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THE ROLE OF CLIMATE IN FOREST MONITORING AND ASSESSMENT: A NEW ENGLAND EXAMPLE

THE ROLE OF CLIMATE IN FOREST MONITORING AND ASSESSMENT: A NEW ENGLAND EXAMPLE

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ABSTRACT

The development of climatological information products to support ecological data collection and analysis is described. The scope of research is narrowed to issues of direct interest to the joint U.S. Environmental Protection Agency Environmental Monitoring and Assessment Program and U.S. Department of Agriculture Forest Service New England Forest Health Monitoring program.

Characteristics of climatological persistence and recurrence that are especially critical to New England forest health and productivity are identified. These include physical disturbance events (tornadoes, high winds and wet snowfall), drought, growing degree days and late spring freezes. Climatological data are assembled and presentations developed based on the analysis issue to be addressed: background (status and persistence); most recent decade (short-term trends); and most recent sampling year (near-term impacts). A Geographic Information System is used for presentation, data management and analysis.

Major research findings focus on the application of climate data and products to operational ecological monitoring and analysis situations. Possible future activities are identified in the areas of new climatologies, program design, database acquisition or development and applied research. All these efforts would result in significant contributions to the development of a more coherent theory of natural disturbance and ecosystem response.

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I. Background

I.A. Project Overview

The primary goal of this report is to define a working hypothesis of climate/ecosystem interactions suitable for operational environmental monitoring programs. Such an exercise is necessary before climate research and analysis can become an integral part of these programs. Although the research has focussed on a specific cooperative EPA and USDA sampling project initiated during 1990, insights are provided pertinent to the general topic of climate/biosphere interactions.

The approach adopted is to establish a common ground of concepts and terminology to facilitate exchanges between the climatological and ecological communities. This is accomplished through the careful definition of key terms and a discussion of the role of climate in current ecological theory (see section I.B. below). The discussion provides an avenue for identifying major environmental policy issues, establishing which of these are significantly climate related, and initiating work on the necessary data and analysis products.

The hypothesis that is developed is that the relationship of climate (the synthesis of weather) to ecosystems depends on the time and space scale of the biological system to be monitored and the analyses to be performed. Climatological averages and ranges reflect one set of physical bounds on the number of possible ecosystem states represented within a landscape. Inter-annual climate variability acts as ecosystem disturbances. Disturbance phenomena impact ecosystem health and productivity as measured by changes in growth, system energetics, plant populations and species characteristics. Disturbance events impact the persistence and recurrence of ecological states. Disturbance events vary with geographic location and can be described by their frequency, size and magnitude. Many EMAP and FHM indicators, particularly those based on directly monitored observations, may not be correctly interpreted and valid associations drawn without consideration of mitigating or compounding climatological factors. A climatological description of background persistence and disturbance regimes is essential if associative (EMAP) or predictive modeling studies (FHM) are to include natural as well as anthropogenic forces of ecosystem change.

This hypothesis is illustrated with data drawn from a particular region. The focus of this effort is the presentation of relatively familiar climatological products and ideas in new ecological contexts. Chapter II describes the cooperative Environmental Monitoring and Assessment Program (EMAP) and New England Forest Health Monitoring (NEFHM) programs, presents current

data resources, future data resources, analysis techniques and display technologies which may be employed. The summaries and analysis products themselves are presented in Chapter III. A summary and listing of future research and application opportunities suggested by this reported are provided in Chapter IV and Appendix A. Additional climatological references of potential interest for work in the New England area are presented in Appendix B.

I.B. Definitions and Conceptual Frameworks for Forest/Climate Research

I.B.1. Definitions

Because the study of climate/ecosystem interactions is a rapidly evolving field, terms must be carefully defined and judiciously used. The definitions that follow have been selected to establish a common language to facilitate communication between ecological and climatological communities. As such, some may appear to be intuitively obvious. Others represent the selection of one particular use from several possibilities. All provide the building blocks for research into (1) climate/ecosystem interactions, (2) the role of climate and climate research in EMAP and (3) the role of EMAP and ecology in climate change detection, analysis and impact assessment.

I.B.1.a. Weather and Climate

Weather is the state of the atmosphere, mainly with respect to its effects upon life and human activities (Huschke 1989). As distinguished from climate, weather consists of the short-term (minutes to months) variations of the atmosphere.

Climate, on the other hand, is the synthesis of the weather. It is the long-term manifestation of weather (Huschke, 1989). More rigorously, the climate of a specified area is represented by the statistical collective of its weather conditions during a specified interval of time (usually several decades).

These are important distinctions for climate/forest research. Although the weather event of interest may take place over the span of minutes (severe weather) or months (drought), forest ecosystems may often respond on the order of seasons to decades. Thus, the appropriate means of analysis is generally climate rather than weather. But, as implied by the definition of climate, this does not mean that we are limited to analyses of "average" conditions, (although for very long-term large area studies this may provide the most useful information). By definition, climate includes

weather variables that describe the state of the atmosphere over time. This is done through comparison to itself (normal, deviation from normal, extremes, variability) or through associations of weather variables (i.e., a synthesis of weather conditions). Examples of the latter would include the Palmer Drought Severity Index or Showalter Stability Index. In each case, a synthetic variable or measure of atmospheric condition has been constructed as a function of several coincident atmospheric conditions.

I.B.1.b. Scale

The resolution of ecological and environmental time and space scales is a critical issue for climate impact assessment research. Many discussions are available in the literature, but Rosswall et al. (1988) contains a recent collection of essays that deal directly with the resolution of scale to address integrated global change issues.

Mesometeorological events occur between meteorological stations, or at least well beyond the range of normal observation from a single point (Huschke, 1989). The types of major weather phenomena that are small enough to remain undetected within a normal observation network include tornadoes, thunderstorms and immature tropical cyclones. This scale also includes events associated with local geographic influences such as isolated areas of freezing temperatures or flash flooding. Fujita (1989) includes events occurring in the range of 50 to 500 km, with duration of 30 min to 5 days and maximum winds of 25 to 60 m s^{-1}.

Synoptic (cyclonic) scale events include the migratory high and low pressure systems of the lower troposphere, with wave lengths of 1000 to 2500 km. This scale would also include events resulting from the presence of these systems such as drought, freezing precipitation, freezing temperatures, general flooding and hurricanes. Fujita (1989) includes events ranging from 200 to 2000 km, lasting 1 to 15 days with maximum windspeeds ranging from 10 to 90 m s^{-1}.

Landscapes are heterogeneous land areas composed of a cluster of interacting ecosystems that are repeated in similar form throughout (Forman and Godron, 1986). Landscape ecology deals with large, connected areas and emphasizes spatial patterns and spatial interactions. Landscape ecology often focuses on studies of spatial patterns subject to some combination of natural and anthropogenic disturbances. This contrasts with the term "ecosystem" which is used to emphasize more localized biotic and abiotic functional interactions. There is considerable overlap in the two terms (ecology and landscape ecology) since spatial pattern and ecological process are inseparable. Both are influenced by the scale of inquiry. One example of such a complex system is a river.

A river is a complex system of many parts that function together as an integrated whole. Headwaters, upland slopes, floodplains, terraces, and river channels are all spatially and structurally integrated and interrelated. River systems cannot be fully understood by a study of these individual parts; their interrelationship is a fundamental property of the system (Gosselink, et al., 1990). Woodward (1987), IGBP (1990) and others state that climate (the long-term synthesis of weather) impacts the distribution, persistence and recurrence of vegetation on the landscape scale. Given this definition, then, appropriate climatological products for landscape analysis could include regional summaries (maps) of climate means, extremes, ranges and other relevant statistics.

Patches are plant and animal communities surrounded by an area with a similar community structure or composition (Godron and Forman, 1983). Patches may or may not have distinct boundaries. Distinct patch types in natural vegetation are normally produced through a variety of mechanisms. Spot disturbance patches result from disturbance of small areas. Environmental resource patches result from the heterogeneous spatial distribution of environmental resources. Remnant patches result from disturbance surrounding small areas. In natural vegetation influenced minimally by human activities, patches are generally long, narrow, irregular in shape and few in number. They are caused by a number of natural factors including fire, insect outbreaks or hurricanes.

Concepts bearing on patch definition and patch dynamics are summarized in a volume edited by Pickett and White (1985). The range of essays presented describe dynamics that span a temporal scale of 10 to 1000 years and spatial scales of 10^{-4} to 10^{6} m^2. This range reflects the variety of biological systems and the variety of scales within each system on which disturbance effects usually occur. Shugart et al. (1988) propose that mesoscale climate is appropriate for gap or patch dynamics analysis and successional models. The analysis of certain synoptic scale events should be of value for these activities as well.

I.B.1.c. Disturbance

Disturbance, as defined by Forman and Godron (1987), is an event that causes a significant change from the normal pattern in an ecological system such as an ecosystem or landscape. This is nearly identical to the definition of ***ecosystem stress*** (Barrett, 1981). Climatologists would more than likely choose to call such an event a perturbation rather than disturbance, but White and Pickett (1985) contend that the use of perturbation in an ecological setting is, most often, inappropriate. In general, perturbation has been used by ecologists with a whole-system orientation in the sense of any change in a defining characteristic

of a system. The problem with applying this term to natural systems is that it is difficult to separate perturbation from the background variance in system parameters. White and Pickett (1985) suggest limiting the use of perturbation to very narrowly defined situations. They propose the following definition: A disturbance is any relatively discrete event in time that disrupts ecosystem, community or population structure and changes resources, substrate availability or the physical environment. This definition includes environmental fluctuations and destructive events, whether or not these are perceived as "normal" for a particular system. This is particularly important for relatively rare but large-scale destructive events such as hurricanes and massive flooding that might be omitted under the Forman and Godron definition. To establish a common basis throughout this report the term disturbance will be used as defined by White and Pickett. This means that a disturbance can be a climatological perturbation, but it is not a necessary condition for the event to be of interest. The remainder of this discussion will focus on developing a more precise definition of climatological disturbances and their relationship to ecosystem health and productivity.

To restate an important point, a disturbance is any relatively discrete event in time that disrupts ecosystem, community, or population structures and changes resources, substrate availability or the physical environment. The most obvious role that disturbance plays in ecosystems is in the deflection of a community from some otherwise predictable successional path (Pickett and White, 1985; also see section I.B.2.c.). Models that describe the successional implications of disturbance are discussed in Shugart et al. (1988).

Gap models are a subset of a class of forest succession models called individual-tree models because the models follow the growth and fate of individual trees. Under optimal growth conditions, the growth of a tree is assumed to occur at a rate that will produce an individual of maximum recorded age and diameter. Modifications reducing this optimal growth are imposed on each tree based on the availability of light and, depending on the specific model, other resources. Depending on the specific model, growth may be further reduced as climate stochastically varies. Shugart et al. (1988) limit their discussion to mesoscale meteorological phenomena including tropical cyclones, mesoscale convective complexes, severe thunderstorms and frozen precipitation. Such events may generate dramatic changes in the successional framework, but other more subtle factors such as drought or unfavorably cool or wet growing season conditions that can impact general forest health and productivity over an extended period of time are omitted. Michaels and Hayden (1987) discuss climatological data sources and suggest ways in which acute climate disturbances can be introduced into such successional models. Chronic stress has been simulated using the FORET (a tree growth and development model) by modifying the growth curves of specific individuals or species by a fixed percent

and following the impact on primary productivity and population distribution (Auerback, 1981).

Table 1, adapted from White and Pickett, lists some natural disturbances and the ecosystem in which literature has been reviewed that fit this broader definition of disturbance. Only weather related disturbances and terrestrial ecosystems represented in the Northeastern U.S. have been included. Note that chronic as well as acute climatological disturbances have been included.

Table 2, adapted from Bazzaz (1983) contains a summary of correlated disturbance, population, and life history characteristics in plant communities. Bazzaz (1983) describes in some detail the role of disturbance in the determination of population characteristics. Reiners (1983) presents a similar discussion for ecosystem energetics. This includes measures of ecosystem productivity such as above and below ground biomass as well as other soil chemistry measurements. Similar studies for aquatic as well as terrestrial ecosystems are summarized in Barrett and Rosenberg (1981). Pickett and White (1985) summarize a number of essays concerning natural disturbance and patch dynamics by saying that disturbance has demonstrated effects on community characteristics, including richness, dominance, and structure. The functional attributes of ecosystems are also governed to some extent by disturbance. Nutrient cycling and energetics respond to disturbance as well as to biotic and abiotic opportunities and limiting factors.

Table 3, adapted from Peer (1990), contains a summary of the role of climate in recent forest growth models. Table 4, taken from Solomon et al. (1984), contains relationships between specific climatological variables (means, frequencies, extremes) and various forest response indicators. This kind of information, in addition to that presented in Table 2 and discussed in Reiners (1983) is particularly critical if disturbance climatologies are to be related to monitoring programs such as EMAP and FHM. Proper interpretation of field samples lead to more accurate identification of trends and potential sources of ecosystem stress for policy analysis and for detection of local manifestations of global environmental change (e.g., greenhouse warming). Although model development is not a primary goal of this study, climate analyses that directly support the integrated assessment of ecosystem status and trends can lead to a more complete understanding of forest/climate relationships and to the development of more accurate models of natural and anthropogenic influences on forest dynamics.

Table 1. Natural disturbances and associated ecosystems present in the northeastern U.S. for which studies are reviewed in Pickett and White (1985).

Disturbance	Ecosystem of geographical area
Fire	Boreal forest Temperate forest Coastal plain
Hurricane	Terrestrial
Other windstorms	Temperate forest
Ice storm	Temperate forest
Ice Push on shores	Temperate and Boreal forests
Freeze damage	Various
Fluctuating water levels in basins	Various
Droughts	Temperate forest
Alluvial processes	Various
Coastal processes	Various
Salinity changes	Various
Insect outbreaks	Various
Disease	Deciduous forest

Table 2. Some correlated disturbance, population, and life history characteristics in plant communities (from Bazzaz, 1983).

A. Disturbance characteristics with relevance to plant response Size Intensity Frequency, regularity and predictability of occurrence Duration Seasonal time of occurrence Level of environmental heterogeneity within the disturbed area Nature of the biotic neighborhood
B. Population characteristics responsive to disturbance Density and dispersion Growth rate Survivorship; age and size structure Levels of gene flow in the population Degree of relatedness among the members of the population Organization of variation within the population Strength of competitive interactions Niche breadth and niche overlap Strength of interactions with other trophic levels
C. Plant life history characteristics responsive to disturbance Spatial and temporal dispersal ability Seed germination Seedling establishment and growth Reproductive strategies Breeding system Fecundity Reproductive allocation and packaging

Table 3. Examples of climatic variables shown to affect tree growth (Peer, 1990)

CLIMATIC VARIABLES	SPECIES AND LOCATION	DEPENDENT VARIABLE	COMMENTS
Fall precipitation =>1.3cm Cold falls and winters July precipitation High June precipitation Low fall rainfall Intense summer precipitation	conifers (8 species) Minnesota, Wisconsin, and Michigan hardwoods (14 species) same locations as above	diameter at breast height (dbh)	Corr. coef. did not exceed .42; Species varied in climate sensitivity; generally conifers more sensitive than hardwoods
Cumulative air temp. degree days Total precipitation	red maple *(Acer rubrum)*, northern red oak *(Quercus rubra)*, paper birch *(Betula papyrifera)*, all in northern Michigan	diameter growth	Proportion of variance explained by regression ranged from .44 to .65
Monthly average temperature Total rainfall	red spruce (Smoky Mountains)	tree ring width	Demonstrated that climate sensitivity varied over time
June temp. previous year November temp. previous year January temp. current year July precip. previous year March precip. current year June precip. current year July precip. current year	hemlock (Pennsylvania)	tree ring width	R-square=.64; hemlock is a climatically sensitive species
34 variables based on monthly temperature and precipitation	European silver fir (Bad Herenalb, FGR)	tree ring width	Method suitable for dealing with both change and sudden shocks

Table 4. Proposed climatological variables, data and ecological reponses (Solomon, 1984).

	Affedted organisms, life-stage, or environmental varieties	Primary responses	Secondary responses
Climate variables			
Temperature variables			
Frequency, intensity of winter low temperature	Saplings Trees	% Death of saplings % Loss of buds, branches	Loss of reproduction, tree damage
Frequency, intensity of spring frosts	Spring-terminating seeds Trees	% Death, by species % Defoliation	% Growth of tree, by species % Increased disease, mortality
Cumulative growning season warmth	Saplings, trees Soil biota	% Growth of tree, by species % Nutrient release rates	% Growth of tree, by species
Frequency, intensity, length of heat waves in midsummer	Seedlings Fire frequency	% Death, by species % Death, damage, reproduction by life-stage, and species	Loss and gain of pathogen population
Frequency, intensity of fall frosts	Fall-germinating seeds	% Death, by species	
Precipitation variables			
Frequency, length of flooding	Seedlings Saplings, trees	% Death % Death, slowed growth, by species	% Increased disease; death by species
Frequency of spring soaking rains	Seedlings	% Death from soil bioat, by species	
Growing season precipitation as days below wilting point of soil moisture	Seedlings Saplings, trees Soil biota	% Death if too little/too much by species % Growth of tree, by species % Nutrient release rates	 % Increased disease, death by species % Growth of trees, by species
Frequency, intensity of growin season droughts	Seedlings Mature trees Fire frequency	% Death by species % Slowed, stopped growth, by species % Death, damage; reproduction by life-stage and species	 % Increased disease, death by species; Loss and gain of pathogen population
Instense wind storms, ice storms	All trees, largest trees, shallow-rooted trees	% Death, damage; enhanced reproduction by species	% Increased disease, mortality

Wissmar and Swanson (1990) suggest that ecotones may be particularly sensitive to disturbance regime. Ecotones are zones of transition between adjacent ecological systems having characteristics uniquely defined by space and time scales and by the strength of interactions between systems (Holland, 1988). They are considered to be sensitive to gradients of limiting factors and landscape changes caused by physical and biological disturbances. A basic scientific problem in the evaluation of landscapes and their ecotones is the lack of testable models with short- and long-term predictive capabilities (Wissmar and Swanson, 1990). The difficulty concerns not knowing the extent to which characteristic or repetitive changes in ecotones and ecosystems of a landscape are caused by disturbances of low frequency and high magnitude extremes. We understand that large disturbance events can dominate the main trends of change. Yet we do not know which events will be formative, or how to recognize temporal and spatial sequences of events and the ability of ecotones and ecosystems to recover to characteristic persistent states. Wissmar and Swanson (1990) present information about representative disturbance recurrences and recovery phases for disturbed hillsides and rivers, but such landscape knowledge for both physical and biotic components of ecotones and ecosystems is generally lacking.

White and Pickett (1985) summarize disturbance characteristics which can be used as a guide to the development of disturbance climatologies. Key descriptors include spatial distribution, frequency, area and magnitude. These attributes are in fundamental agreement with descriptions contained in Reiners (1983) and Bazzaz (1983).

Spatial distribution includes the relationship of the disturbance to geographic, topographic, environmental and ecological community gradients. Table 1 suggests some guidelines for the geographic distribution of disturbance events. The list should be considered only an initial starting point. Summaries of other disturbance studies for specific geographic areas or applications include Peer (1990) and Solomon et al. (1984).

