climate signals existing in ecosystems must be extracted before variations in ecosystem components can be attributed to other causes.

The theme of this book is how ecosystems respond to climate variability. This theme is examined at a variety of LTER sites and over a variety of timescales. The subject matter of the book is focused on a series of questions that are outlined here. The theme of climate variability and ecosystem response is inherently deterministic and implicitly carries with it the notion of climatic cause and ecosystem result. The analyses in this volume will amply demonstrate that this is a valid and fruitful working assumption. However, we acknowledge that this approach is limited in several senses. First, we recognize that, although in many instances climate may be recognized as the prime ecosystem driver, it is becoming increasingly clear that many ecosystem functions directly or indirectly affect the climate (e.g., Hayden 1998a). Second, there are many factors, both biotic and abiotic, that affect ecosystems besides climate. Third, many internal operations of ecosystems lead to ecosystem response and change. Fourth, many aspects of climate variability and ecosystem response have important implications for human systems. Human activities can sometimes overwhelm or strongly modify climatic influences. The change from grassland to shrubland over the last 150 years at the Jornada and Sevilleta LTER sites is an interesting example (chapters 17 and 15). It is impossible for us to deal with all these aspects, and so some degree of focus is necessary. That focus is provided by the more "simple" climate variability and ecosystem response approach. We also concentrate, for the most part, on results of research conducted at LTER sites. We are well aware that many other researchers and groups are addressing the issue of climate variability and ecosystem response within other contexts.

Despite these caveats, we think it is legitimate to treat climate variability as a prime driver of ecosystem responses. In this volume we also tend to approach climate in isolation from other factors. Climate differs from other ecosystem drivers: It has a certain regularity, expectedness, and predictability. Even in the areas of uncertainty, it is often possible to put outer bounds on the kinds and sizes of variability that might be expected. This cannot be said with so great a confidence for many biotic factors. Directional evolutionary trends in some cases, and complete extinction in other cases, make the biotic world a very surprising one. When one adds such anthropogenic factors as land-use change, genetic engineering, and the development of new technologies, the uncertainties mount ever higher. Our approach in dealing with what we know about climate variability and ecosystem response is simple, but it contains the possibility of developing new knowledge.

The LTER Program

The LTER program conducts and facilitates ecological research at 24 sites in the United States and the Antarctic. More sites are likely to be added to the LTER network in the future. There is also an important and growing International LTER (ILTER) program (LTER Network Office 1998). The U.S. LTER research sites operate as a network with a network office located at the University of New Mexico at Albuquerque. The network is a collaborative effort involving more than 1100 scientists and students. The current 24 LTER sites are located in various biomes throughout the United States and Antarctica (figure 1.1; Callahan 1984; Franklin et al. 1990; Van Cleve and Martin 1991; http://lternet.edu/). One of the missions of the LTER program is to conduct a cross-site synthesis. LTER research, like much Global Change research, focuses mostly on timescales of months to centuries. The operation as a network enables LTER to address large-scale questions concerning ecological phenomena such as the variations in stream organic matter budgets across the United States (Webster and Meyer 1997). The network also creates opportunities for comparisons between ecosystems across regional, continental, and global gradients such as organic matter decomposition (Long-Term Intersite Decomposition Experiment Team [LIDET] 1995). The network operation also allows scientists to distinguish system features controlled by absolute and relative scales. Neither the large-scale questions, such as what the decomposition rates are across the country, nor questions of absolute and relative scale, such as how decomposition rates vary along soil moisture gradients within LTER sites, can usually be answered without a detailed specification of the climate of LTER sites. The importance of cross-site synthesis has been expressed by an external review of the program as follows: "The power of the network approach of the LTER program rests in the ability to compare similar processes (e.g., primary production or decomposition of organic matter) under different ecological conditions. As a result, LTER scientists should be able to understand how fundamental ecological processes operate at different rates and in different ways under different environmental conditions" (Risser and Lubchenco 1993).