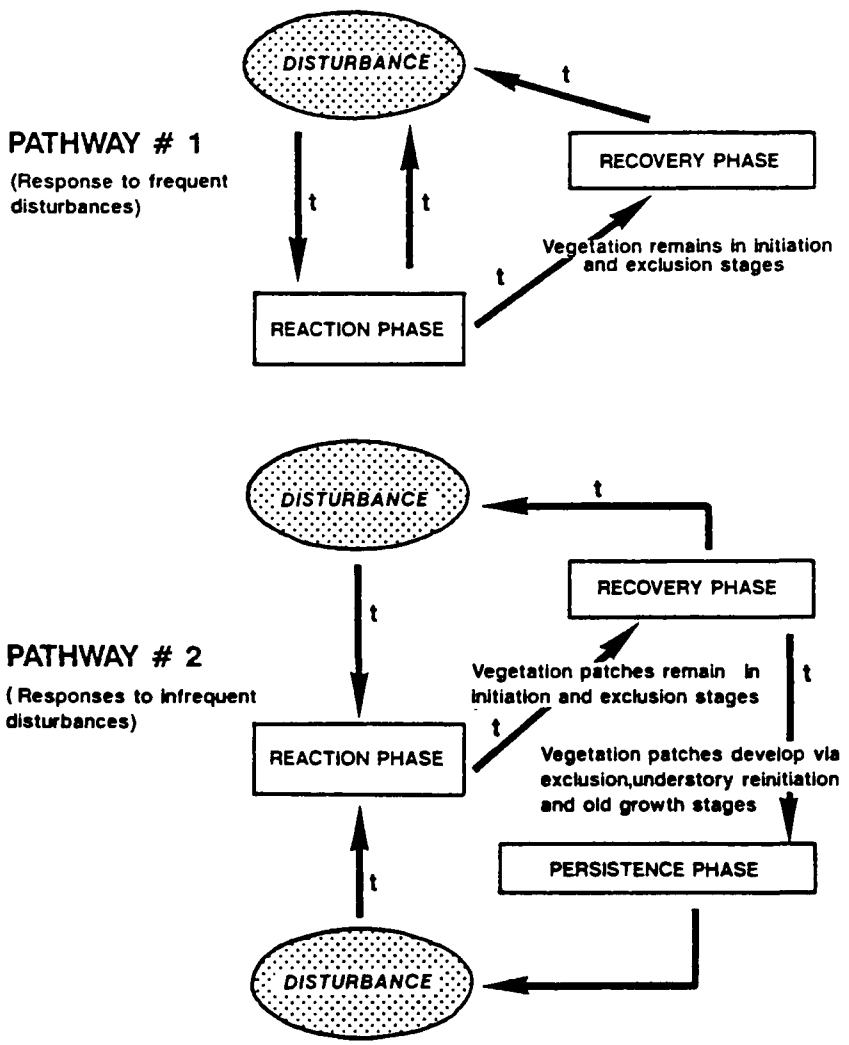
Disturbance frequency is the mean number of events per time period. Frequency is often used for probability of disturbance when expressed as a decimal fraction of events per year. Disturbance frequency is of particular interest to climatologists as well as ecologists. Overpeck et al. (1990) report General Circulation Model (GCM) results that suggest changes in disturbance frequency resulting from greenhouse warming. The authors used a mixed-species, mixed-age stochastic stand-simulation model to estimate the impact on forest biomass of these changes. Given the uncertainty in GCM scenario results, an alternative approach is to explore ways in which changes in forest health and productivity can suggest the existence of trends in disturbance event frequency. Reiners (1983) suggests measures of above, as well as below, ground

biomass as an indicator of changes in disturbance frequency. He suggests that as disturbance frequency goes up, biomass and associated detritus production will decrease. This is reflected in the model generated results of Overpeck et al. (1990). Bazzaz (1983) states that frequency of disturbance may regulate age structure of the population, life cycle and reproductive strategies.

Reiners (1983) also discusses the "kind" or "uniqueness" of the disturbance. Species composing an ecosystem must have, to varying degrees, adaptations to normally occurring disturbances. The more frequent the disturbance, the stronger the representation of better adapted species and theoretically, the stronger the selection pressure for adaptive traits. Thus the impact of a unique disturbance is likely to be more profound than that of a "normal" disturbance. Similar distinctions are emphasized by White and Pickett (1985) in their review of the terms "disaster" and "catastrophe." A "disaster" occurs so frequently that it is likely to occur within the life cycles of successive generations, while a "catastrophe" occurs rarely, so that it is unlikely to be experienced as a repeated selective force. A disaster would be likely to increase fitness through selection, while a catastrophe would generally decrease fitness. Figure 1 illustrates differences between developmental pathways of frequently and infrequently disturbed riparian forest patches. Pathway 1 includes stand initiation and exclusion stages during reactive and recovery phases in ecotones following disturbances. Pathway 2 includes stand exclusion, understory reinitiation, and old growth stages after the recovery and during the persistence phases.

Size of area disturbed can be expressed as area per event, area per time period, area per event per time period, or total area per disturbance type(s) per time period. It is frequently given as a percentage of total available area. Disturbance size ranges from very small gaps created by the death of an individual in an herbaceous community, to the breakage of a tree limb to the fall of a single tree creating a canopy gap, to the fall of several trees, to very large disturbances created by fires and windstorms. Bazzaz (1983) states that disturbance size and heterogeneity interact in determining size and identity of plant populations. Reiners (1983) states that areal extent impacts system energetics through environmental modification and re-colonization potential. A larger disturbed area will, within limits, create more extreme microclimates for regenerative processes. Depending on the form of ecosystem disruption generated by the disturbance, a larger catchment for runoff can result, leading to a higher potential for erosion on upland sites and deposition in lowland sites. A larger disturbed area, particularly as it takes a round and fully contiguous shape, creates a longer dispersal distance for recolonizers, including both the spores and seeds of plants and vectors such as specific and critical pollinators.

Figure 1. Developmental pathways of riparian forest patches in response to frequent and infrequent disturbances. The letter 't' indicates different transition times for riparian patches (successional stages) (Wissmar and Swanson, 1990).



Magnitude of disturbance can be characterized by intensity and severity. Scaling intensity is relatively simple within a disturbance type and for a particular ecosystem. The Palmer Drought Severity Index for drought and the Fujita scale for tornadoes are examples of scaled disturbance intensities. Reiners (1983) points out, however, that at present we have no means of making comparisons of intensity between disturbance types, or of predicting responses of different ecosystems to the same intensity of a particular disturbance. Intensity responses may be non-linear, not monotonic and threshold behavior, particularly at the ecosystem level, is likely. These thresholds may be critical points at which recovery rates are significantly slowed, or more importantly, at which recovery to the original state is impossible. Defoliation either by pests or weather events is a case in point (Stephens, 1981; Johnson, et al., 1988).

I.B.2. Conceptual Frameworks

The importance of climate to the health, productivity and even the existence of particular ecosystems has long been recognized (Woodward, 1987). But the field of ecology and, along with it, the study of climate and ecosystems, has evolved rapidly during the last two decades. Prior to this, most ecological research focused on the observational characterization of ecological patterns. Research consisted primarily of qualitative descriptions with few theories based on physical or mathematical principles. In recent years, interdisciplinary concepts of ecosystem behavior and dynamics have gained prominence. Quantitative models have been developed for relationships that had previously been expressed only in qualitative terms.

For the applied climatologist, an introduction to these theoretical "frames of reference" serve two functions. First, it emphasizes the use of theory and mathematical techniques that are also found in predictive climate and meteorological research. Markov chains and Chaos theory are two such examples. Second, it illustrates the limited role of climate and weather in previous ecological research. This is as much the responsibility of climatologists as ecologists. Ecologists performing climatological analyses introduce new perspectives concerning climate/biosphere interactions, but to take advantage of these contributions, the applied climatologist must gain an appreciation of dynamic bio-centric as well as more familiar atmosphere or man-centered systems.

From the ecological side, the selected frameworks will be familiar, but the role of climate in these settings is highlighted. In some cases, climate interactions have always been present implicitly, but rarely expressed explicitly. For instance, under the dynamic stability framework, the role of energy dynamics is

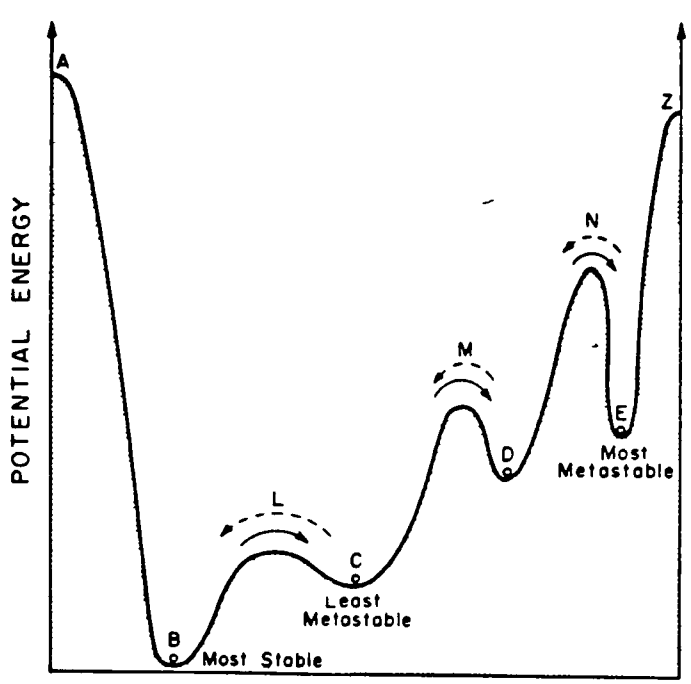
discussed at length, but the influence of climate and climate disturbances on the storage or release of ecosystem energy is less apparent.

The discussion that follows highlights three conceptual frameworks proposed in the recent ecological literature. These approaches include dynamic stability, Markov chain analysis and catastrophe theory. The selected frameworks are presented both for their range of disciplinary appeal, but also for their similar portrayal of climatological influences.

I.B.1.a. Dynamic Stability

The first approach appears frequently in the literature of the late 1970's and early 1980's. It borrows prominently from physics, specifically the field of mechanics. A representative example is illustrated in Figure 2 adapted from Godron and Forman (1983). Living organisms often start from highly stable states represented as state B in Figure 2. Organisms build locally metastable ecosystems represented by points C, D or E. At these points, a system will return to equilibrium after small (but not large) displacements. The greater the energy required to displace the system from equilibrium, the more metastable that system is said to be.

Figure 2. Mechanical dynamic stability in terms of potential energy (Godron and Forman, 1983).



Landscapes represent an interesting special case for this framework. As defined earlier, a landscape is made up of many smaller patches. Borman and Likens (1979) develop an example of this framework applied to forest clear-cuts. The authors example begins at a highly metastable point located to the left of point A of Figure 2. This point represent a system with high biomass (potential energy). Energy, in the form of some disturbance event, clear-cutting in the Borman and Likens example although fire or hurricane would work in a similar fashion, is input to the system (point A) and the biomass is released until point B is reached. Disturbance and increased decomposition promote an increase in available water and nutrients. As time passes, living biomass again accumulates and the system progresses through metastable points C, D and E. Based on output of the forest growth model JABOWA (Botkin, et al., 1972), Borman and Likens (1979) suggest that dynamic equilibrium, or shifting mosaic steady state is achieved when the total biomass across all patches begins to oscillate about a mean. When a dynamic equilibrium is reached, the proportions of landscape patches in states B, C, D or E remain more or less constant with time, but the state of any individual plot may change as it gains or looses biomass (points L, M, N or Z). For example, new patches in state B arise when gaps are created by the fall of large trees. This results in a "blip" in the level of biomass which is later compensated for by biomass gains (increased metastability) in other patches.

Under a dynamic equilibrium framework, climate plays two roles. First, climate means and long-term patterns of variability impose upper limits to the accumulation of potential energy in the ecosystem. Second, climate can act to move systems from metastable states to higher or lower states. For example, metastability can be increased by directly supplying or facilitating the storage of additional energy (e.g. Photosynthetically Active Radiation (PAR), moisture, conditions favorable for nutrient fixation). Metastability could be decreased by bringing about the release of stored energy through, the addition of mechanical energy (wind, hurricane), heat energy (lightening and fire) or direct removal of potential energy (e.g., reduced available moisture resulting from drought), thus triggering decomposition and the loss of potential energy from the system. The importance of this framework to ecosystem status and health monitoring is that these climate related energy exchanges take place continually and are part of normal ecosystem behavior. Changes in these relationships or patterns of climate related energy accumulation and release may indicate changing forest status, health or define the initiation of forest or climate trends. More detailed discussions of ecosystem energetics including climatological aspects are provided in Reiners (1983) and several papers in Zonneveld and Forman (1990).

I.B.2.b. Recurrence and Persistence

This conceptual framework is closely related to principles of Markov processes. The Markov chain is a special case in which a finite (or countably infinite) number of outcomes or states are possible. A first order Markov chain is one in which each state depends only on the immediately preceding state.

Models using Markov techniques are useful as a first approximation to changes from one ecological state to another when only the probabilities of the transitions can be estimated (Jeffers, 1988). Within major states, substates can also be modelled as a Markov chain. Markov models (and related approaches) have been used successfully as landscape modeling paradigms in both applied and basic contexts. Markov models of forest succession are mathematically and conceptually the most straight forward of the succession models that are presently in use (Shugart et al., 1988). This approach is also found in more complex "gap" models. Several examples of the use of Markov process models for successional modeling are mentioned in Weinstein and Shugart (1983).

Early stand dynamics models held climate constant using only average conditions. Climate impacted forest composition only through growth response to temperature and competition for light and moisture. Movement through the successional chain was driven by forest-gap initiation and overturn through old-age mortality. Later research recognized that changes in disturbance or climatological regime short-circuits these slower processes and modifies the rate of successional change. Overpeck et al. (1990) tested the sensitivity of a widely used stochastic stand-simulation model (FORENA, Shugart, 1984) to changes in disturbance frequency. The practical impact of climate disturbance in these simulations was to reset the Markov chain to earlier successional stages. More frequent disturbance resulted in greater dominance by early successional species.

As yet, Markov chains have not been employed to simulate temporal patterns of large scale disturbance, but research that explores the use of Markov chains to predict large-scale atmospheric patterns is underway (S. LeDuc, personal communication). The need to relate such large-scale circulations to models of forest ecosystem dynamics is discussed in Michaels and Hayden (1987).

Botkin (1980) uses the concept of Markov chains to address some highly general ecological concepts. He suggests that ecosystem behavior through time can usually be described by two characteristics. First, particular ecosystem states come and go, or recur. Second, the recurrence of ecosystem states depends on the total amount of variation (the total number of possible states) which, in turn, must be bounded. This suggests the concepts of ecosystem ***persistence*** within bounds and the ***recurrence*** of specific

ecosystem states.

Under this framework, long-term patterns of climatological means and variability can influence the establishment and persistence of dominant ecological landscapes, i.e., climate features set the bounds for the state space (Woodward, 1987). Conversely, climate is dynamic, with weather conditions that can vary widely from one year to the next. Climate can, therefore, affect the range of variation (the number of possible states), the rate of recurrence of particular states and the average time that the ecosystem is in any of its possible states.

I.B.2.c. Theories of Catastrophe and Chaos

Catastrophe theory has recently attracted considerable attention in studies of non-linear mathematical dynamics and chaos theory. Chaos theory has shown that regular equations can produce irregular behavior. Minor variations in the system's initial state cause behavior that is, in effect, unpredictable even though overall system change is predictable. It is strictly determinate in a mathematical sense. Catastrophe theory suggests that a gradually changing system (with its associated characteristics) converges on and crosses particular points (chaotic attractors). Only a slight change in the immediate vicinity of a point will divert the system in a quite different direction. A change in system non-linearity acts in a fashion similar to changes in initial system state. Not only might the final equilibrium condition be altered, but the ability of the system to converge to equilibrium may be eliminated (Gleick, 1987). One example which could lead to a system of equations that contain changing non-linearities is plant growth and development under variable moisture stress.

Forman and Godron (1986) propose that major alterations in landscape development take place in this way. An abrupt change in the distribution of climatological events is one factor that, alone or in combination with other factors, can push an ecosystem beyond its critical threshold point. For instance, tree species that normally tolerate degraded air quality conditions may experience a precipitous decline when frequency and intensity of severe winter conditions change. The determination of the short or long term nature of such interactions would influence the interpretation of present status and monitored trends in forest health (Johnson et al., 1988).

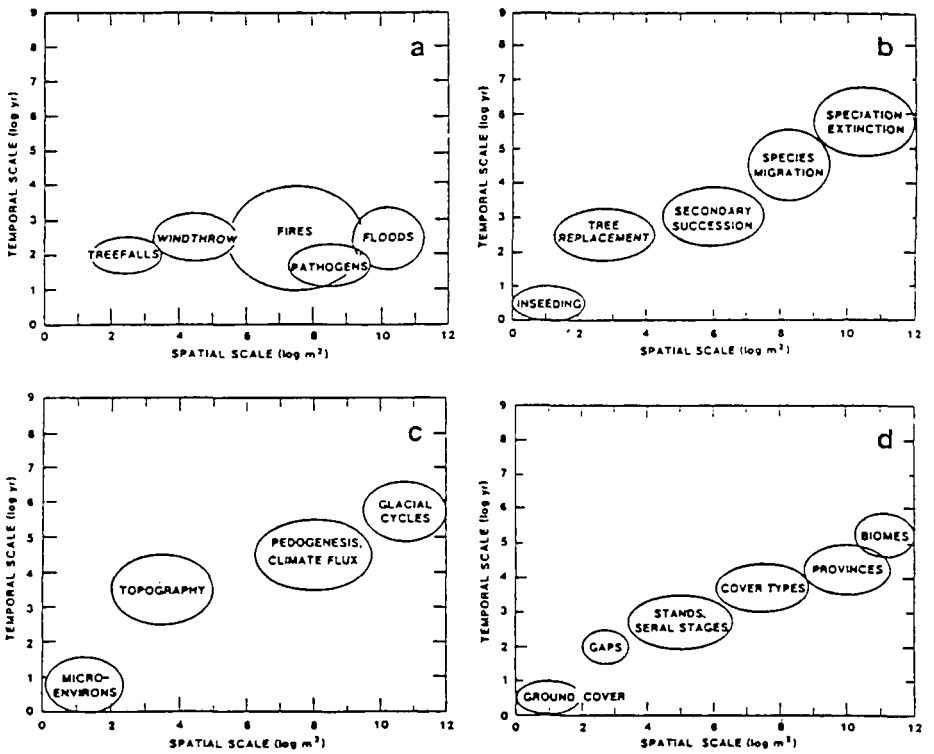
I.B.2.d Temporal and Spatial Hierarchies

To fully understand the role of climate (changing climate) in an ecological context, its place in a bio-centric temporal and spatial hierarchy must be considered. In the context of the present study, compatibility of spatial scale is fairly straightforward, but temporal scale must be approached more cautiously. Although the disturbance event (e.g., windthrow) may take place in the space of a few minutes, it is the response of the biological system to this disturbance that is of interest. For example, even though a tree is partially uprooted, it may take several seasons to die. Changes in crown density and nutrients may respond on the order of weeks to months to prolonged drought, but normal growth and reproduction may not be observed for one or more growing seasons even with a return to more moderate temperature and moisture regimes. This represents a radical departure from more traditional mono-crop agriculture applications common in the climate literature that most often deal with single or short-term events occurring within a particular growing season. With the exception of extremely rapid-growing species such as loblolly pine, forest/climate impacts span periods from one to ten years and frequently include multiple, interacting disturbance events.

Figure 3 relates time and space distributions of disturbance regimes, forest processes, environmental constraints and vegetation patterns. In the case of disturbance regime, spatial scales fall neatly into the mesoscale and synoptic scale definitions provided in Huschke (1989). The temporal scale represents the return period of the disturbance event. As an example, one interpretation of Figure 3 is that a windthrow event with a return period of 1 in 100 to 1 in 1000 years and impacting an area on the order of 1000 m^2 can be expected to affect tree replacement processes within topographic constraints and may manifest itself in changes in gap (canopy disruption) and stand or seral stage vegetation pattern.

Climate change events, typified in Figure 3 by glacial cycles, is defined as spanning more than 10000 years and impacting more and 10000 km^2. From Figure 3, affected processes include species extinction and impacts would be noted in vegetation patterns of ecological provinces and biomes. If, as some studies suggest, climate change takes place on smaller spatial scales (i.e., 10^5 m^2) and over a shorter time (i.e., 10^2 years), new impacts and constraints can be quickly noted. For instance, under glacial change, the importance of disturbance regime all but disappears. Disturbance reemerges as an important element under a scenario of rapid environmental change. Secondary succession and species migration processes emerge as new impact areas. Soil properties (pedogenesis) and fluxes of moisture and energy become limiting constraints. Changes in stand and cover patterns may become evident.

Figure 3. (a) Disturbance regimes, (b) forest processes, (c) environmental constraints and (d) vegetation patterns, viewed in the context of space-time domains (Gosselink, et al., 1990).



I.C. Summary - A Working Hypothesis of Climate/Ecosystem Interactions

The relationship of climate (the synthesis of weather) to ecosystems depends on the time and space scale of the biological system to be monitored and the analyses to be performed. Climatological averages and ranges reflect one set of physical bounds on the number of possible ecosystem states represented within a landscape. Inter-annual climate variability acts as ecosystem disturbances. Disturbance phenomena impact ecosystem health and productivity as measured by changes in growth, system energetics, plant populations and species characteristics. Disturbance events impact the persistence and recurrence of ecological states. Disturbance events vary with geographic location and can be described by their frequency, size and magnitude. Many EMAP and FHM indicators, particularly those based on directly monitored observations, may not be correctly interpreted and valid associations drawn without consideration of mitigating or compounding climatological factors. A climatological description of background persistence and disturbance regimes is essential if associative (EMAP) or predictive (FHM) modeling

studies are to include natural as well as anthropogenic forces of ecosystem change.

The remainder of this report applies this hypothesis to the New England region of the U.S. Data availability, analysis and display options are discussed in section II. Climate analyses are performed to address three levels of inquiry: large-scale climatologies that establish system boundaries (e.g. means and extremes); climatologies of shorter duration and smaller scale disturbances that are characterized by frequency, size and magnitude; and climate summaries that permit comparisons of recent regional and local conditions to pre-determined baseline or historical conditions.

II. Data and Methodology

II.A. Targeting the Study

The vast array of possible climate/ecosystem interactions that could be examined is substantially narrowed by "targeting" the analysis to a particular setting. In this case, the cooperative US EPA/EMAP-Forests pilot and USDA Forest Service New England Forest Health Monitoring (NEFHM) project has been selected.

EMAP is a long-range program to monitor status and trends in the condition of the major ecological resources of the U.S. A discussion of the sampling design and landscape characterization under EMAP is presented in Norton and Slonecker (1990). Six broad ecological categories have been defined within EMAP, one of which is Forests. The use of indicators to measure ecological status and trends for forests as well as the other resource categories is discussed in Hunsaker and Carpenter (1990). An indicator is defined to be a characteristic of the environment that, when measured, quantifies habitat characteristics, the magnitude of stress, degree of exposure to the stressor, or degree of ecological response to the exposure. Under this definition, for example, drought is a climate stressor, but Palmer Drought Severity Index quantifies the magnitude of stress and so is a stress indicator. Climate as a whole could also be considered a landscape indicator. A landscape indicator is defined as a characteristic of the environment used to describe spatial distribution of physical, biological and cultural features across a geographic area. Although all examples of stress and stressors given in Hunsaker and Carpenter (1990) are negative, a stress does not necessarily correspond to a decline in forest status or health. The authors' definition of stress indicator suggests only "changes in exposure and habitat." This conincides with literature definitions of ecological stress which closely resemble our earlier definition of disturbance (Barrett, 1981). Throughout the remainder of this

report, disturbance and stress will be used interchangeably with no value judgment as to the detrimental or beneficial nature of the resultant ecosystem response.

The U.S.D.A. Forest Service (USDA-FS) has designed a national system to annually monitor the health of the Nation's forests as an integral part of the USDA-FS Global Change Program proposed under the Forest Ecosystems and Atmospheric Pollution Research Act of 1988. The program involves coordination with the USEPA's EMAP. This new program, Forest Health Monitoring (FHM) is a multi-tiered, long-term process to 1) detect unexpected deviation from established baseline conditions or trends, 2) identify causes of change, and 3) define basic relationships sufficiently to predict consequences. Detection, evaluation and research monitoring levels are planned. Implementation of the FHM program began during the summer of 1990 in New England (NEFHM).

The initial year of the cooperative NEFHM/EMAP-forest project consisted of 263 nearly equally spaced sampling areas, each being equivalent to an EMAP sampling hexagon. EMAP plots are 40.6 km^2 hexagons with a density of a one-sixteenth sample of total area. These points represent potentially forested locations. Some hexagons fell in urbanized areas so that the final sampling network consisted of 206 forested hexagons distributed throughout Connecticut, Maine, Massachusetts, New Hampshire, Rhode Island and Vermont (Figure 4). As time goes on, present forested sites may become urbanized or previously inaccessible sites may become available. Although 206 locations were sampled during 1990, all 263 sites remain available for future sampling seasons. Specific NEFHM objectives are provided in Table 5. Lists of the variables selected for observation are provided in USDA Forest Service (no date). The initial sampling project was completed during the summer months of 1990. A summary of this collection season is provided in Brooks et al. (a) (in press).

Figure 4. The New England Forest Health Monitoring Program network of potential sampling sites.

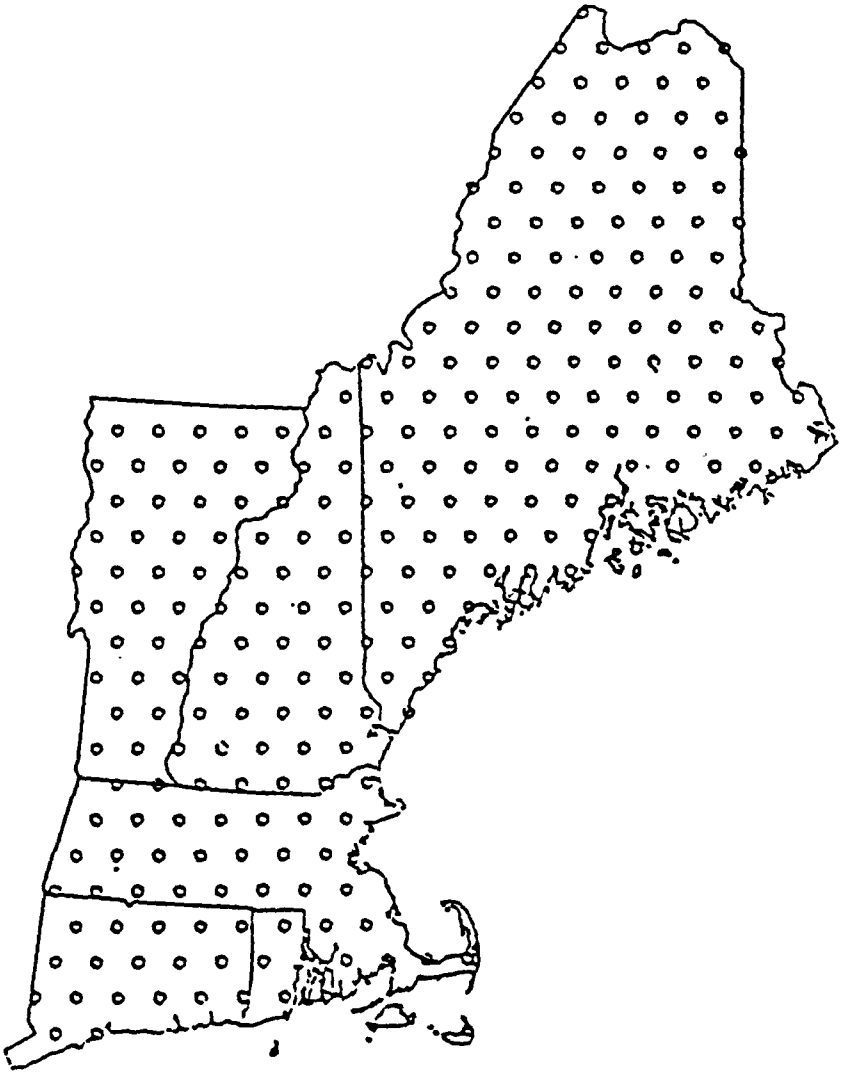


Table 5. USDA Forest Service New England Forest Health and Monitoring Program objectives (USDA, no date).

To characterize the following forest conditions:

a. growth rates
b. tree vigor
c. soil/site
d. stand composition
e. landscape

To characterize the following potential forest stressors:

a. insect and disease pests
b. climate (long-term)/weather (short-term)
c. atmospheric pollution/deposition
d. other (direct anthropogenic activities, e.g harvesting)

To quantify changes in forest conditions, and

To correlate changes in forest condition with potential forest stresses.

II.B. Data Resources

Section I has suggested general frameworks for describing climate features relevant to the analysis of forest landscapes and patch dynamics. The importance of climate related disturbance regime to these frameworks is clear. For example, disturbance related mortality impacts tree population structure, community structure, the release of light, nutrient and moisture resources, resources stored by decomposers and the creation of new resources such as complex organic compounds and decomposer habitat (Franklin et al., 1987). Climate and forest scientists agree that changes in disturbance regime can result in major ecosystem impacts and could be an early indicator of greenhouse warming (Overpeck et al., 1990; Michaels and Hayden, 1987; Graham et al., 1990). To be able to more fully understand forest/disturbance interactions and to detect changes in these relationships, data must be assembled and baseline climatologies constructed.

Data sets bearing on several major categories of ecosystem disturbance have been assembled. Methodologies are explored to illustrate the relevance of specific climate features to forest status and health assessment. The pertinent climatological data sets are outlined below. Examples of their use in selected climate analysis products will be presented in section III.

II.B.1. Severe Weather (High Winds and Tornadoes)

Windthrow, the toppling or uprooting of trees by wind, can be a frequent disturbance phenomenon in northern and New England forests. Catastrophic windthrow in presettlement Wisconsin is discussed in Canham and Loucks (1984). They conclude that the majority of windthrow damage conforms to downburst phenomena such as those described in Fujita (1978). Bormann and Likens (1979) take a larger spatial view and conclude that the importance of such events varies with geographic location, but windthrow is a frequent disturbance throughout the Northern Hardwood Forest area of North America. Ferris (1980) reports that windstorms are not uncommon in Maine and mature spruce-fir stands are particularly susceptible to windthrow because they have shallow root systems. Henry and Swan (1974) summarize an analysis of the affects of windthrow on an experimental forest in southwestern New Hampshire.

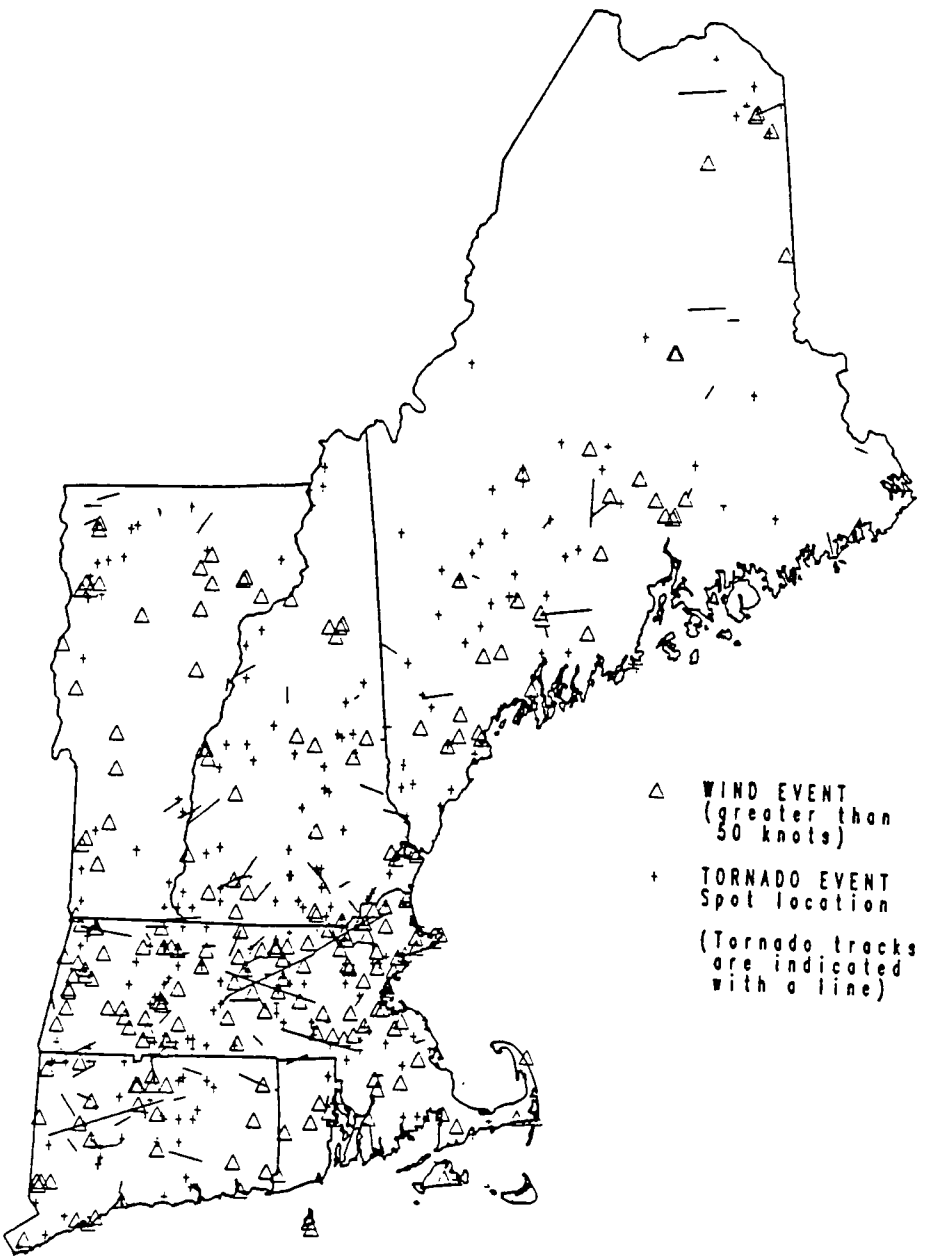
Tornado and damaging wind data bases were obtained from the National Weather Service's (NWS) National Severe Storms Forecast Center (NSSFC) in Kansas City, Missouri. They contain digitized records from 1950 (for tornadoes) or 1955 (for wind) through 1989 and have been updated for the New England states through September of 1990 using preliminary weather service reports. Similar records have been acquired from Environment Canada, Atmospheric Environment Service to supplement data-sparse portions of northern New England.

Michaels and Hayden (1987) suggest that frequency, strength and area affected are important characteristics of severe storms for the estimation of atmospheric effects on ecosystems. These correspond with disturbance frequency, magnitude and size characteristics recommended by Pickett and White (1985). A number of descriptors are available from the NSSFC database; only a few are selected for analysis. In the case of tornadoes these include location of touchdown, direction, length and width of path and strength as described by the Fujita scale given below (Fujita, 1981).

Fujita Tornado F-scale	Classification categories maximum estimated wind velocity (m/s)
F-0	18 - 32
F-1	33 - 50
F-2	51 - 70
F-3	71 - 92
F-4	93 - 116
F-5	117 - 142

Although these may be critical characteristics, time-series taken from the best digitized weather records available must be used with care. Reporting and verification criteria vary throughout the record. The tendency of reported events to converge on population centers is also easily noted in a 30-year summary map of severe weather events (Figure 5).

Figure 5. Digitized location of severe weather events, 1961-1990.



Because of these limitations, time series of tornado characteristics are not presented in any of the climate summaries. Particularly when detection of trends and changes in disturbance regimes are priorities, observational biases in this historical database are too great. Analyses of other characteristics such as tornado strength (magnitude) and area affected (size) may also suffer from similar biases, but, if it is assumed that the storms randomly hit populated areas, a pooled sample of these population-centered storms should still provide reasonably reliable general information concerning the characteristics of tornadic events in New England. Aggregate summaries of monthly distribution(intra-annual frequency), F-scale (intensity) and extent of affected surface area (size) are presented in the climate summaries (section III).

Reporting errors aside, other problems arise when attempting to relate point observations of storm damage to an operational monitoring program such as EMAP or FHM. Figure 5 displays the location of reported severe weather events. Figure 6, generated with a GIS, represents the intersection (co-location of latitude and longitude coordinates) of New England tornado events of the most recent decade and the NEFHM sampling hexagons. First, population bias is again evident. Second, the impression from the sampling network alone is that tornadic events are far less frequent than the weather database suggests. That is, the likelihood of noting the effects of these events at a forest sampling point is quite small. This latter point is even more evident in Figure 7. Figure 7 is a representation of a specific hexagon in southwestern New Hampshire in which tornado events were reported. The dashed lines surrounding the tornado locations represent imprecision in the coordinate locations of the digitized weather record. The large open circle represents the forest sampling location within the hexagon.

The implications of these comparisons are twofold. First, tornadoes and other severe storm events may best be summarized in an aggregate, landscape, manner. Knowledge of the individual events will be essential to future forest model development and interpretation of site specific health indicators (e.g., mortality and crown condition), but will likely not be useful for the detection of overall resource condition and trends. Second, remotely sensed data from Doppler radar and space based earth observing systems should play a vital role in establishing accurate regional summaries. For example, by the turn of the century it is anticipated that instruments on the Earth Observing System will provide global coverage; surface winds are expected to be measured at 100 km resolution with errors less than 5 ms^{-1} (Baker, 1991). Although this still represents a fairly high degree of error as compared to <u>in situ</u> instrumentation, it will fill large geographic "gaps" in our present databases.

Figure 6. Intersections of digitized severe weather events with NEFHM Program sampling hexagons, 1961-1990.