Two other features of the LTER program are important in the present context. First, the program prides itself on its interdisciplinary nature. The wide range of ecosystems studied demands that these studies be made in an interdisciplinary manner and that no single subdiscipline dominate. The LTER program also prides itself on its environmental information management system. This information man-

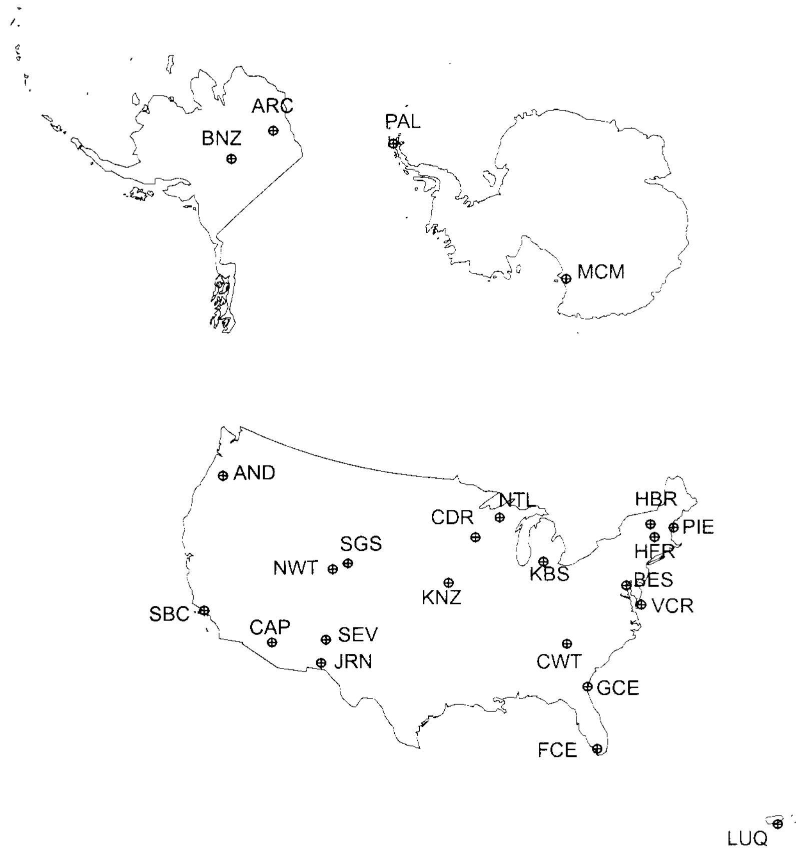

Figure 1.1 Location of the LTER sites. For an explanation of codes, see table 1.1 or the list of abbreviations in the frontmatter of the book.

agement system, and its climate data component, is regarded as a model for such systems worldwide (Michener et al. 1998; Baker et al. 2000).

The LTER program encourages coherence in ecological research over the long term to take advantage of the fact that many ecosystem processes operate at long time scales and show directionality and periodicity. Studies that have recognized this (e.g., at Hubbard Brook [Likens and Bormann 1995; Likens et al. 1996]) have made fundamental contributions to ecology. Within these sites it was found that human-derived as well as natural perturbations act over a long time period.

Studies at the LTER sites are organized around five core themes: (1) pattern and control of primary production, (2) spatial and temporal distribution of populations selected to represent trophic structure, (3) pattern and control of organic matter accumulation in surface layers and sediments, (4) patterns of inorganic input and movement through soils, groundwater, and surface waters, and (5) patterns and frequency of disturbance. Although climatic aspects affect all these themes, the role of climate is paramount in the last theme.

The LTER sites (table 1.1; figure 1.1) were not selected primarily to give good geographic coverage. They were selected first based on the quality of research proposed at the site. As a result, the sites together do not necessarily provide a systematic spatial coverage of the country or its climate and biomes. The network was not designed to replicate the spatial cover of meteorological observations given by the National Weather Service stations. The temporal rather than the spatial emphasis of the LTER network is one of the reasons why this book takes on a structure categorized by timescale.

The LTER Program and Climate

Both ecologists and climatologists recognize climate research as having a key role in long-term ecological research. Climate is one of the largest driving forces of ecological and hydrological processes at all of the LTER sites. Each LTER site is required to organize its 6-year research program around a central fundamental working hypothesis. A majority of the sites have climate as a central component of their research hypothesis. For example, one of the central questions of the H. J. Andrews Experimental Forest LTER research is, How do land use, natural disturbance, and climate change affect three key ecosystem properties: carbon dynamics, biodiversity, and hydrology? The goals of the Arctic LTER Project are to understand how tundra, streams, and lakes function in the Arctic and to predict how they respond to changes, including changes in climate. It is therefore essential to investigate the climate of the LTER sites in a systematic manner. Each LTER site maintains its own climate program and, at many sites, climate data represent the longest time sequence of data available. Increasing attention to possible ecological consequences of global climate change requires that we understand how climate varies and what the potential is for rapid directional climate change (LTER 1989; Greenland and Swift 1990 and 1991; IPCC 2001).

An example of the importance of long-term climate, or climate-related, information to ecosystem science may be taken from an aquatic LTER site. The number of days of ice cover on Lake Mendota, Wisconsin, which is part of the North Temperate Lakes (NTL) LTER site, illustrates the importance of long-term records and the need for benchmark climatic studies (Magnuson 1990; Robertson et al. 1992; Magnuson et al. 2000). If one started observing in 1998, one might conclude there are about 50 days of ice cover on the lake. However, the data for the decade 1989–1998 indicate that the average length of ice cover was about 100 days and that the 1998 value was "unusual." Fifty years of data (1949–1998) show a downward trend from about 110 to 90 days, with El Niño years having very short values of ice cover, as in 1998. The complete observed record starting in 1856 confirms the downward trend in the number of ice cover days as well as suggests interesting interdecadal variability. The duration of ice cover in this aquatic ecosystem determines the productivity and activity at all trophic levels during the ice-free summer period.

Although many of the analyses presented in this volume could be made with any subset of data from U.S. climate stations or climate divisions, there are specific rea-

Table 1.1 Long-Term Ecological Research (LTER) Sites

Site	Abbreviation	Ecosystem	Climate
H. J. Andrews Exp. Forest (Oregon)	AND	Coniferous Forest	Marine West Coast
Arctic Tundra (Alaska)	ARC	Arctic Tundra	Arctic Tundra
Baltimore Ecosystem Study (Maryland)	BES	Urban Ecosystem	Moist Subtropical (urban)
Bonanza Creek Exp. Forest (Alaska)	BNZ	Boreal Forest	Subarctic
Central Arizona, Phoenix (Arizona)	CAP	Urban Ecosystem	Desert (urban)
Cedar Creek Nat. History Area (Minnesota)	CDR	Hardwood Forest/ Tallgrass Prairie	Humid Continental
Coweeta Hydrol. Lab. (N. Carolina)	CWT	Deciduous Forest	Humid Continental
Hubbard Brook Exp. Forest (New Hampshire)	HBR	Northern Hardwood	Humid Continental
Harvard Forest (Massachusetts)	HFR	Hardwood/Whitepine/ Hemlock	Transition Humid Continental
Jornada (New Mexico)	JRN	Desert	Subtropical Desert
Kellogg Biological Station (Michigan)	KBS	Agricultural	Humid Continental
Luquillo Exp. Forest (Puerto Rico)	LUQ	Tropical Rainforest	Tropical Rainforest
Konza Prairie (Kansas)	KNZ	Tallgrass Prairie	Midlatitude Steppe
North Temperate Lakes (Wisconsin)	NTL	N Temperate Lake Mixed Forest	Humid Continental
Niwot Ridge/Green Lakes Valley (Colorado)	NWT	Alpine Tundra	Highland
Plum Island Ecosystem (Massachusetts)	PIE	Coastal Estuary	Moist continental
Sevilleta (New Mexico)	SEV	Desert/Grassland/ Forest Transition	Low-latitude Desert
Shortgrass Steppe Formerly Central Plains Exp. Range (Colorado)	SGS/CPR	High Plains Grassland	Midlatitude Steppe
Virginia Coast Reserve (Virginia)	VCR	Barrier Island	Humid Subtropical
Florida Coastal Everglades (Florida)	FCE	Freshwater Marsh, Coastal Estuary	Humid Subtropical
Georgia Coastal Ecosystems (Georgia)	GCE	Barrier Island	Humid Subtropical
Santa Barbara Coastal (California)	SBC	Semiarid Coastal and Marine	Mediterranean
McMurdo Dry Valleys	MCM	Desert Oases	Polar Ice Cap
Palmer Station Antarctica	PAL	Coastal and Ocean Pelagic	Polar Marine

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sons for concentrating on LTER sites. First, the analyses are directly focused on the LTER sites that have a legacy of ecosystem research. Second, the sites have ongoing, coherent programs of ecosystem research. Third, several of the LTER sites have climate stations at places rarely sampled by national weather observing systems. The alpine tundra NWT D1 site at an elevation of 3749 m (12,300 ft.) is a case in point.