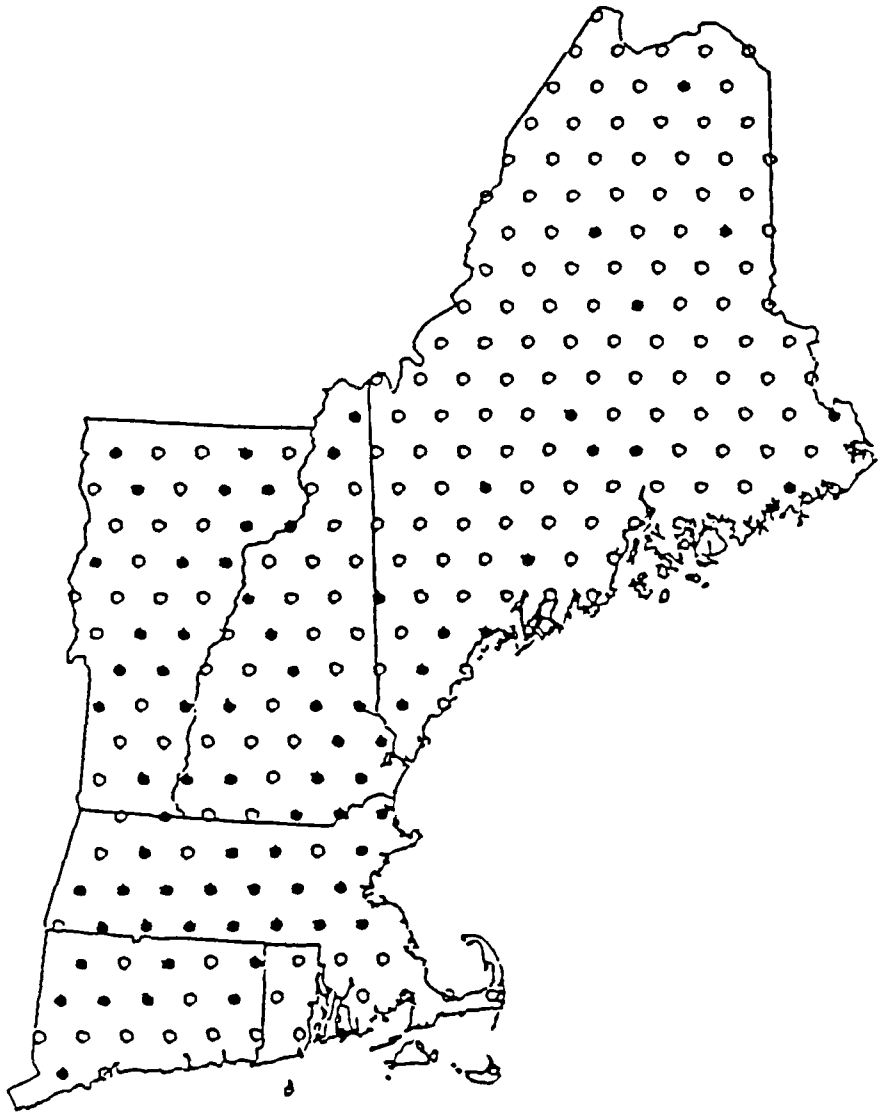
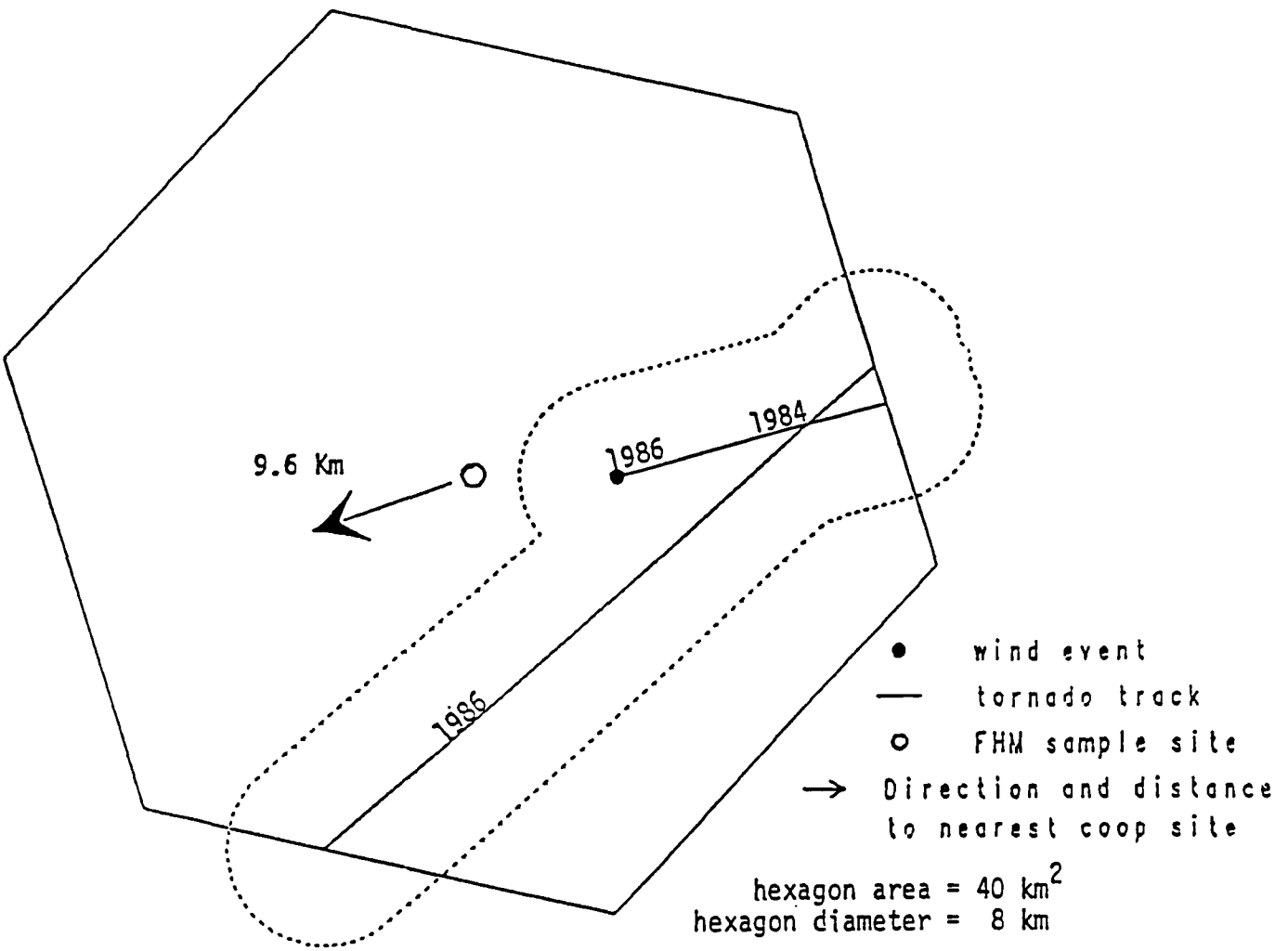


Figure 7. Location of tornado touchdown and path within a forest sampling hexagon in southwestern New Hampshire, 1981-1990.



Wind reports contained in the NSSFC database are events that meet certain criteria. There must be verified peak gusts in excess of 26 ms^{-1} (50 knots) for inclusion in the database. On occasion, no windspeed measurements are available and gusts are estimated from damage surveys. In these cases it can be determined that windspeeds in excess of 26 ms^{-1} occurred, but the exact value of the peak cannot be established.

Because of reporting uncertainties similar to those of the tornado database, no time series summaries have been prepared. A seasonal frequency distribution (intra-annual frequency) of events is presented for wind. The data do not support a wind speed magnitude analysis. Area impacted (disturbance size) information are not available in digitized form.

Additional events of interest are reported in the serial publication, Storm data (USDOC, 1991). The digitized severe weather data that has been analyzed here is abstracted from these publications. Storm Data may be of limited "real time" help to the FHM program since its publication schedule runs six or more months behind the event. However, it is useful for information about the previous season. For instance, data are available in October 1990 for storms which occurred in February 1990.

II.B.2. Tropical Cyclones

The passage of tropical cyclones or hurricanes represents a synoptic scale, ecosystem level disturbance. Severe storm (mesoscale) events such as high winds, hail and tornadoes may accompany or be imbedded in these systems, but overall, impacts are more widespread. The terms tropical depression, tropical storm, or hurricane are assigned depending on whether the sustained surface winds near the center of the system are, respectively, < 17 ms^{-1}, 17 ms^{-1} to 32 ms^{-1} inclusive, or > 32 ms^{-1}. Tropical cyclones are not archived (or named) unless they reach at least tropical storm strength. The maximum wind speed often must be inferred from indirect evidence, and a wind speed is subjectively assigned by the analyst after considering all available information.

The passage through the New England area of disturbances associated with or derived from North Atlantic tropical cyclones is not uncommon. Most often, the original tropical system has been highly modified by contact with continental air masses and is rated as extratropical by the time New England is reached. When a tropical cyclone becomes extratropical, the size of the circulation usually expands, the speed of the maximum wind decreases, and the distribution of the winds, rainfall, and temperatures around the center of the cyclone become increasingly asymmetric. While these characteristic features develop, some tropical features, such as a

small area of strong, often hurricane-force winds near the center and extremely heavy rainfall, may be retained for a considerable time.

A 1938 New England cyclone is a good example of a storm which was technically classified as extratropical, but which still maintained hurricane-like characteristics (Neumann, et al., 1990). Figure 8 shows the track of this system, labeled as storm number 4 for that year, as it passed through the region. Henry and Swan (1974) summarize the ecological impacts of damage associated with this storm while still rated at hurricane strength at a research forest site in southwestern New Hampshire (Figure 9). Historical reconstruction at this site indicates the forest canopy remained essentially intact between 1665 and 1897. After this date, four windstorms, culminating in the 1938 hurricane, completely destroyed the canopy trees and set in motion the growth of a new forest. The authors compare forest characteristics prior to the 1897 to 1938 disturbance period (pre-hurricane) to those of the period 1938-1967 (post-hurricane). They conclude that the post-hurricane forest exhibits higher tree density, smaller stem diameters and changed species composition. Although the pre-hurricane and post-hurricane forests have beech (*Fagus grandifolia*), white birch (*Betula papyrifera* Marsh.) and hemlock (*Tsuga canadensis*) in common, their composition differs in that the current forest also contains red maple (*Acer rubrum* L.), black birch (*Betula lenta* L.), sugar maple (*Acer saccharum* Marsh.) and striped maple (*Acer pensylvanicum* L.). White pine (*Pinus strobus* L.), present before the hurricane, is absent in the post-hurricane forest.

Neumann et al.(1990) compile map displays (referred to as "best tracks") of annual and multi-year tropical storm track summaries in the North Atlantic. They represent best estimates of the smoothed path of the cyclone eye as it moves across the earth's surface. These tracks should be considered as the average path of the larger scale storm circulation system and not necessarily the precise location of the eye at any given time.

Since the introduction of continuous weather satellite surveillance, there is little chance that a tropical cyclone will go undetected. There also is a high probability that the center of the storm can be located within 46 km of its actual position and the intensity determined to within 5.1 ms^{-1} of its actual intensity. Since all of the storm tracks and intensity classifications for the 1964 through 1989 Atlantic hurricane seasons were prepared with the benefit of satellite imagery (as well as aircraft reconnaissance and other data), the track accuracy should be near optimum, considering the scale of the maps and the scale of motion depicted.

Figure 8. North Atlantic cyclone tracks for 1938 (Neumann et al., 1990).

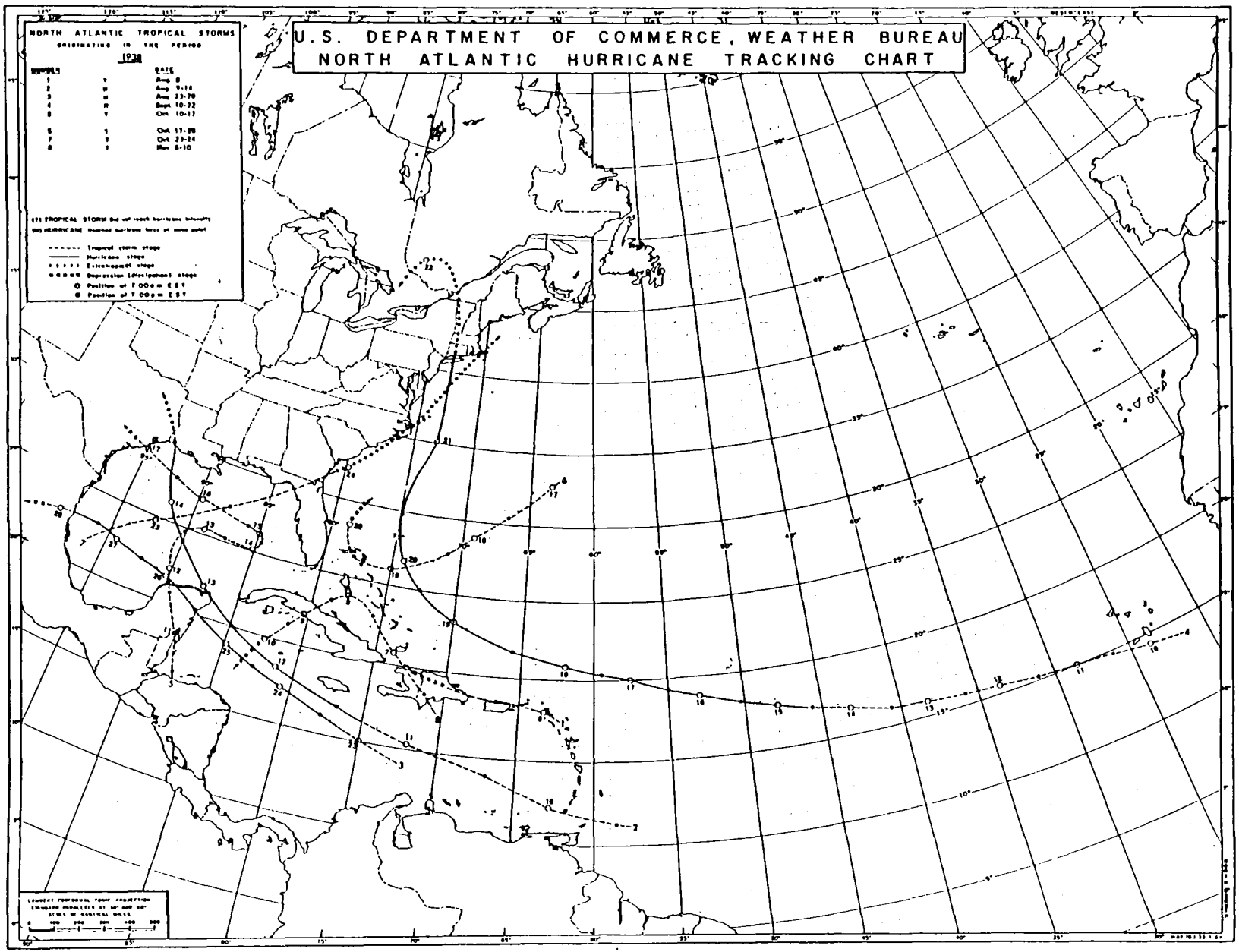
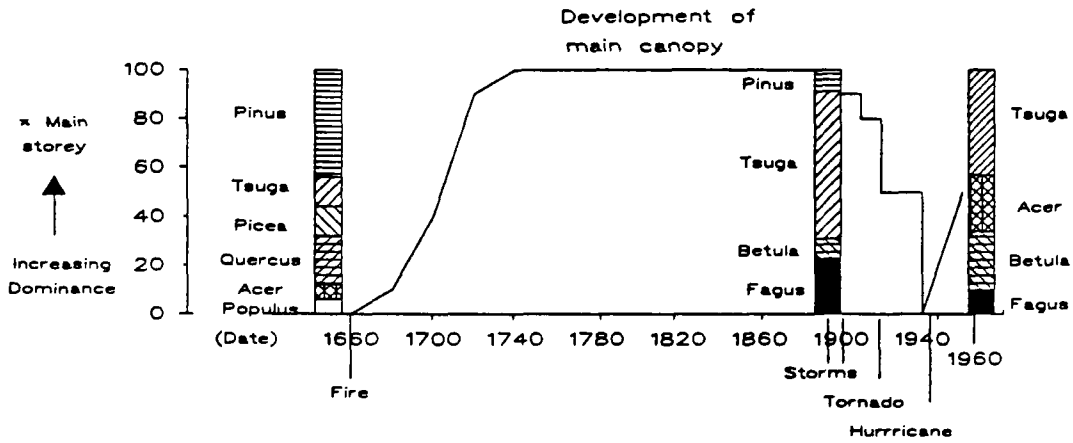


Figure 9. The influence of weather-related disturbance events on a mixed coniferous and broadleaf deciduous forest in New Hampshire (after Woodward, 1987).



There is some suggestion that there has been an increase in U.S. east coast storminess since the early 1940's and a shift in dominant storm track to a position further off the coast (Hayden, 1981). Hayden concludes that these trends are part of a secular variation of a longer time scale. Future trends in tropical and extratropical storms and storm tracks under greenhouse warming is a hotly debated topic. While some scientists argue for increases in the destructive potential of hurricanes (Emanuel, 1987; Emanuel, 1988) and a higher frequency of hurricanes (AMS Council and UCAR Board of Trustees, 1988) under greenhouse warming, others maintain there will be no change in the frequency of occurrence of Atlantic/Caribbean hurricanes and a significant decrease in the intensities of such storms (Idso, et al, 1990).

For this report, North Atlantic cyclone events during the most recent 30 years are enumerated. Magnitude is summarized by life-stage at landfall and during its passage through the New England region. Size is broadly summarized by listing the states through which the storm path passed. Each storm is somewhat unique and should be individually researched if site specific detail is required.

II.B.3. Drought

Next we move from disturbances resulting in direct windthrow damage and mortality to a disturbance with more subtle implications for forest ecosystem health. Drought impacts many aspects of forest health. As a drought develops, leaf cells progressively dehydrate and the reduced turgor of leaf cells inhibits cell expansion (Kozlowski, 1985). At the same time the stomata close, thereby reducing the rate of photosynthesis by impeding absorption of CO_2 through stomatal pores. Changes in hormonal growth regulators also occur. If drought is prolonged, the reduced transport of carbohydrates and hormonal growth regulators from leaves to roots will reduce root growth which will decrease absorption of water and mineral nutrients. Production of fruits and seeds can be arrested by drought at any stage of reproductive growth, including flower bud initiation, opening of flowers, pollination, fertilization, embryo growth, or fruit and seed enlargement. Trees in chronic drought areas typically allocate an abnormally large carbon component to their roots (Smith, 1990). Field observations of prolonged droughts in the Allegheny Plateau region of northwestern Pennsylvania result in heavy mortality of shallow-rooted tree species such as hemlock (*Tsuga canadensis*) and yellow birch (*Betula alleghaniensis*) (Runkle, 1985). Drought has been implicated as an initiator or important contributor to many forest declines (Smith, 1990).

A secondary impact of drought is pest infestation. For instance, spruce budworm outbreaks occur in Maine in stands of overmature balsam fir under warm, dry May and June conditions (Ferris, 1980). Trees begin to die after 5 years of defoliation and mortality is nearly complete after 8 years. Trees under drought stress may also have lower resistance to pests such as bark beetles (e.g., reduced resin exudation)(Graham, et al, 1990). In pine-oak forests of the southeastern United States, drought predisposes most of the resident pines to successful invasion by the southern pine beetle (Michaels et al., 1986)

One measured forest response to drought is tree ring width. A summary of current tree ring analysis techniques is provided in Fritts and Swetnam (1989). The authors also provide examples of dendrochronological applications to the assessment of spruce budworm effects on forest growth, forest decline and climate variability and change. Puckett (1981) reconstructs a drought climatology using tree rings and Zahner and Myers (1989) use an index of drought severity to help identify sources of stress as reflected in tree ring histories.

One prominent indicator of meteorological drought is the Palmer Drought Severity Index (PDSI) (Palmer, 1965). The PDSI represents the deviation of meteorological conditions from climatological "normals" for some specified area or location.

Although the temporal characteristics of the algorithm makes it poorly suited for estimating the impact of short-term drought on biological systems (Sadowski, 1975; Cooter,1982; Alley, 1984), it appears to be a reasonable measure of longer duration drought stress for forest ecosystems (e.g. Puckett, 1981 and Zahner and Myers, 1989). The PDSI response time is of the same order as forest growth and development, and its use to define large-scale climatological patterns is well established (Karl, 1983; Eder et al., 1987).

The PDSI uses mean monthly temperature and precipitation data and a hydrologic accounting system based upon simple soil and atmospheric demand models. Moisture is removed linearly from the top layer of the two-layer soil model. Moisture removal from the underlying layer is proportional to how close the profile is to moisture capacity. Potential atmospheric moisture demand is a non-linear transformation of mean monthly temperature and monthly precipitation. Actual demand is a function of the potential and the moisture available to meet the demand. Once atmospheric demands are met, the remaining precipitation is assumed to refill the soil profile linearly from the top layer, down. Any precipitation in excess of that needed to refill the soil profile and meet atmospheric demand (evapotranspiration) is treated as runoff.

Palmer (1965) documents the original development of the PDSI. Monthly PDSI for climate divisions across the U.S. from 1895 through 1990 have been digitized and are distributed through the National Climatic Data Center (NCDC). Climate Divisions (CDs) are groups of political (e.g. counties) or geographic (e.g. hydrologic basins) entities considered to be climatologically homogeneous. Documentation for these data is available in Karl et al. (1983).

In this study, drought frequency is represented in two ways. First, time series of area-weighted PDSI values are computed. Growing season (April-September) means are provided for a baseline summary and individual months are provided for shorter term summaries. Statistics of PDSI must be examined with care because of the influence of the method of calculation. For instance, a baseline summary of "mean PDSI" would be meaningless if the baseline was equivalent to the normalizing period of the time series. By definition, the mean PDSI for this period should be zero. Likewise, the frequency distribution of PDSI values is predefined by the characteristics of the normalizing period.

Drought disturbance magnitude has two components, intensity and duration. Frequency, intensity and duration are summarized in the baseline climate summary using a return period presentation. The return period is the amount of time expected to pass before these or more extreme conditions are experienced. Figure 3 suggests that a 100 year return period would be an appropriate definition of drought disturbance. The entire computed PDSI record

is used in the baseline summary. Frequency and intensity summaries are based on mean growing season (April through September) PDSI values. This eliminates higher frequency events that might not appear in growth indicator measures such as changes in diameter at breast height (dbh) and tree ring widths. Individual months are examined to determine drought persistence. A PDSI value of -3.0 or more negative indicates severe drought. Runs of consecutive months with PDSI values of -3.0 or less were computed for the period of record, and the number of consecutive drought months expected once in 100 years of record was computed.

Size of drought disturbance is estimated in two ways. First, the map presentations of intensity and duration provide some indication of the area impacted by drought of similar character. A second estimate is presented in a decadal summary. In this case, the percent of the New England region impacted by drought of a given magnitude is estimated for each year of the time series. Although similar calculations could be performed for the entire period of record and regional statistics computed, this kind of pooled summary should be approached with caution. There are several different characteristic drought episodes associated with large-scale atmospheric circulation patterns, each having distinct spatial and temporal characteristics. An average, aggregate area mean could be misleading. A more detailed study including stratification by circulation pattern may be more informative. For those interested in trend detection, some scientists suggest that greenhouse warming will first be detected by noting changes in such large-scale circulation patterns (Michaels and Hayden, 1987).