It is helpful to pause and reflect on exactly what the "climate" in climate variability and ecosystem response actually is. This question is raised by Goodin et al. (chapter 20) for the context of Net Primary Productivity (NPP) at the Konza Prairie. In this specific context the "climate" has been defined using values of air temperature, precipitation, and pan evaporation with various indexes derived from these variables, while bearing in mind subsets of time such as the "growing season." We use the term *climate* differently for almost every different ecosystem considered in this book. The climate that ecosystems experience is most truly represented by values of heat, moisture, gas, and momentum exchange at what the Russian scientist Alexander I. Voeikov called in 1884 the "outer effective surface" of the ecosystem components. Except in cases of the most detailed microclimatological studies, ecologists and climatologists usually deal with values of variables such as air temperature and precipitation that act only as surrogates of the variable that we ought to be measuring. Thus we see "through a glass darkly." This approach is forced on us partly by practical and economic considerations and partly because most meteorological observing networks are established with weather forecasting rather that climate/ecosystem interaction purposes in mind.

Climate Variability and Ecosystem Response in the LTER Program

The LTER community has provided insights into the area of climate variability and ecosystem response at several meetings over the last two decades. The insights may act as a point of departure for the present volume. In several cases the insights previously noted have become even more important as new discoveries have been made.

First, we are reminded that long-term studies are especially suited to exploring four major classes of long-term ecological phenomena (Strayer et al. 1986). Strayer and coworkers identify these phenomena as (1) slow processes, (2) rare events, (3) subtle changes in the systems, and (4) complex processes involving multivariate studies where the long-term context can add degrees of freedom to the solution of the problem. The first three of these classes of change may readily be identified in climate data and the fourth is also applicable to climate data in certain circumstances.

The 1988 LTER Climate Committee focused on four main areas of climate variability and ecosystem response (Greenland and Swift 1990, 1991): (1) the importance of terminology, (2) the ubiquitous importance of time and space scale, (3) a consideration of climatic indexes, other than temperature and precipitation, which may be useful in ecosystem studies, and (4) the similarities and the dissimilarities among the LTER sites. Scale is so important that we will consider it throughout this volume.

Regarding terminology, the consensus was that climate variability should be taken as a given and we should concentrate on "episodes" and "events" within the existing variability. An *event* is taken as a single occurrence such as an individual large rainstorm often embedded in the functioning of the synoptic climatic scale. An *episode* is taken as a string of items and is in some way related to the time constant of the system. Events or short-lived episodes often have the characteristic of resetting the time clock of the system. They are marked by a large change in the ecosystem at the time of the occurrence, followed by a long tail of less obvious adjustments. The operation of streams is a good example of this. Although not all the authors in this volume use this terminology, we find it very useful in the concluding section (chapter 21) of this book when comparing the climatic variability and ecosystem response among LTER sites.

There are at least three, often overlapping, kinds of climate episodes. Each of these must be distinguished to minimize confusion. First, there are climate episodes defined by the data of the climatic series themselves, their time series, and indications of changes of states. Second, there are climatic episodes as perceived by humans, which, though often described by means of climatic data, are importantly frequently related to the timescale of the human life span, somewhere between 40 and 80 years. An example would be the drought of the Dust Bowl years in the 1930s in the United States. Third, there is the type of climate episode as perceived, or defined, by the individual components, or groups of components, of the ecosystems themselves. The latter type is especially scale dependent and important to Long-Term Ecological Research. There is a tendency to impose human-oriented concepts of scale on our systems instead of letting the functions of the ecosystems themselves define the scale that is most important.

Similarities and dissimilarities across the LTER network were considered in 1988, and many of the issues remain the same today. Many LTER sites do not yet show clear or obvious ecosystem effects from slow trends or even from intermediate-scale events but do show a marked effect to a severe atmospheric event. As the LTER program has developed over the past two decades, the presence in the ecosystem of the legacy of a severe atmospheric event or episode has emerged as a signature finding at almost every LTER site. The Hubbard Brook ecosystem, for example, was not markedly affected by the droughts of the 1960s, but the ecosystem still shows the effect of a single hurricane that traversed its area in 1938 (Merrens and Peart 1992). Major ecosystem changes stem from catastrophic events at many LTER sites. Windthrow of trees is a repeated catastrophic event. However, many ecological events that owe their existence to atmospheric occurrences are mediated through the operation of geomorphic processes. The redistribution of sediment, for example, in the dry Jornada, New Mexico, site during an intense rainstorm may have marked consequences on the biota either by covering them or by providing new microhabitats.