II.B.4. National Weather Service Cooperative Network Data

Much of the climatological data available for analysis are from the National Weather Service's (NWS) cooperative network stations "summary of the day." These daily arrays contain 24-hour maximum temperature, minimum temperature, total precipitation, snowfall and snow depth. At present, cooperative station density is maintained nationally at a minimum of one station per 1600 km^2. Standard sample variables and methods of collection are detailed in NWS (1989).

An initial array of potential weather sites were provided based on a minimum 30-year period-of-record, current reporting status and completeness of record. For a given station in this network, several potential inhomogeneities are usually present (Karl and Quayle, 1988). Changes in instrument location, the type of instrument, the local environment, exposure and changes in observational procedures average about five to ten potential discontinuities per 100 years of record. Karl and Williams (1987) provide examples of the magnitude and frequency of these

inhomogeneities.

Next, the GIS was used to associate each forest sampling area (hexagon) in Figure 4 with a weather observing site. Climatological data for 1990 which were unavailable from the NCDC were obtained from the Northeastern Regional Climate Center at Cornell University.

Distributions of stations and station distances for NEFHM hexagons and "nearest" temperature and precipitation data are summarized in Figures 10 and 11. Overall, 43% of the sampling sites have access to 30-year precipitation data within 15 km of the site, 33% can utilize rainfall reports from between 15 and 30 km away and 24% of sampling locations must use data more than 30 km away. The maximum distance is 106 km. Most distances greater than 30 km are for sampling hexagons located in the population sparse sections of northern Maine.

Twenty-nine percent of sampling hexagons are within 15 km of a cooperative temperature site, while 28% of sampling sites have access to data within 30 km and 33% of sampling sites must be characterized by weather observations more than 30 km distant. The maximum distance is 110 km. All distances greater than 42 km are again for sampling hexagons located in northern Maine. Future studies should examine the availability of Canadian data to fill some of these gaps.

The significance of the spatial distribution of available climate data for future forest and climate analyses should be explicitly addressed. For instance, the use of "nearest" station analysis may be adequate for regional summaries and status, but more closely associated values, perhaps through statistical interpolation, may be more appropriate for sampling point analysis or for making associations between sampling points. The NWS and the National Environmental Satellite and Data Information Service (NESDIS) are in the process of considering various strategies for modernizing the cooperative network. At this time, the NWS does not anticipate any major changes in cooperative network density or station locations arising from such efforts (Robert Leffler, personal Communication).

Once the stations have been selected and assigned to sampling sites, climatological variables of interest are designated. Basic variables such as means and extremes of precipitation and temperature have been identified as important to the NEFHM program by Brooks et al. (b, in press) and Brooks et al. (c, in press). The relationships between these variables and forest response are fairly well known and are presented in the climate summaries with no additional explanation. Additional climate variables have been selected for analysis based on the NEFHM project work plan, Solomon et al. (1984), Kozlowski (1985) and Peer (1990). Cumulative growing degree days, last spring freeze and warm spring snowfall

Figure 10. Distance between "nearest" cooperative temperature observation sites and potential NEFHM sampling hexagons.

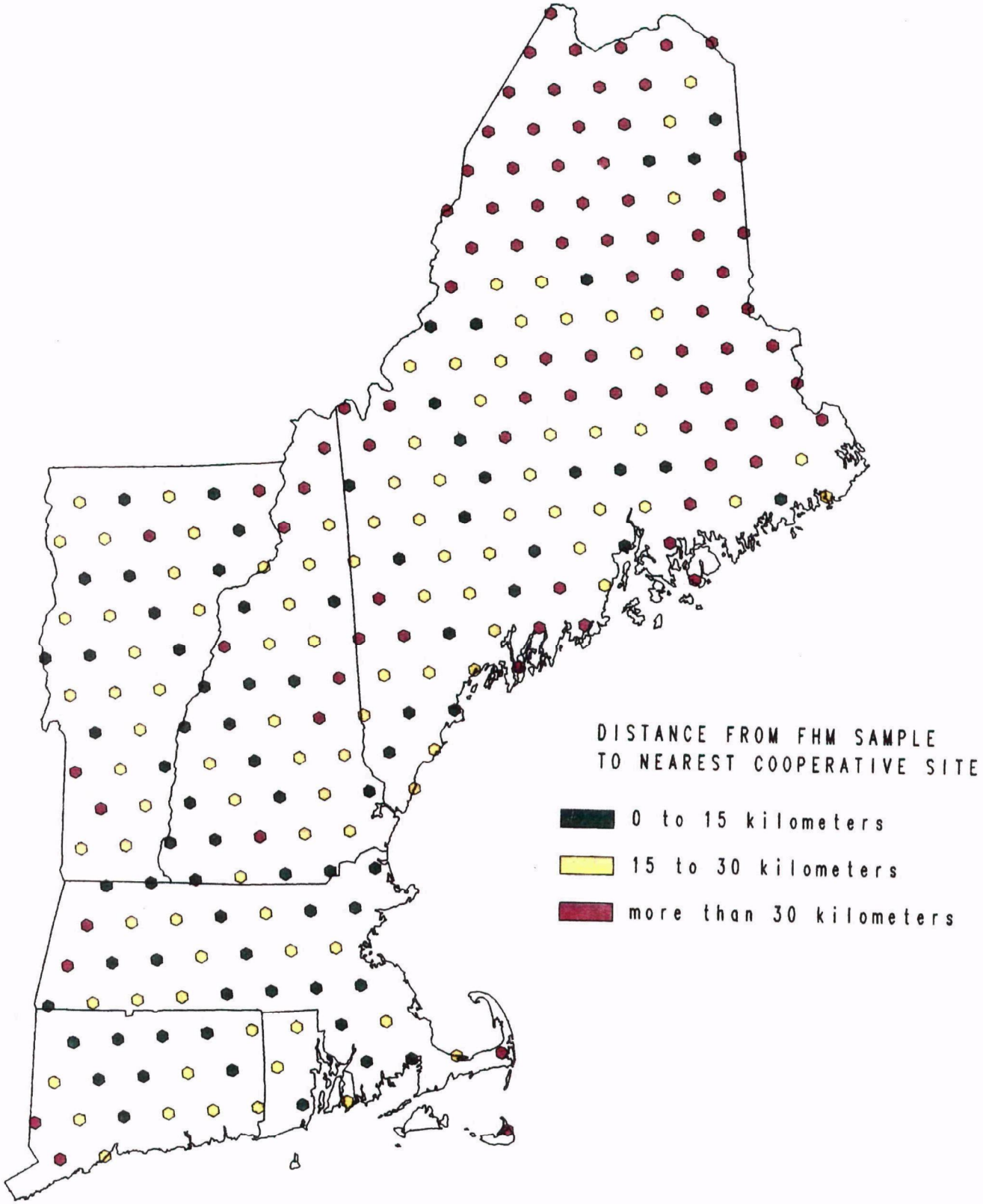
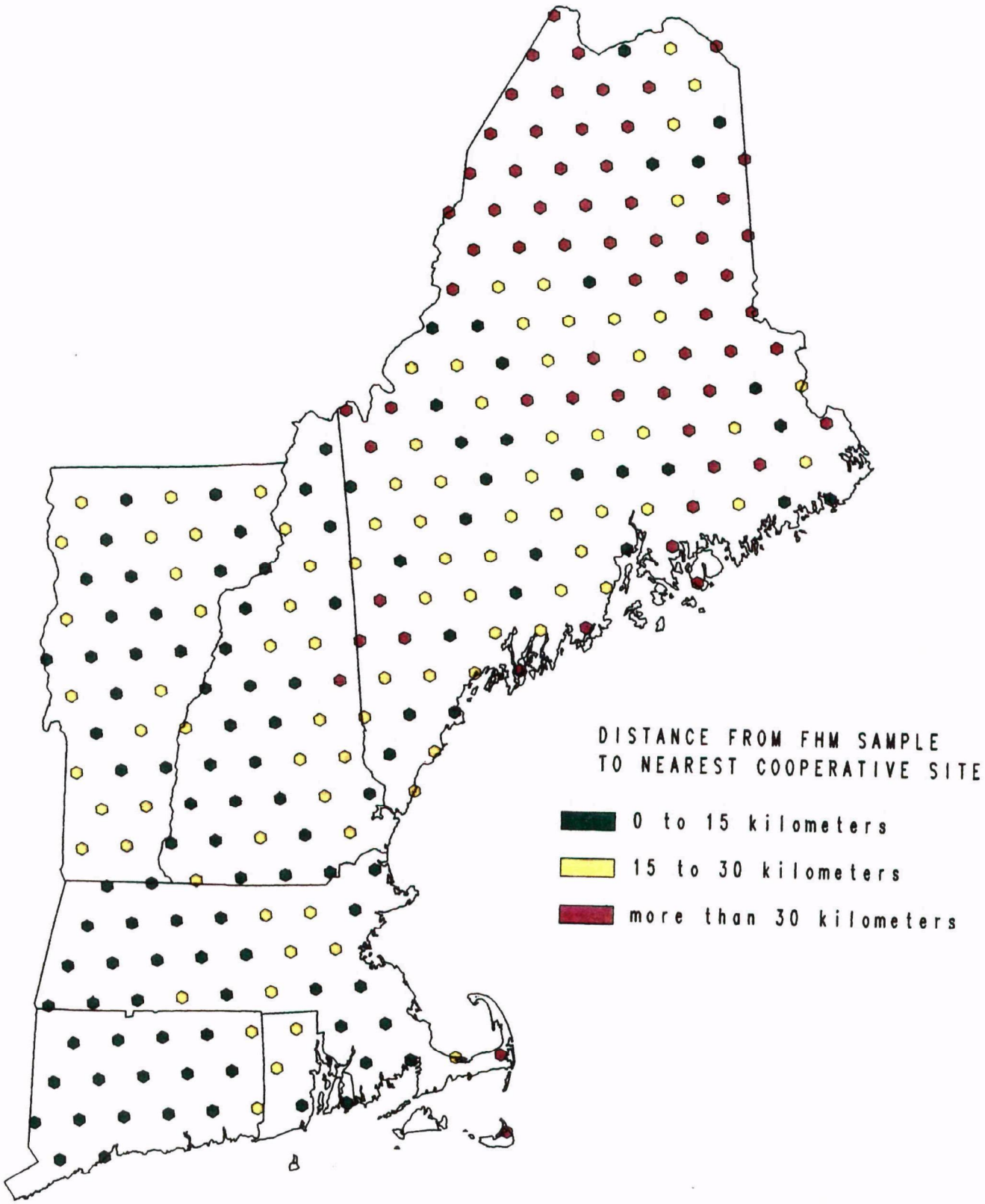


Figure 11. Distance between "nearest" cooperative precipitation observation sites and potential NEFHM sampling hexagons.



dates were selected. Since the availability and use of these secondary data may be less obvious, their derivation and relationship to forest physiology and monitored response will be discussed in some detail.

Disturbance regime characteristics are summarized in a similar fashion for each of these primary and secondary variables. Mean conditions are determined for the baseline summary to delineate geographic and climatological boundaries for ecosystems. For instance, high elevation locations can often be identified by regions of cool seasonal temperatures. Rain shadow effects can be detected as precipitation minima on the leeward side of these cooler temperature areas. If we assume that at each location the distribution of weather observations approximates the normal, the mean also approximates the mode and so is a measure of greatest frequency.

As in the case of drought, disturbance magnitude can be a function of both intensity and duration. The PDSI relates present conditions to historical record for a particular area. The index at a point in time captures both intensity and duration aspects of drought. For instance, an equally negative (severe) drought stress could represent a short duration intense event as well as the cumulative effects of long duration less intense events. This is another reason that time series analysis of PDSI is a far more useful tool than single value presentations. No such integrated measures *apropos* to forest ecosystems exist for the climate variables included in this discussion.

An alternative approach is to use event likelihood as a surrogate for magnitude of intensity. Under this system, it is assumed that existing vegetation has adapted to prevailing (most frequent) climatological means and variability. Excursions from these conditions represent situations that could result in ecosystem change. The more unusual the event, the more likely it is that some change will result. In this sense, frequency defines the magnitude of the disturbance (stress). Following this system we will arbitrarily declare an event with a local return period of 1 in 20 years to be mildly stressful (i.e., there is some chance that an ecosystem change will result). An event with a return period of 1 in 50 years is moderately stressful (i.e., there is a moderate chance that ecosystem change will result). Using Figure 3 as an endpoint, an event with a 1 in 100 year return period is considered to be extremely stressful(i.e., it is likely that some ecosystem change will result from this event).

For this report, these probabilities have been estimated from the instrumental record. Relatively few stations in the reporting network have 100 or more years of recorded observations. Values for returns greater than 50 years represent only rough estimates based on the most recent history. Statistical techniques exist to estimate more accurate values of rare events and should be explored

in future studies.

Disturbance size is characterized by the percent of the New England region reporting a specified level of disturbance. An integrated size, frequency and intensity analysis is presented and discussed in the decadal climate analysis (section III).

II.B.4.a. Growing Degree Days

Solomon et al. (1984) and Peer (1990) provide examples of research associating cumulative growing degree days (GDD) directly to forest growth. GDDs are a specific example of the heat unit concept. This represents a measure of the energy available for biologic activity or growth. The heat unit has proven to be useful in a variety of biological settings. For instance, cumulative GDD totals are associated with winter wheat phenology in Nuttonson (1955). They are used to limit the number of daily timesteps permitted for carbon transfer in corn plants in Jones and Kiniry (1986). The use of degree day totals to predict Southern Pine Beetle larvel survival and generation survival are discussed in Gagne et al. (1980). Species specific GDD ranges as used in a forest stand simulation model are summarized in Solomon et al. (1984).

GDDs are usually computed as a temperature deviation from some physiologically significant base temperature. Upper and lower temperature thresholds representing limiting conditions may also be defined. In these cases, GDDs are not computed (i.e., GDD=0). Solomon et al.(1984) states that forest processes begin between 0 and 10°C. According to Kozlowski (1985), growth of most trees is optimal between 20 and 35°C, depending on the species. A GDD base of 10°C is used for this illustration. A lower threshold is defined as a 24-hour minimum temperature of 0°C. No explicit upper "capping" temperature is used. Small annual GDD sums are assumed to represent unfavorable growth conditions and are highlighted in the climate stress analysis. Physical interpretation of GDDs must be done cautiously. For instance, similar GDD totals could result from either long periods of mild temperature conditions or short periods of extremely warm temperatures. Growth response could vary markedly given these two sets of conditions.

II.B.4.b. Last Spring Freeze

Primary forest response to late spring hard freezes are defoliation and, in extreme cases, death. Gerardi and Grimm (1979) summarize physiological stress to trees as the result of defoliation. Stress on individual trees depends upon the species, duration and degree of defoliation, stand site, location of defoliation in the tree crown and the age and health of the tree at the time defoliation occurs. Defoliation also affects seed and

flower production, wood quality, foliation timing, respiration and efficiency of photosynthesis, size, abundance and food storage capacity, metabolic food conversion pathways and hormone production in much the same way as drought. Removal of new foliage, such as that at first flush in the spring, decreases growth of the upper stem more than in the lower stem. Late season defoliation (from early freezes or warm snow events) reduces twigs of woody tissue and subjects them to winter damage. Specific growth losses from defoliation include reduced height growth, radial growth losses and reduction of shoot elongation. Stomatal resistance to transpiration is also affected by defoliation. This resistance is less in fully emerged, secondary foliage produced after defoliation than in primary foliage that has escaped defoliation in oak and aspen; however, as leaf surface area declines, the demand for moisture decreases. The decreased demand for moisture improves the internal water balance of defoliated trees if ample soil water is available; but defoliation also may increase tree hydration. Drought compounds the effects on the physiological make-up of trees during and after defoliation.

A knowledge of interactive effects of natural and anthropogenic disturbance factors is also critical if climate change trends are to be detected. Forest response to winter or freezing conditions is a good example of interacting stressors. For instance, an exhaustive treatment of the response of red spruce to winter conditions alone and in combination with anthropogenic disturbances (ozone, SO_2, NO_2 and acid deposition) is contained in Adams and Eagar (1989). A second summary that focuses exclusively on the ecosystem-wide impacts of nitrogen deposition is presented in Aber et al. (1989). Both reports discuss the effect of nitrogen deposition on the development of frost-hardiness in spruce. These research results could mean that future changes in freeze related foliar damage to New England forests could be in response to changing anthropogenic stressors rather than an indication of a changing freeze disturbance regime.

A freeze analysis can be used to confirm or supplement observations of adverse weather conditions that might cause growth decline and tree mortality. Late spring freezes do not leave sufficient sign for later identification even though, in combination with other stresses, they have been implicated in most forest declines (USDA Forest Service, no date). Knowledge of possible climate related defoliation is also important for pest and disease studies. Defoliation resulting from freezing temperatures may combine with later pest related defoliation to contribute to tree mortality. Spring freeze defoliation can remove a source of food for pests and actually act to curb epidemics. Spring defoliation can also weaken trees and predispose them to later pest infestation. For example, Gerardi and Grimm (1979) report that the action of shoestring root rot fungus, *Armillaria mellia*, and the two-lined chestnut borer, *Agrilus bilineatus* in the outer wood may

be controlled by the chemical changes occurring there as a result of defoliation.

Other factors related to frost/freeze damage are the duration of stressful temperatures and the degree of cold hardiness in affected plant tissues at the time of freeze (Kozlowski, 1985). The NWS Cooperative Observer data set provides only 24-hour extremes with no indication of persistence within the day. Supplemental hourly data are available from a limited number of National Weather Service First and Second Order observing stations. These data could be used to perform more detailed studies if freeze duration within a 24-hour period is determined to be a critical factor. A second analysis could focus on minimum temperatures preceding the freeze event (cold hardiness) and the duration across 24-hour periods of the freezing event. In the present analysis, a hard freeze is recorded if the 24-hr minimum temperature is -2.2°C or colder.

II.B.4.c Last Spring Snowfall

Snow has a variety of implications for forest ecosystem health and productivity. An insulating blanket of snow protects tender understory species from winter desiccation or damage from periodic soil heaving. Snow also provides an important source of surface water storage. Wintertime evapotranspiration is low, and substantial supplies of moisture can be held until spring. A slowly melting layer of snow in the spring releases moisture and nutrients in a fashion that permits maximum vertical infiltration and minimum surface erosion.

When ice crystals fall through a layer of relatively warm air, the crystal surface melts. These "wet" flakes then stick to any surface they come in contact with. The accumulated weight of this trapped liquid water on leaves and branches causes loss of limbs and uprooting of entire trees. One particular case, the "warm snowstorm of May 9, 1977" is discussed in Gedzelman and Lewis (1990). This storm was one of the latest occurring major snowstorms in the lower Hudson River Valley on record. The accumulated weight of the wet snow on newly sprouted leaves caused extensive destruction to trees (see impacts of defoliation in section II.B.4.b.).

A traditional source of snowfall data is the NWS Cooperative Observer Network. Unfortunately, these data are particularly poor in terms of quality control and spatial coverage. But when used with caution, they can provide valuable information for forest scientists. For example, it is difficult to determine from the digitized summary-of-day reports if a snowfall event was warm or cold. As an alternative to extensive archival research, the present study assumes that if, at a particular location, a spring snowfall event is expected on a later spring date fewer than one

year in 20, it is likely to be a warm snow event.

A discussion of snow data error and bias is presented in Robinson (1988). Although unavailable for the present study, a new quality controlled set of snowfall data have recently been developed based on the work of Robinson and can be ordered from the National Climatic Data Center. Future work should consider warm fall snow events, use of the Robinson data base and more accurate determination of event occurrence from the digitized record.

II.C Display Technology (GIS)

Geographic Information System (GIS) software was used to study these spatial relationships between the climatology of the New England area and the sampling locations in the Forest Health Monitoring Project. The GIS system used for the display and analysis of these relationships was Environmental Systems Research Institute's ARC/INFO. The types of spatial analysis performed were proximity analysis, surface modeling and overlay analysis. The procedures used for each of these three analyses are discussed below.