Most LTER sites follow hemispheric, or at least regional, trends in temperature and precipitation (Greenland and Kittel 2002). This bodes well for the extrapolation of results from the LTER network to larger areas. Yet, occasionally, as in the case of the Niwot Ridge, Colorado, data, larger spatial and temporal trends are not displayed by an individual LTER site. Even more specifically, Pielke et al. (2000) conclude the spatial variation in climate variables indicate that the direction and magnitude of regional climate trends cannot necessarily be inferred from single-site records, even over relatively homogeneous terrain. They based their analysis on the other Colorado LTER site, the Short Grass Steppe site. When examined in 1988, several sites showed time coincidence for changes in the values of certain variables. The change in the lake freezing data of the North Temperate Lakes in 1880, 1940, and possibly 1980 was reflected in different series at other sites and is also reflected in general climate data. Since that time, a major LTER-related project at NTL has demonstrated the hemispherewide concurrence in the thawing dates of lake ice (Magnuson et al. 2000).

We should also note that the geography of the LTER network is such that particular spatial scales are emphasized. The individual LTER site is typically 50 km or less between boundaries. A few—PAL, NTL, CWT, and SEV—are rather larger. An exercise to investigate the spatial representativeness of individual LTER sites concluded that most sites generally represented a larger area than the size of the site itself, but that area was quite variable from site to site (http://lternet.edu/collaborations/syn_09.html). Consequently, the emphasis of many, although not all, LTER studies is at the local or regional scale. On the other hand, the distribution of sites (figure 1.1) does sample much of the North American continent and part of the Caribbean and Antarctica and a wide variety of climates (figure 1.2). Indeed, there is a significant latitudinal gradient between the Arctic Tundra (ARC, 68.6° N) and Palmer Station (PAL, 64.7° S) and the stations in between. This sampling is not systematic in terms of spatial distribution. The current network of sites is biased toward mid- and high latitudes. Results from cross-site studies therefore represent gradients of variables and processes rather that the systematic geographic distribution of the variables and processes. The LTER network of sites is oriented primarily to "long-term" rather than "large-area" studies.

The 1988 workshop suggested several fertile areas for further research related to 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 that appear to exist at several sites and the effects on the ecosystems of the related changes from one episode to another, and (3) the relationship of climate and phenological studies across the LTER network. Some progress has been made on the first two, but LTER scientists have paid little attention to the third even though the topic is receiving considerable attention elsewhere (Schwartz 1999). Participants in the 1988 workshop also identified some exciting ways, such as airmass analysis, by which we can go beyond the use of simple temperature and precipitation values in defining breakpoints between climatic episodes. This technique has been explored effectively for the Konza Prairie LTER site by Hayden (1998b).

A 1997 LTER workshop on climate variability and ecosystem response was equally fruitful. The growth of the LTER network has led to a greater diversity of ecosystems studied and consequently a wider range of the types of interactions be-

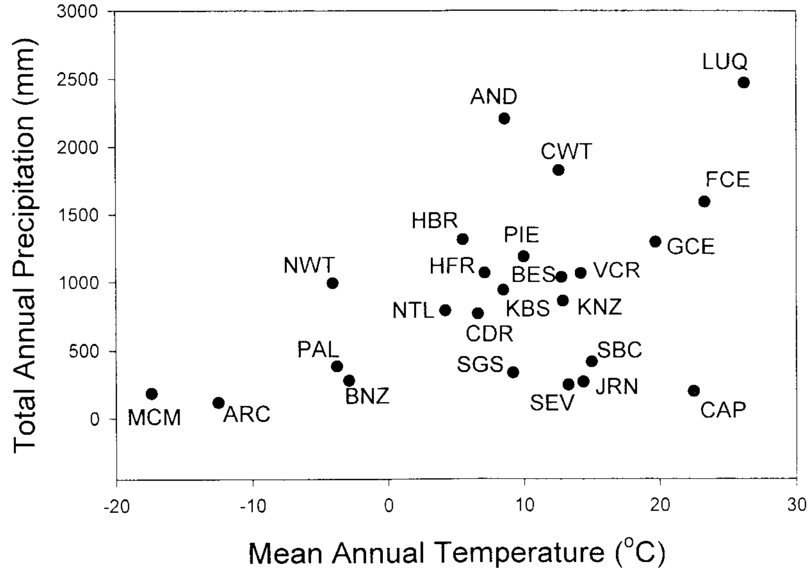

Figure 1.2 Distribution of LTER sites by annual mean temperature (°C) and total annual precipitation (mm). Data are for the period 1961–1990. For an explanation of codes, see table 1.1 or the list of abbreviations in the frontmatter of the book. Reprinted with permission from Greenland et al. 2003. Long-Term Research on Biosphere-Atmosphere Interactions. *BioScience* 53(1):33–45. Copyright American Institute of Biological Sciences.

tween climate and ecosystems. A sampling of the papers presented at the workshop demonstrates this, as discussed subsequently.

Some papers of the 1997 workshop were consistent with the suggestion of warming in the high latitudes of Earth. Dr. Fraser of the Palmer Marine Antarctic site examined, with some success, the hypothesis that changes in the population abundance of penguins occur when environmental frequencies no longer match the requirements of evolved life histories. The environment has seen a decrease in frequency of cold years with heavy ice over the last 50 years and a 4–5°C increase in temperature (chapter 9). Drs. Chapin and Juday of the Bonanza Creek Boreal Forest site in Alaska documented strong climate warming in last three decades, which has led to the melting of permafrost and the earlier breakup of ice from rivers. Furthermore, a higher snow amount tends to open the crowns of trees, providing more suitable conditions for the outbreak of spruce budworm infestations (chapter 12).

Workers from other LTER sites investigated the longer term paleoclimatic aspects of their environments. Caroline Yonker noted three periods of climatic instability in the Holocene paleosoils of the Shortgrass Steppe in Colorado. Dr. Laura Huenneke of the Jornada site is interested in separating the climatic and human influences on desertification processes. She uses evidence from C_3 and C_4 vegetation in buried soils to suggest that human modifications of the landscape are superimposed on natural long-term cycles of landscape stability and instability. Further evidence is found on terraces in the Rio Grande valley and nearby eolian deposits. By way of contrast, Janice Fuller, at the Harvard Forest site, provided pollen evidence to suggest that European settlement activities may have obscured the effect of natural spatial climate change in the New England area. Dr. Fountain reported that the lakes of the McMurdo Dry Valleys in Antarctica have a layer of saline water that could possibly be sea water left over from the past. Furthermore, organic carbon in the Taylor Valley may be associated with a paleolake in the valley (chapter 16).

Scale

Scale is an ever-present issue in many disciplines of science. Scale is so important that, in many ways, it determines the kinds of questions that may be asked about the operation of the ecosystem, and it often determines the answers to the questions as well. A specific recurrent issue is how to relate the scales at which climate systems operate to those scales at which the biotic parts of the ecosystems operate. The 30-year period over which "climatic normals" are taken is an artificial human construct and may have little bearing on ecosystem realities. Decadal averages of climate data might be more meaningful. At the very least, we should recognize that the averaging period will have a very large role in what we consider to be an "episode." The definition of climate as perceived by the individual component of the ecosystem is directly related to scale. A soil microorganism might regard an individual rainstorm as a significant climatic event, whereas a tree at the Andrews LTER site in Oregon would be acclimated to a "climate" far exceeding any 30-year climatic period. The ecosystem responder defines its own climatic scale.

The Framework Questions

In planning this volume we decided to focus on a set of questions that emphasize the dynamic nature of climate variability and ecosystem response. An important consideration was the need for generalization. Within the LTER program, modeling is a fertile method for generalization. Whereas the material we deal with does not lend itself to cross-site modeling per se, we decided to ask questions that will lead to a modeling framework. With this in mind, we next discuss the questions that were used at the outset.

The first framework question is, What kind of climate variability is being investigated? 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; (6) an oscillation in which the interval between the maximum and minimum values is approximately equal is called a periodicity, particularly where the maximum and minimum values are more or less equal over the period of interest. Even at the outset, we recognize that one or more of these types of climatic variability may operate simultaneously at any one LTER site. In addition, the distinction between the different types of climatic variability is not always clear, as is pointed out by McHugh and Goodin (chapter 11).

The next part of the framework consists of a series of questions.

1. 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. Is the climate effect direct or does it go into a cascade? If a cascade is entered, how many levels does it have and is the interaction between each level linear or nonlinear? A cascade system is generally regarded as one that exhibits flow of material, energy, or information (Chorley and Kennedy 1971; Strahler 1980; Thomas and Huggett 1980). This is one of the more important questions. In introducing the framework questions, we note that the question about the existence of cascades, or a cascading set of events, lays the groundwork for systems analysis and modeling approaches. During this cascade identification, or modeling process, the parts of the cascade about which little is known are sometimes highlighted, thus establishing a potential agenda for further research needs.
3. Is the primary ecological effect completed by the time of the next climatic event or episode (or part thereof) or not? If the effect is complete, we may consider 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.
4. Does the climatic event or episode or the ecological response 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 limits that may exist in later parts of the cascade.
5. Does the climatic event or episode or ecosystem response reverse to some original state? If so, what timescales 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 has occurred, do the values of the climatic or ecosystem 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 of these questions relate to a deterministic, nonchaotic system. We may also ask whether the system is chaotic or random. If the system is random, 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 must compute, or otherwise find, the parameters of the chaos such as its attractors and Lyapunov exponents.