For the proximity analysis, the GIS was used to associate conditions measured at nearby National Weather Service Cooperative Observer locations with the 263 potential NEFHM sampling locations. The ARC/INFO "NEAR" command was used to identify the closest cooperative observer station for each of the 263 NEFHM sampling locations. Once identified, the information from the observer station is linked to the associated NEFHM sampling location and used to characterize the likelihood of forest response to climatological disturbances.

Surface models were created from long term cooperative observer station data for annual growing degree days, date of last spring freeze and date of last spring snowfall using Dynamic Graphics' Interactive Surface Modeling (ISM) software. The contour lines generated from ISM during the modeling process were then moved to ARC/INFO for overlay and display purposes.

The GIS was then used in the final overlay analysis which characterizes individual sampling hexagons from a weather event perspective. This process involves displaying and analyzing events that occur in the same spatial domain. The events analyzed included wind, hail and tornado events. The analysis produced maps of individual hexagon sampling sites displaying with the associated weather events that have occurred at that location. This analysis also produced descriptive statistics on the number of weather events (intersections) occurring within the sampling frame of 263 NEFHM locations.

These analytical techniques were also used in combination to further analyze relationships. For example, to estimate the growing degree days at a particular sampling location the surface model for the growing degree days was overlaid on the sample locations. Similar analyses were performed for the spring snow and freeze data.

II.D. Summary

Disturbance regime climatology examples have been prepared targeted to the joint, 1990 EPA EMAP-forest and NEFHM project conducted in six states in the northeastern United States. Weather and climate databases have been assembled from a variety of sources. Secondary or derived variables of potential interest to these programs have been identified. The physiological impacts of these variables on forest ecosystems have been summarized and expected forest responses were noted. Table 6 summarizes all climate disturbance products developed using the techniques discussed in Chapter II that are applied to the New England region in Chapter III. A blank entry in Table 6 indicates disturbance attributes that have not been quantified for this report.

Table 6. Examples of climate disturbance (stress) products for New England (see Chapter III).

CLIMATE VARIABLE	FREQUENCY	MAGNITUDE	SIZE
Tornadoes	intra-annual	intensity only	X
Wind	intra-annual		
Tropical Cyclone	X	intensity only	X
Drought	X	intensity duration	X
Temperature	X	intensity only	X
Precipitation	X	intensity only	X
Growing Degree Days	X	intensity only	X
Late Spring Freeze	X	intensity only	X
Late Spring Snowfall	X	intensity only	X

III. Example Disturbance Climatologies

III.A. Introduction

The results presented below represent examples of disturbance (stress) climatologies. The use of, and caveats associated with these products are discussed. A portion of this material already appears in Brooks et al. (b, in press) and Brooks et al. (c, in press) and is being used by the EMAP Forest and Assessment teams (Kucera and Martin, 1991). Further operational and research applications are anticipated in the future.

III.B. Baseline Conditions (1961-1990)

The first analysis characterizes aspects of the long-term, or background climate of the New England region. Using the earlier analogy of ecological persistence and recurrence, the background climate defines, in part, the "bounds" for the recurring ecosystem states. Table 7 summarizes elements of a disturbance regime climatology for which baseline examples have been developed. With the exception of event duration, frequency and magnitude of disturbance (stress) are well represented at this level of analysis. In most cases, event size is not characterized until the decadal analysis.

Table 7. Elements of a New England disturbance regime climatology for which baseline examples have been developed.

CLIMATE VARIABLE	FREQUENCY	MAGNITUDE	SIZE
Tornadoes	intra-annual	X	X
Wind	intra-annual		
Tropical Cyclone	X	X	X
Drought	X	X	
Temperature	X	X	
Precipitation	X	X	
Growing Degree Days	X	X	
Late Spring Freeze	X	X	
Late spring Snowfall	X	X	

III.B.1. Severe Weather and Tropical Cyclones

These phenomena are presented together because their primary impact on forest ecosystems is through windthrow. The primary difference between these events is their frequency and size. Disturbance frequency is presented in terms of intra-annual variability for wind and tornado events and by enumeration for tropical cyclones. Time series are not appropriate for severe weather events because of observational biases discussed previously and because of the infrequency of cyclone events.

Figure 5 illustrated that there have been numerous tornado and damaging wind event reports throughout New England during the last 30 years. There has been confirmation of 278 tornadoes and 1351 damaging wind reports in the region from 1961 through September, 1990. Figure 12 summarizes the intra-annual frequency distribution of these events. Figure 12 shows that the within-year distribution of wind and tornado events are similar, with a wintertime minimum and July maximum. This is to be expected since both phenomena are generated by similar kinds of unstable atmospheric conditions.

Figure 12. Relative intra-annual frequency of tornado and damaging wind events in New England, 1961-1990.

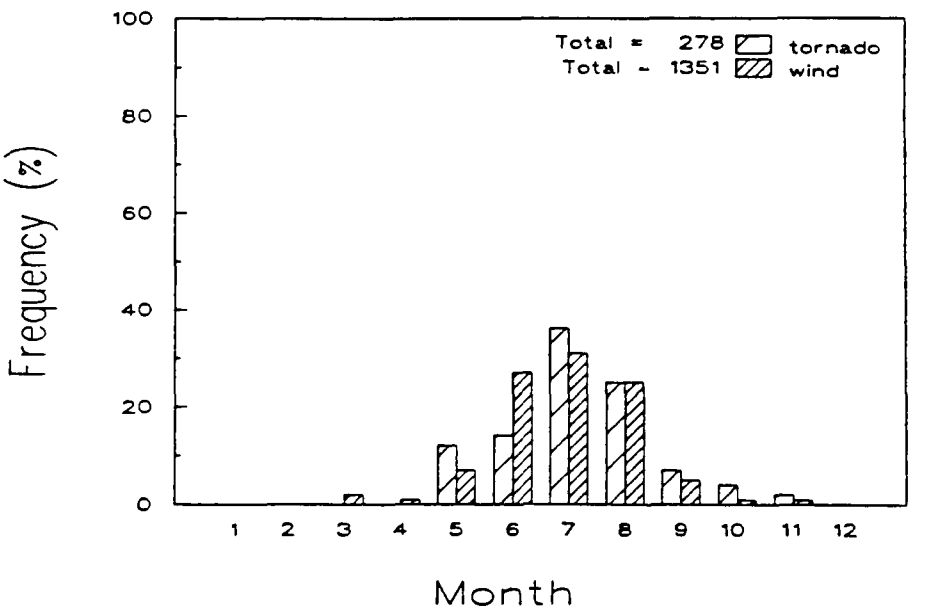
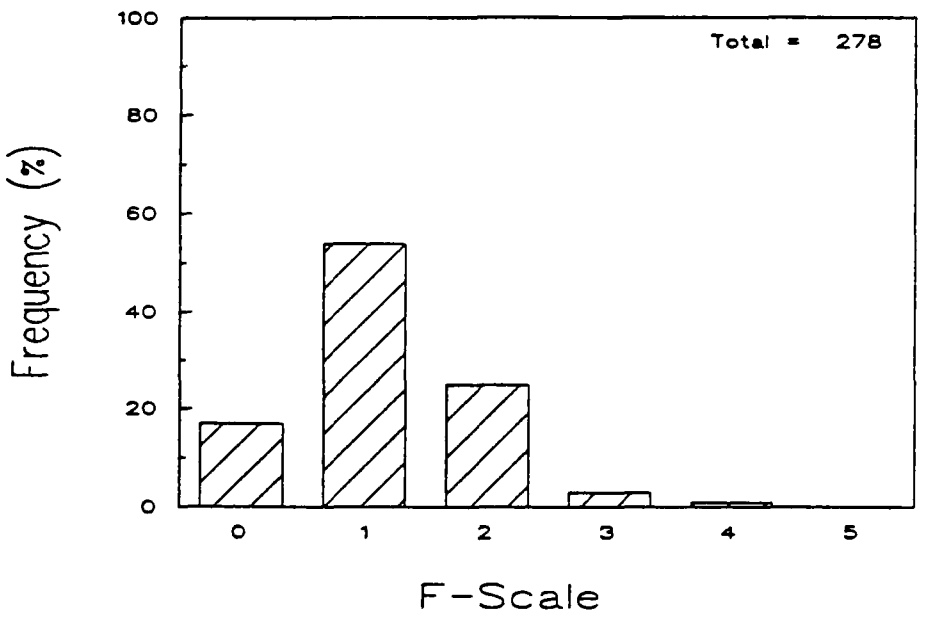


Figure 13 contains a summary of the distribution of New England tornado magnitude (F-scale rating). No intensity analysis is performed for damaging winds because of poor records of peak gusts. Windspeeds associated with F-0 events break branches off trees and push over shallow-rooted trees. Windspeed associated with any event rated F-2 or higher can result in large trees being snapped or uprooted. Figure 14 indicates that these events account for nearly 30% (about 83) of all tornadoes reported since 1961.

There have been approximately three tornado events containing windspeeds in excess of 89 ms^{-1}.

Figure 13. Distribution of tornado intensity for New England, 1961-1990.



The majority of reported tornadoes either touch-down only briefly (point events) or have such short paths that they are not recorded. Based on the available record, however, the average of 2.59 km^2 is a conservative estimate of the area impacted by tornadic events each year. The largest documented area impacted in a single year between 1961 and 1990 was 24 km^2. This damage was generated by three storms reported in 1979.

Although not as common as tornado or wind events, tropical cyclones pass through the New England area with some regularity. Table 8 enumerates these events and estimates storm strength and the states impacted. There have been nine storms in the last 30 years capable of damaging the forest canopy. The last confirmed storm (through September, 1990) capable of producing significant windthrow in the New England states occurred in 1976. The most frequently impacted states are Connecticut, Massachusetts, Maine and New Hampshire. For more detailed information concerning the tracks and life stages of these events, see Neumann et al (1990).

Table 8. Tropical cyclones impinging on the New England states, 1961-1990.

Year	Name	Life Stage*	Dates	States Impacted
1961	-	T	Sept 12-15	CT,MA,ME,NH
1961	Esther	D	Sept 11-26	ME
1966	Alma	EX	June 4-14	MA
1971	Doria	T EX	Aug 20-29	CT,MA,ME,NH
1971	Heidi	T EX	Sept 10-14	ME
1972	Carrie	EX	Aug 29-Sept 5	ME
1976	Belle	H T	Aug 6-10	CT,MA,ME,NH
1979	Frederic	T EX	Aug 29-Sept 14	VT
1979	David	T EX	Aug 25-Sept 7	ME,NH,VT
1985	Gloria	EX	Sept 16-Oct 1	CT,MA,ME,NH
1988	Chris	EX	Aug 21-29	CT,MA

* H = Hurricane (windspeeds equivalent to F-1 or greater)
T = Tropical Storm (windspeeds equivalent to F-0 to F-1)
EX = Extratropical Storm (windspeeds may vary from F-0 to F-1)
D = Tropical Depression (windspeeds of F-0 or less)

III.B.2. Temperature and Precipitation

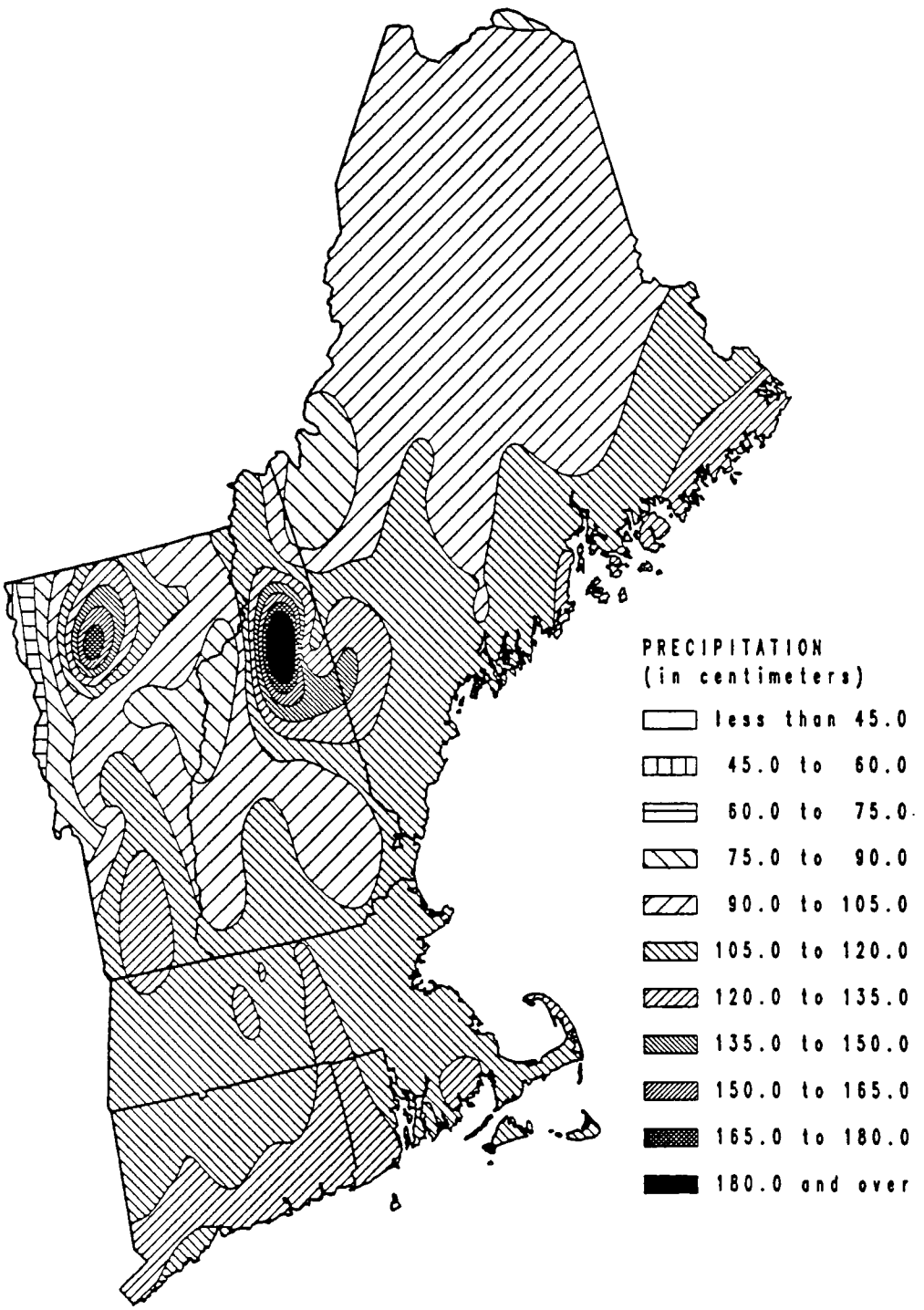
There are many possible averaging periods and derived variable options to represent temperature and precipitation conditions. Temperature extremes (annual maximum and minimum) and annual precipitation (October through September) were identified as particularly useful in monitoring forest health in the Northeastern U.S. (Brooks, et al., b, in press). Persistence characteristics of these variables are summarized in contour maps of mean conditions. Frequency is illustrated by weighted time series graphs. Relative magnitude of disturbance can be visually estimated from the time series presentation. No size (area) summary is presented at this time.

Contour map summaries of the most recent 30 years for mean New England precipitation and temperature extremes are presented in Figures 14, 15 and 16. Two features make these products unique. First, atlas summaries have often focussed on the presentation of all available data, rather than data selected for specific applications. In this study, only data from stations that have been associated with NEFHM program sampling locations are analyzed. The selected station data are then spatially smoothed using a bi-harmonic cubic spline to generate spatial contours. The degree to which these data, some of which are from instruments located more than 40 km away from the FHM sampling location, represent conditions at a monitoring site has yet to be explicitly addressed. Statistical estimation techniques, such as kriging or cokriging could be applied to climate means (e.g., Dingman et al., 1988). Interpolation of extreme values such as annual maximum and minimum temperature is significantly more complex. The selection of appropriate interpolation techniques should be dictated by the needs of the monitoring program and will be addressed in future research.

A second feature of the contour presentation is that annual values are based on the months October through September rather than a calendar year. This period was chosen so that a 1990 value represents events leading up to and including the forest sampling period and does not overlap previous or following growing seasons. All values on contour or time series graphs are labeled with the calendar year in which the averaging period ends. This label also corresponds to the year containing months of significant tree growth.

The most obvious ecological boundary effects illustrated by these figures are a function of latitude and elevation. Latitude and elevation play an important part in patterns of annual precipitation (Figure 14). Moist conditions prevail in the southern portion of New England and on the windward side of mountain peaks and extensive mountain ranges. Slightly drier conditions are observed in the colder more northern latitudes and

Figure 14. Mean annual New England precipitation, 1961-1990.



leeward of significant mountain ranges. Latitudinal affects are also reflected by zonal bands of northward-decreasing temperatures in homogeneous geographic areas and are most notable in minimum temperature patterns (Figures 15 and 16). Distortions of these broad patterns occur in mountainous areas. Elevation does not play a dominant role in annual minimum temperature patterns across New England, but is more apparent in patterns of annual maximum temperature.

Temporal variability of regional temperature and precipitation variables can be visually summarized by weighted time series (Figures 17, 18, 19 and 20). Since the NEFHM sampling design generates a nearly uniform grid of points, weighted area means are constructed by associating climate values with their appropriate sampling hexagons, summing and dividing the results by the total number of hexagons in the region.

Area-weighted annual precipitation in New England ranges from a low of 78.7 cm in 1965 to a high of 140 cm in 1983 (Figure 17). The time series appears equally variable throughout the 30-years of data and no statistically significant linear trend has been detected. The largest year-to-year change, 45 cm, occurs between 1984 and 1985.

Inter-annual variability is a notable feature in the time series of area-weighted minimum temperatures (Figure 18). Values range from -32°C during 1971 to -23.5°C during 1980. Particularly large year-to-year variability is noted from 1979 through 1985. A small but statistically significant linear trend of .18 °C/year has been estimated for the 30-year time series.

Periods of smaller year-to-year change are seen in the time series of area-weighted annual maximum temperatures (Figure 19). The greatest year-to-year change occurred between 1974 and 1975. 1974 was such an extreme year that it dominates our perception of the slope. The combined effect of area-weighted maximum and minimum temperature trends could narrow annual temperature ranges. This, in fact is the case. A significant linear trend with negative slope equal to that determined for the annual minimum temperature has been estimated. Figure 20 indicates increased annual range variability beginning in 1979. Such possible trends in regional climatological averages and variability must be interpreted carefully. For instance, for global or hemispheric averages, it is likely that random inhomogeneities in the station data will tend to cancel each other out (Karl and Quayle, 1988). This is not as likely in the calculation of regional averages where far fewer stations are used. Furthermore, station inhomogeneities add artificial variance to the time series.