This initial framework is summarized for convenience in a schematic in figure 1.3. A complete answer to these questions would place investigators in a good position to develop a model of the important climate variability and ecosystem re-

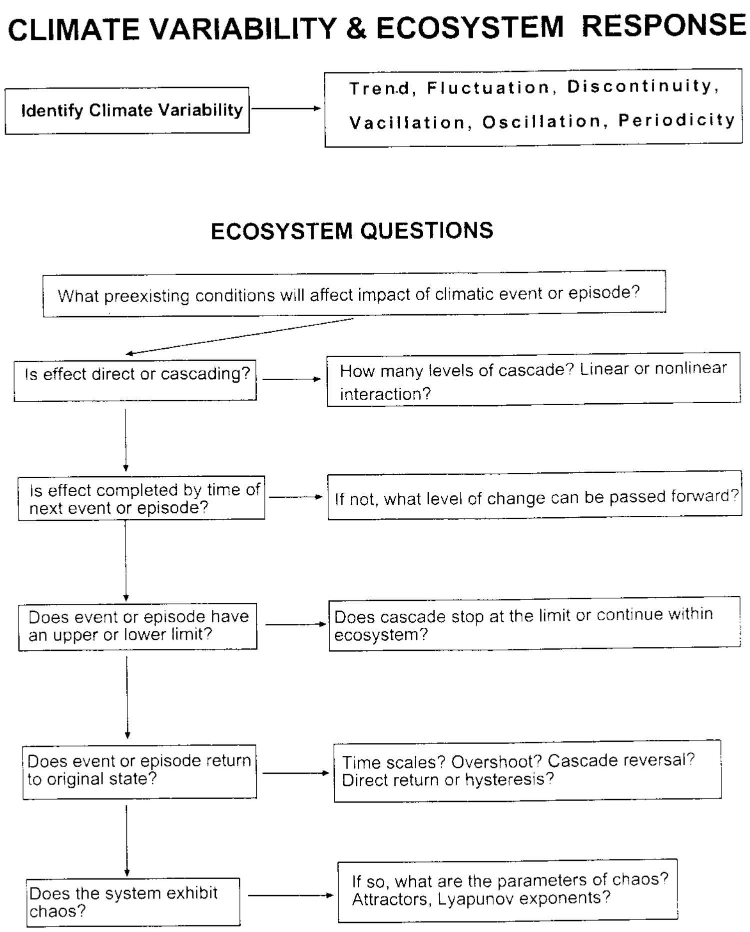

Figure 1.3 Schematic of the original framework questions used in the book.

sponse factors for the LTER site in question. Possibly more important, the aim of the questions is to ensure that the topic is treated in a systematic and thorough manner. The questions were "field tested" in conference presentation and in print (Greenland 1999) and found to be quite useful. Once more we recognize the limitations of this "one size fits all" approach, but we believe the need for focus and the quest for generality surpass the inherent limitations of any particular set of questions. The authors of the chapters in this book were presented with an early version of these questions and asked to address at least one or more of them in the preparation of their chapter. They were free to choose whether to deal with the question implicitly or explicitly.

After all the individual investigations that form the chapters of this book were complete, we reexamined the framework questions. We found that some changes in the ordering of the questions was necessary and that some questions are more fruitful than others. In retrospect, the framework questions fall into two categories (fig-