Figure 15. Mean annual maximum New England temperature, 1961-1990

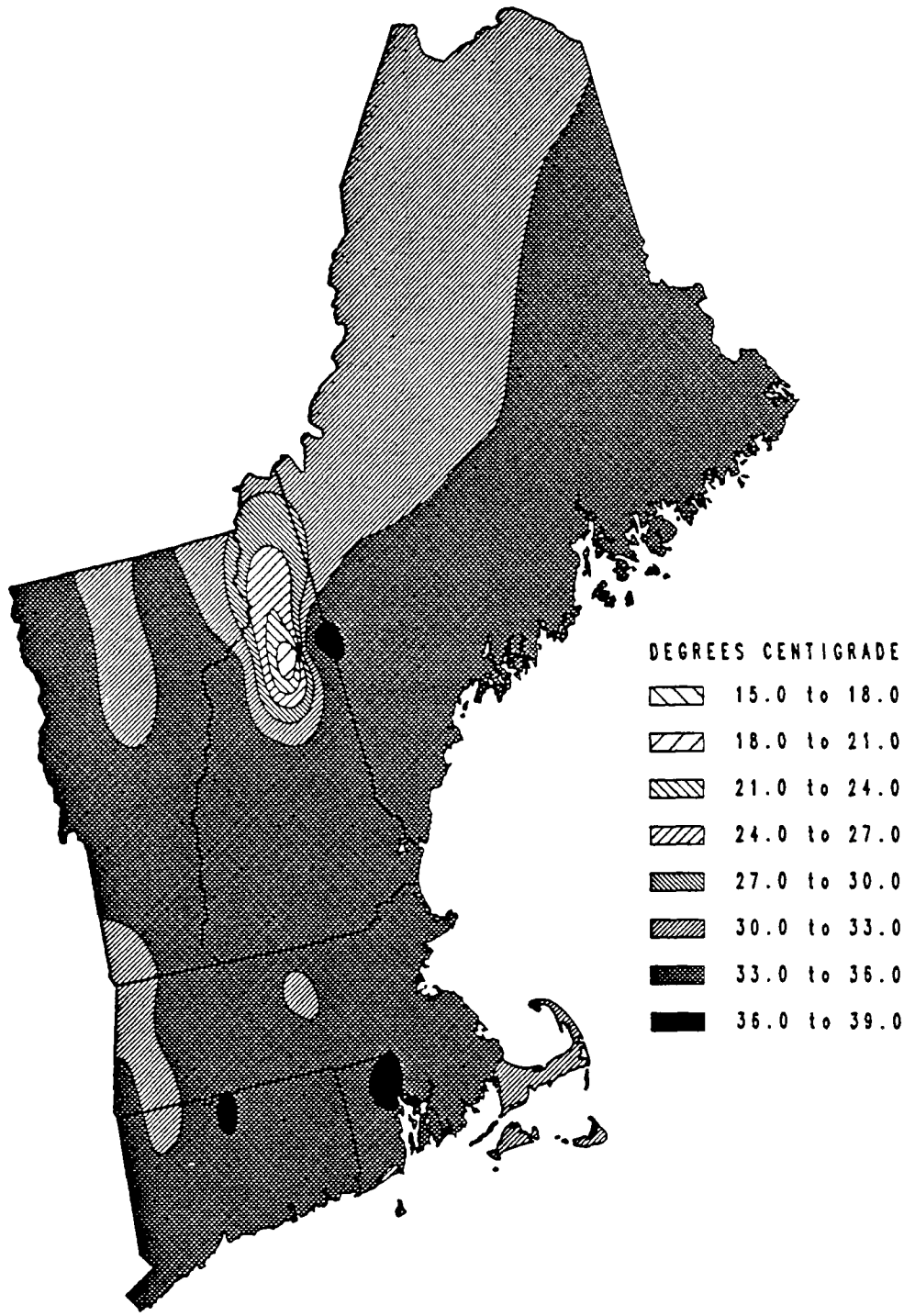


Figure 16. Mean annual minimum New England temperature, 1961-1990.

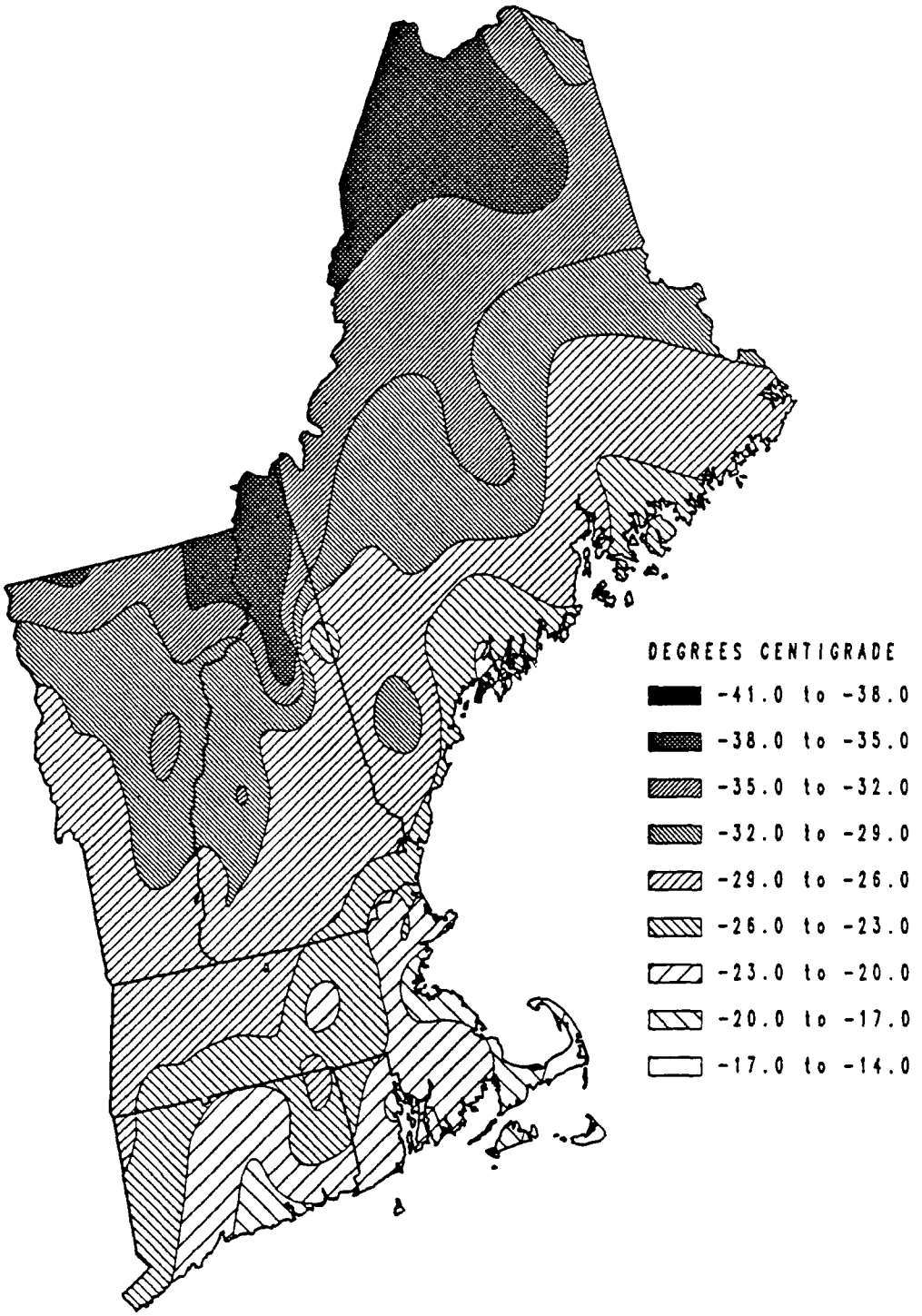


Figure 17. Area weighted time series of annual New England precipitation (cm), 1961-1990.

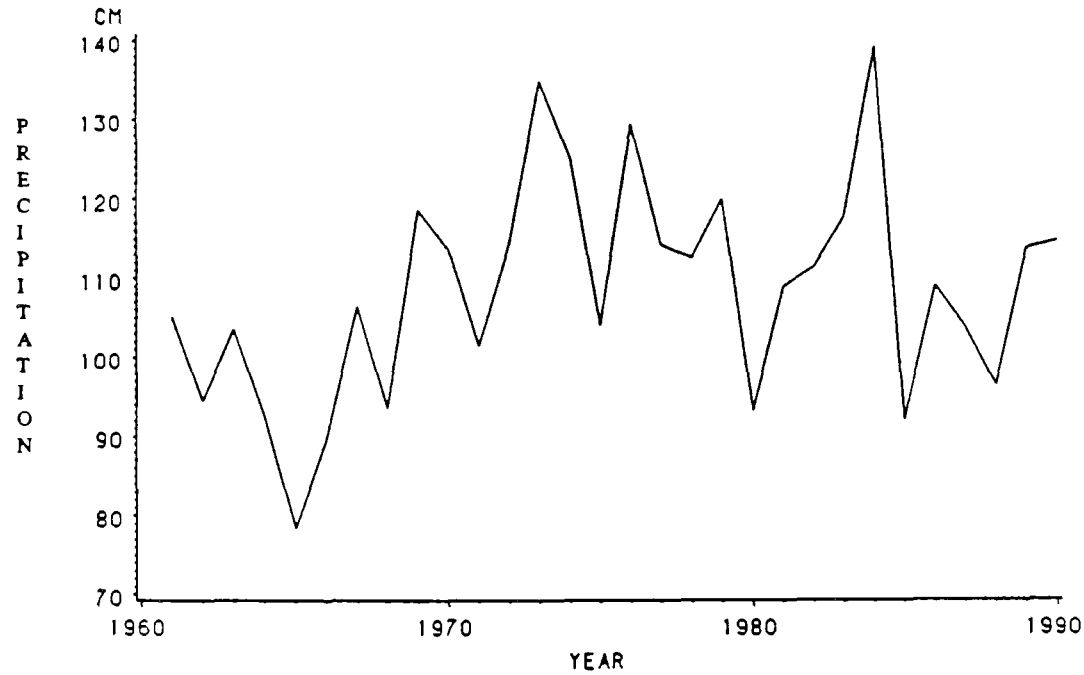


Figure 18. Area weighted time series of annual minimum New England temperatures (°C), 1961-1990.

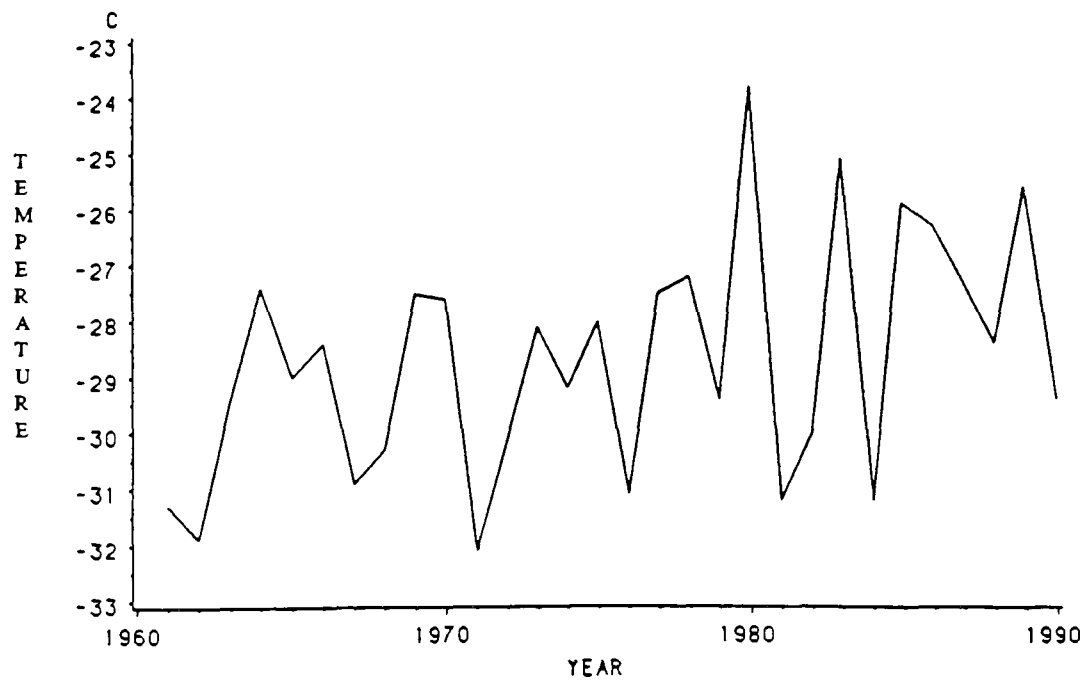


Figure 19. Area weighted time series of annual maximum New England temperatures (°C), 1961-1990.

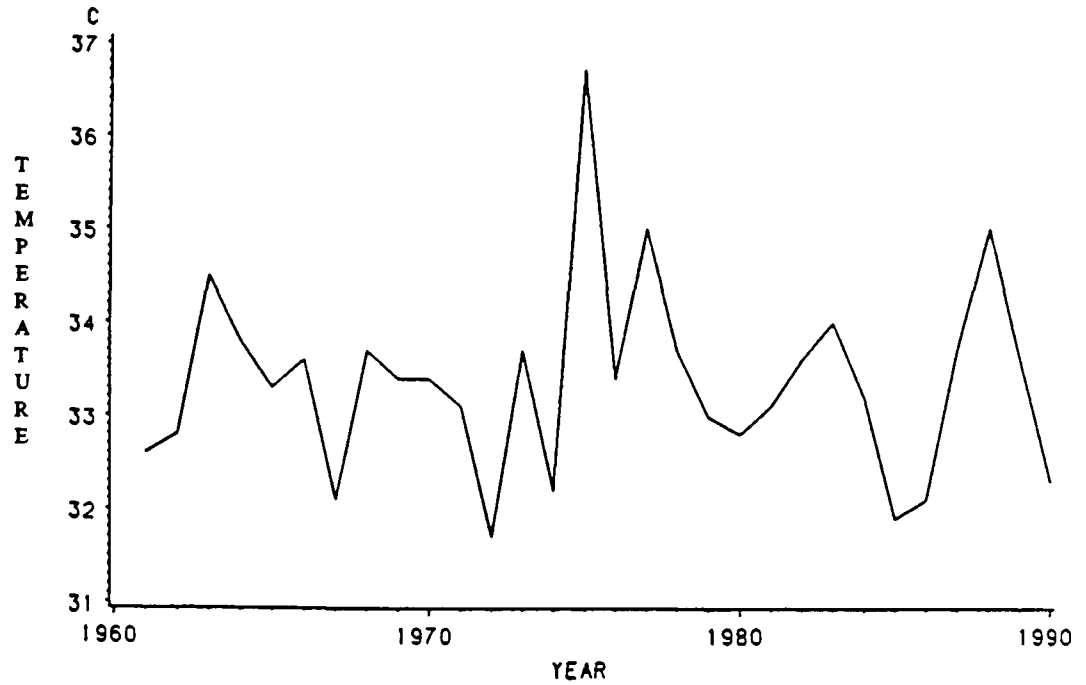
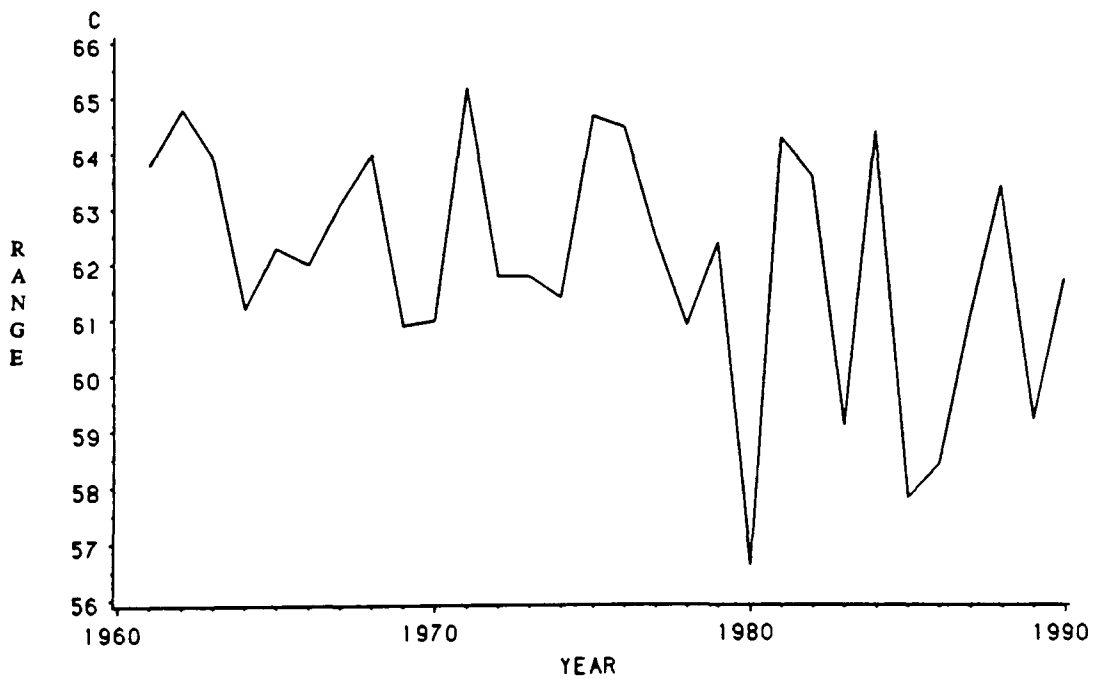


Figure 20. Area weighted time series of annual New England temperature range (°C), 1961-1990.



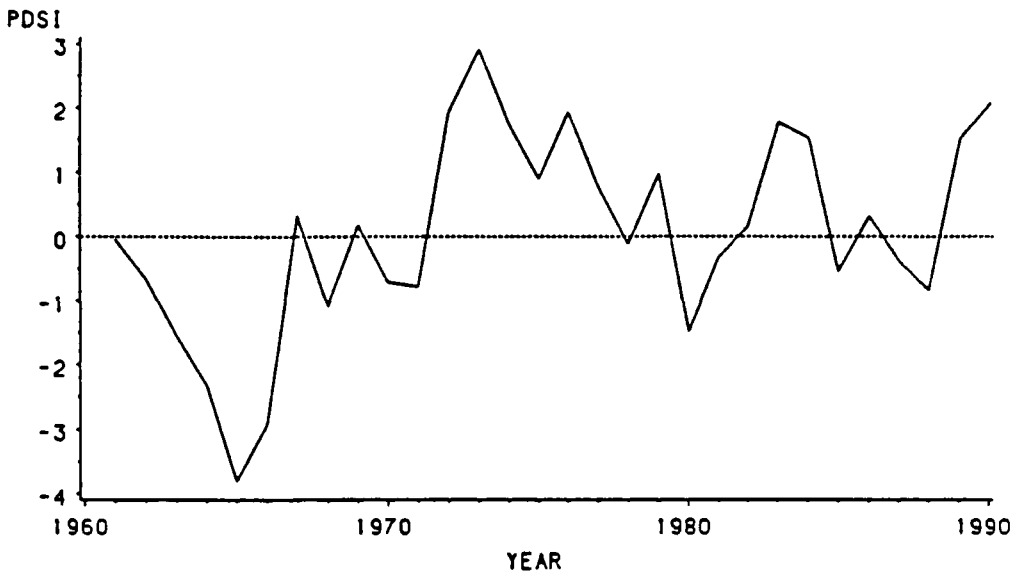
In the New England forest case, such inhomogeneities may not represent a significant problem in well instrumented areas where each station may represent from 1 to 3 sampling locations. However, significant bias may be introduced into a time series when a larger number of forest sites must be represented by a single weather observation. In New England, all such cases occur in Maine - the state which also dominates the region in area. Thus, a situation exists in which the greatest influence on the regional estimate is derived from the region with the least data. Errors in sparsely instrumented areas of Maine could easily be responsible for visually detected trends in the regional time series (e.g., Figure 17). If studies of ecosystem behavior at these latitudes are considered to be critical for climate trend detection and impact analyses, additional long-term climate observation sites are needed.

The accuracy of climatological data and summaries aside, a second fundamental question concerns the importance of such changes for forest ecosystems. For instance, if we assume that existing vegetation is ideally adapted to prevailing climatological means and extremes, how great a change is necessary before detectable ecosystem changes occur? Although the majority of plant growth and development can be generalized as responding to modal (most frequent or dominant) climate conditions, it is extreme conditions or events that most severely constrain species range and potential productivity. Responses to trends such as that noted in annual temperature range would most likely be observed at the margins of species range (ecotones). Warmer minimum temperatures (Figure 18) could create conditions in these areas favorable for expansion of marginal southern species into existing ecotones, or facilitate expansion of the ecotone itself. Although answers to some "how important is this?" questions are already available in the literature, other such questions require more detailed modeling studies. The goal of this report is to develop ways of describing climatological conditions so that associations between climate conditions (e.g. means, trends and variability) and indicators of forest status and health can be postulated and tested. This is a fundamental EMAP activity. If such associations can be confirmed, then research aimed towards the development of predictive response models can be pursued. This could occur either within the FHM program of entirely outside the EMAP/FHM initiative.

III.B.3 Drought

Drought frequency, intensity and duration products have been prepared as a baseline analysis. The spatially aggregate nature of the drought database makes contour presentations inappropriate. A time series of regional mean growing season PDSI can be used to estimate drought frequency (Figure 21). In this case, Climate Division (CD) PDSI values were assigned to each NEFHM sampling hexagon within the division. The 1960s are dominated by drought

Figure 21. Area weighted timeseries of mean growing season PDSI, 1961-1990.