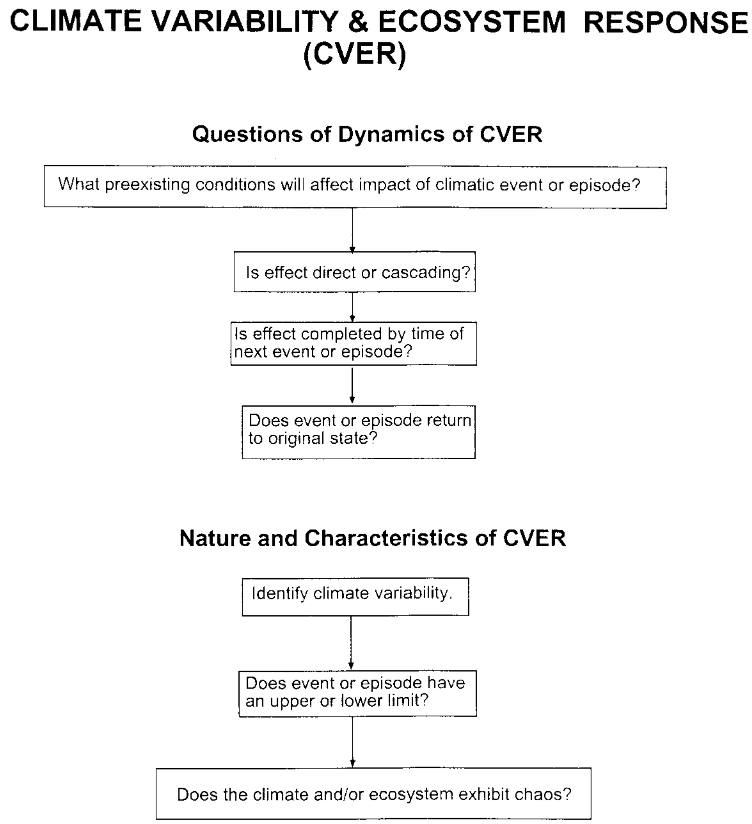

Figure 1.4 Schematic of the revised framework questions used in the book.

ure 1.4). The first category deals with the dynamics of climate variability and ecosystem response and assumes an underlying temporal sequence. The questions that fall most naturally into this category are those dealing with the preexisting conditions, the cascade of effects, whether the effects are completed by the time of the next climatic event or episode, and whether the event or episode and/or the ecosystem return to some original state. The second category of questions deals with the nature and characteristics of climate variability and ecosystem response. The questions of this type include the identification of the climate variability, whether the event or episode and/or the ecosystem response have an upper or lower limit, and whether the climate and/or ecosystem exhibit chaos. The discussion in the final chapter of the book (chapter 21) resequences the framework questions to better match the distinction between these two categories of questions.

Most of the questions that refer to the ecosystem are dependent on the scale of the particular ecosystem under consideration. On the other hand, the climate variability usually crosses multiple timescales and often has its root causes in other, larger, spatial scales. Both climate variability and ecosystem response, and the questions relating to them, cross multiple temporal scales. Beyond the scope of this book is the probability that the ecosystem effects may also be large spatial-scale effects and that the ecosystem effects may ultimately feed back on to the climate system at multiple scales.

Overview of Book

Two nonmutually exclusive sets of concepts emerge from our studies. The first set of concepts is that initial and intermediate cascade elements may act as gateways, filters, and/or catalysts to the climatic signal. Gateways can be open or closed; that is, they can either permit the passage of material, energy, or information or not. Filters may pass a variable amount of material, energy, or information along through the cascade. This amount varies from all to none and includes all the possibilities in between. Thus, the filters in the system help promote a buffering function to a climate disturbance. Catalysts occur where the presence of one component greatly enhances the effectiveness of two or more other components in the system. The second set of concepts deals with classes of ecosystem response to climate variability. There are at least three broad classes of interaction between systems and climate. First, the ecosystem buffers climate variability. Second, the ecosystem simply responds to individual climate events and episodes that exceed some threshold for response. Third, the ecosystem moves into resonance with the climatic variability with positive and negative feedbacks that produce a strong ecosystem response. These two sets of concepts will be discussed in the final chapter.

This first chapter of this book is an introduction to the general topic of climate variability and ecosystem response in the LTER program. We have also introduced our framework questions. Chapters 2–20, which form the body of the work, are organized into five parts, each one, except part V, dealing with the separate timescales at which we are looking. Each part, except part V, has its own introduction and a section synthesizing the material and results as they apply to the particular timescale being studied. Part I considers the short timescale ranging from an individual storm to a year or less. Part II focuses on the quasi-quintennial scale and concentrates on events that have a recurrence interval of about 5 years, such as the El Niño–Southern Oscillation. The group of chapters in part III addresses the timescale of several decades. Part IV treats climate variability at the century to millennial timescale. Individual chapters do not always fit with ease into one or the other divisions of timescales. Perhaps the best example of this is chapter 14, which deals with individual short period extratropical storms. The frequency of these storms is found to vary at a century timescale. Similarly, the Sevilleta chapter (chapter 15) could equally well fit into the quasi-quintennial or the decadal or even the century-scale section. Part V includes chapters from individual sites that cover the topic at several timescales. This material seeks to address the issue of climate variability and ecosystem response without being constrained to a particular scale. Chapter 21 is a review of the answers to our framework questions, concluding comments, and suggestions for further research.

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