GE 4.00 EXTREMELY WET
3.99 - 3.00 VERY WET
2.99 - 2.00 MODERATELY WET
1.99 - 1.00 SLIGHTLY WET
0.99 - 0.50 INCIPIENT WET
0.49 TO -0.49 NORMAL
-0.50 TO -0.99 INCIPIENT DROUGHT
-1.00 TO -1.99 MILD DROUGHT
-2.00 TO -2.99 MODERATE DROUGHT
-3.00 TO -3.99 SEVERE DROUGHT
LE -4.00 EXTREME DROUGHT

conditions that peak at a region-wide PDSI value of nearly -4.0 in 1965. This was followed in the early to mid 1970s by wet conditions. Regional growing season PDSI values have ranged from "slightly dry" (-1.50) to "slightly wet" (+1.50) from 1975 through 1990.

Drought magnitude is described by intensity and duration. Based on relative frequency, Figure 22 contains monthly CD PDSI values expected to occur once in 100 calendar years of record. Figure 3a indicates that disturbances of this order are hierarchically compatible with a number of ecological process and responses. Since nearly 100 years of computed PDSI values are available for analysis (1895-1990), no statistical modeling is required and these estimates may be considered to be relatively accurate representation of drought disturbance events. Most intense drought conditions have occurred in coastal Maine, western and southern Vermont, western and coastal Massachusetts, northwestern and coastal Connecticut.

New England drought magnitude expressed as duration is summarized in Figure 23. Over the past 96 years, each CD has averaged 28 multiple-month droughts of PDSI equal to or less than -2.00. The values shown on Figure 23 were computed from a frequency analysis of these data, and represent drought duration expected once in 100 such multiple-month events. Length of the 1 in 100 chance drought varies from 23 months in Eastern Massachusetts to 42 months in Western Vermont. There is substantially more geographic variability in New England drought persistence than in drought intensity.

III.B.4. Growing Degree Days

A contour map of mean growing degree days and a weighted time series are presented as baseline products (Figures 24 and 25). Return periods have also been calculated and will be used in the decadal analysis.

Figure 24 indicates the fewest number of degree days in northern Maine and the mountains of New Hampshire. A tongue of GDD maximums follows the Connecticut River valley northward into Massachusetts. Other areas of warmth center on major metropolitan areas of Massachusetts and Rhode Island.

An area weighted time series of annual GDD is presented in Figure 25. No trend is evident in the time series. A maximum of 1030 GDD is estimated in 1988. A minimum value of 810 GDD is estimated for 1986. Maximum year-to-year change appears to have occurred between 1986 and 1987.

Figure 22. Monthly PDSI values for New England with a 1 in 100 year chance of occurrence, 1895-1990.

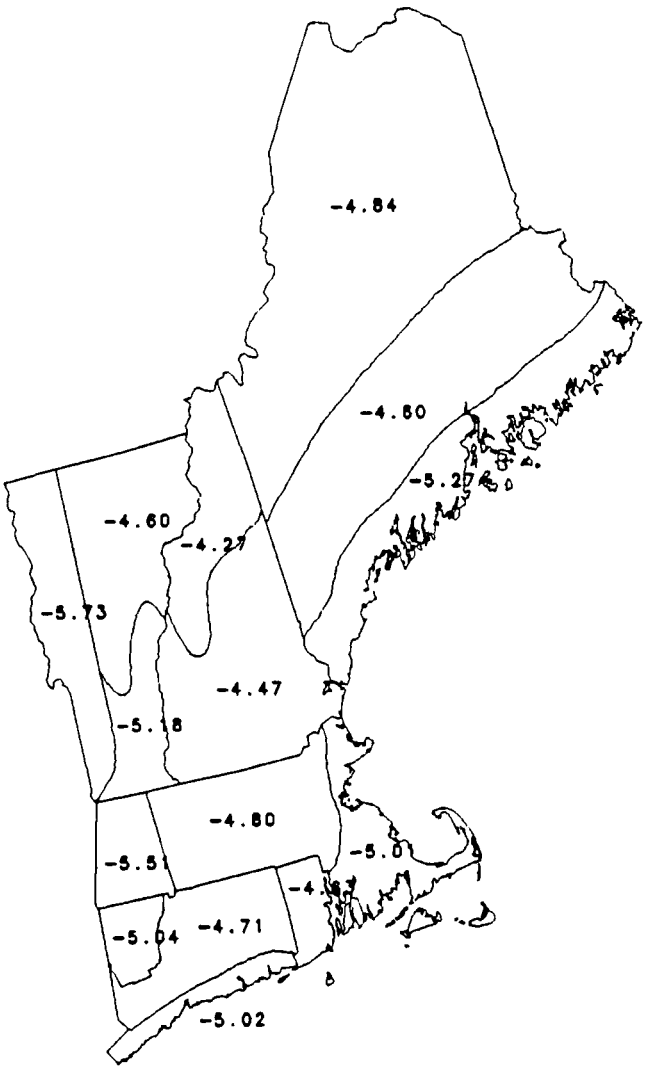


Figure 23. Duration of New England drought episode (PDSI with consecutive months of -2.0 or less) with a 1 in 100 event chance of occurrence, 1895-1990.

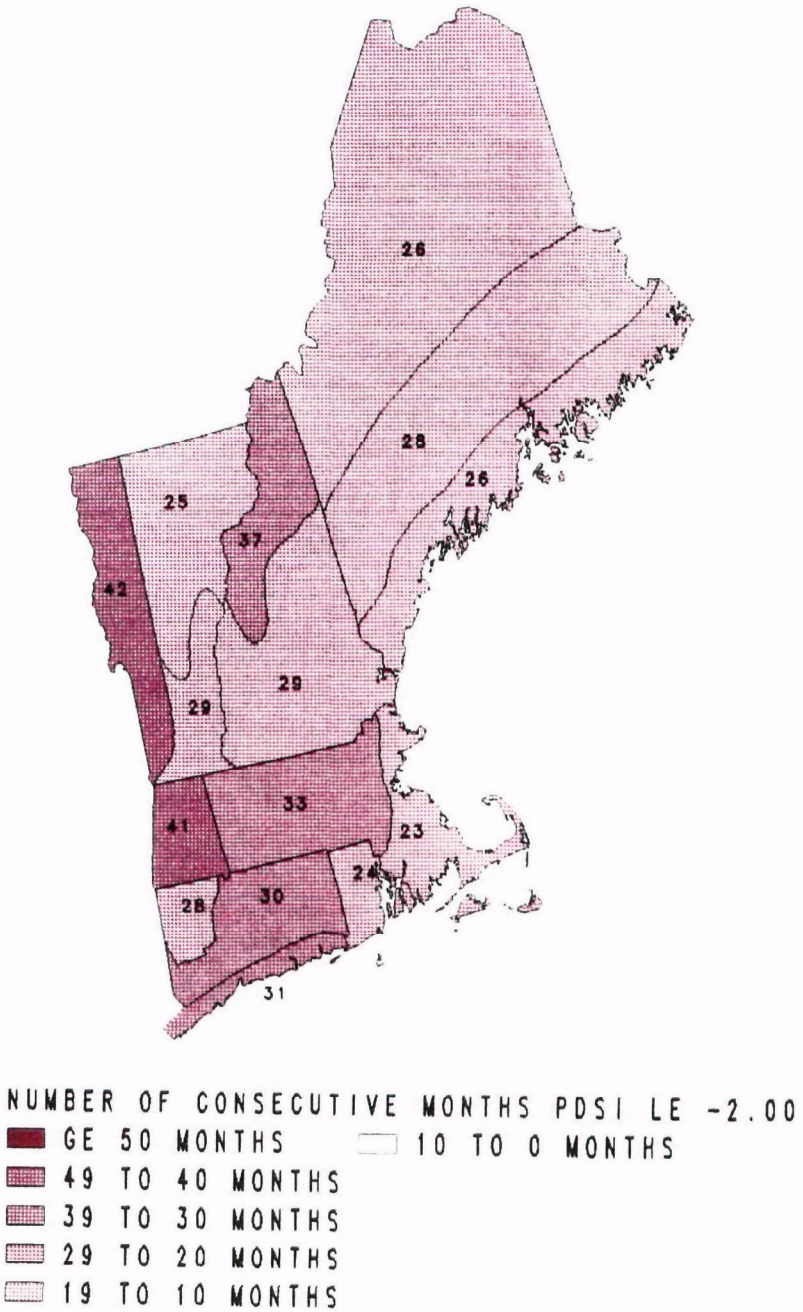


Figure 24. Mean annual New England growing degree days (base = 10°C, lower limit = 0°C), 1961-1990.

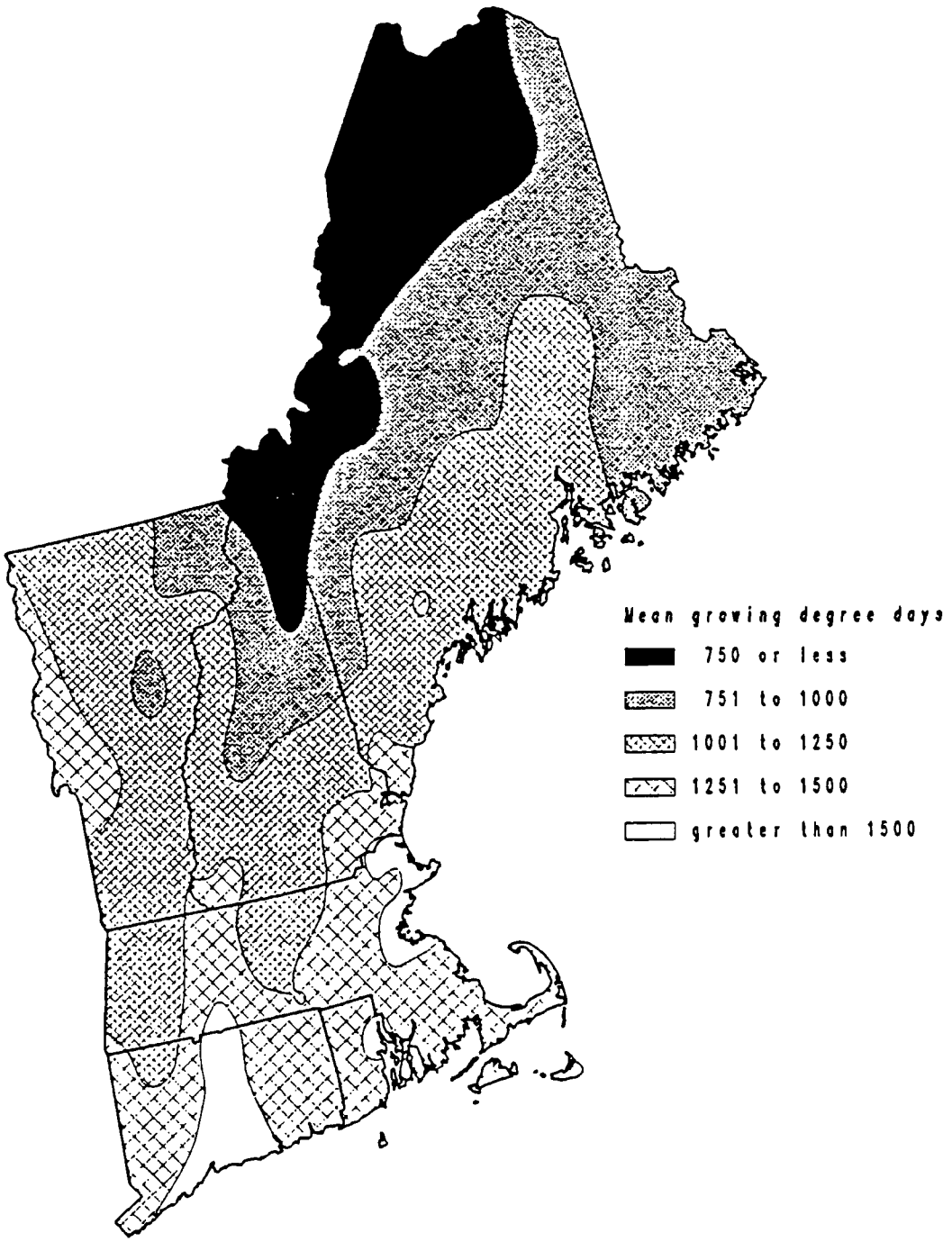
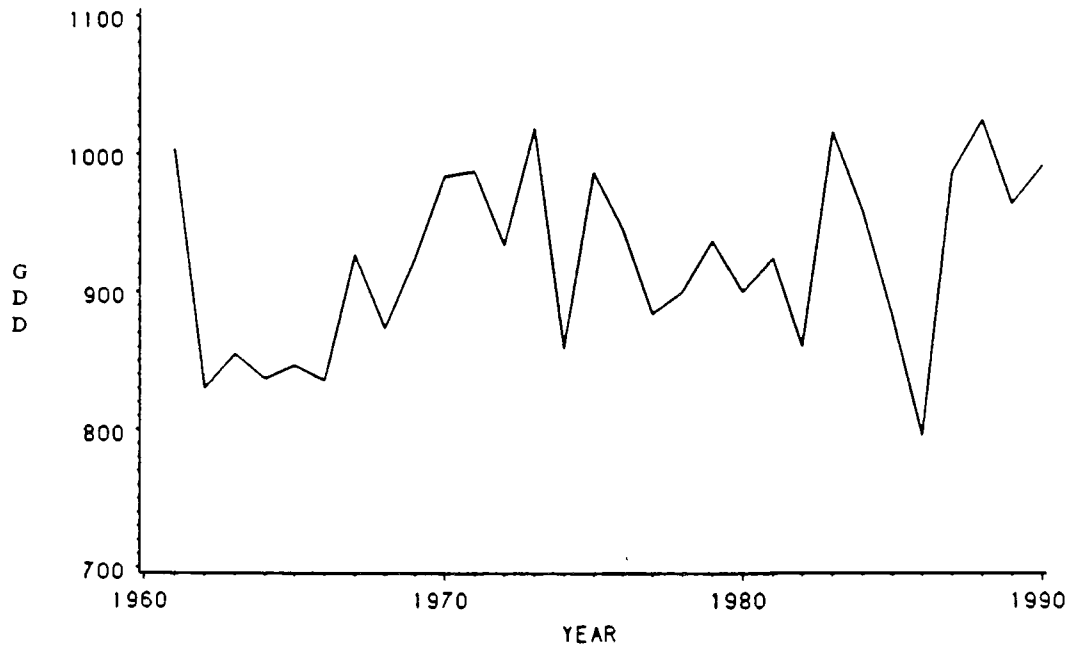


Figure 25. Area weighted timeseries of annual New England growing degree days (base = 10°C, lower limit = 0°C), 1961-1990.



III.B.5. Last Spring Freeze

A contour map of the mean last date on which a minimum daily temperature of -2.2°C or less is reported in the spring and a weighted time series of these dates are presented as baseline products (Figures 26 and 27). Return periods have also been calculated and will be used in the decadal analysis.

Figure 26 shows essentially the same latitudinal and elevation patterns as GDD. On average, the latest spring freeze dates occur at northern latitudes and at higher elevations. Freezing temperatures disappear earliest in the spring along the eastern seacoast and large metropolitan areas.

Figure 27 contains an area-weighted time series of last spring freeze dates. Between 1960 and 1980, the average date of the last spring hard freeze event occurs progressively earlier in the season. Although Figure 27 could be interpreted to reflect a changing climate in New England, other potential sources of observational or recording error should be investigated in future studies. One potential source of error reported in Karl and Quayle (1988) involves shifts in time of observation from evening to a morning observation. This can create cooling bias in the data record.

III.B.6. Last Spring Snowfall

A contour map of the 30-year mean date of the last spring snowfall and a weighted time series of these dates are presented as baseline products (Figures 28 and 29). No accumulation (snow-on-the-ground) is considered because of the poor quality of these data. This variable, then, represents a risk of snow damage, but not that damage has actually occurred. The later in the spring the snow event occurs, the more severe the forest stress is assumed to be and the greater the likelihood of defoliation. No underlying physical assumptions concerning atmospheric conditions conducive to warm snow events are made, and this presentation is meant only to be illustrative.

Figure 28 suggests a geographic pattern of last season snowfall similar to that of GDDs and late spring hard freeze dates with at least one interesting exception. An unusual area of warm and dry conditions (last snowfall prior to March 1) appears in central Maine. Although this site is on the drier, leeward side of the Appalachian Mountains, the record should be investigated to further identify the source of this unusual signal.

Figure 26. Mean date of last spring hard freeze (minimum temperature of -2.2°C or less), 1961-1990.

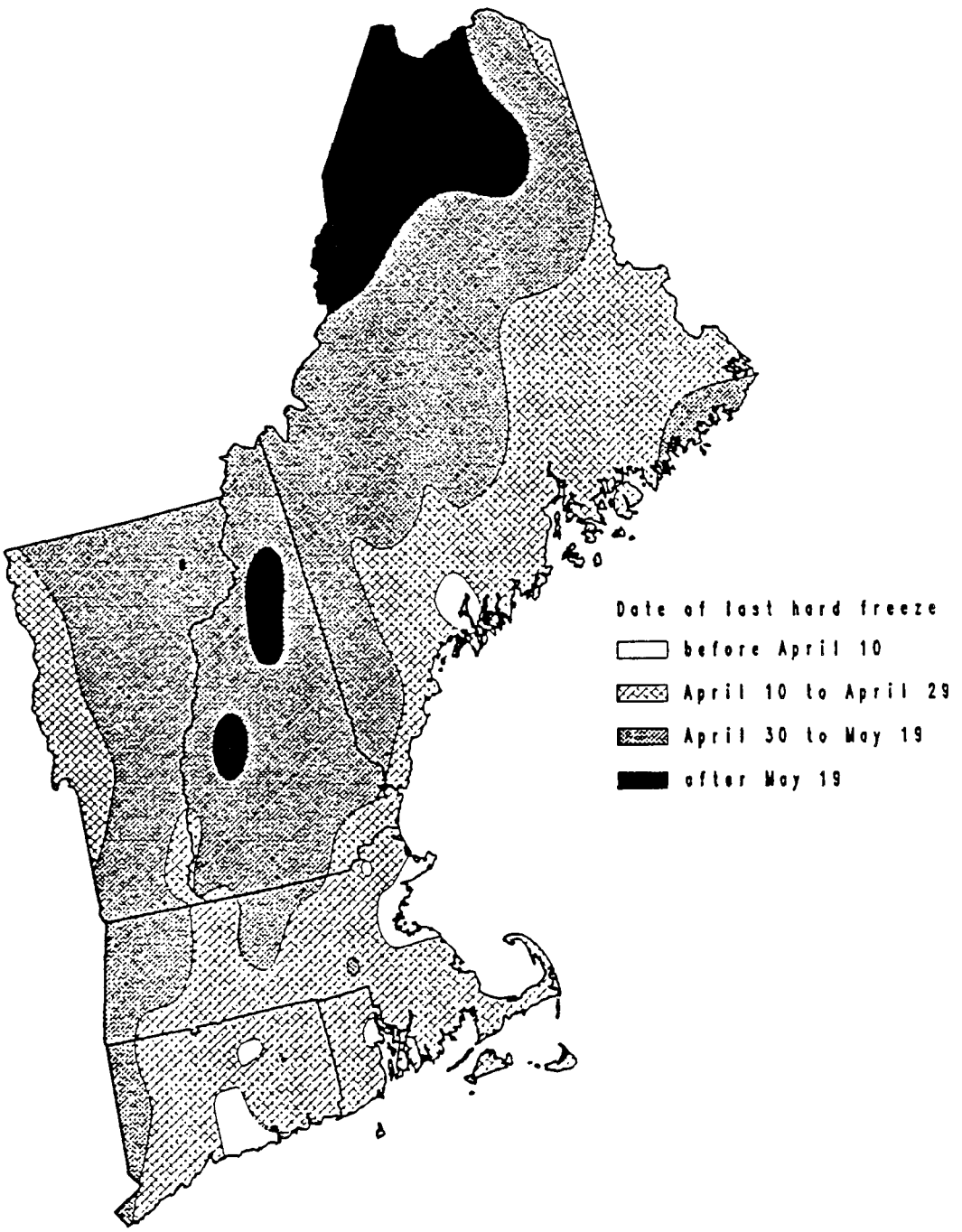


Figure 27. Area weighted timeseries of last spring hard freeze event dates (minimum temperature of -2.2°C or less) in New England, 1961-1990.

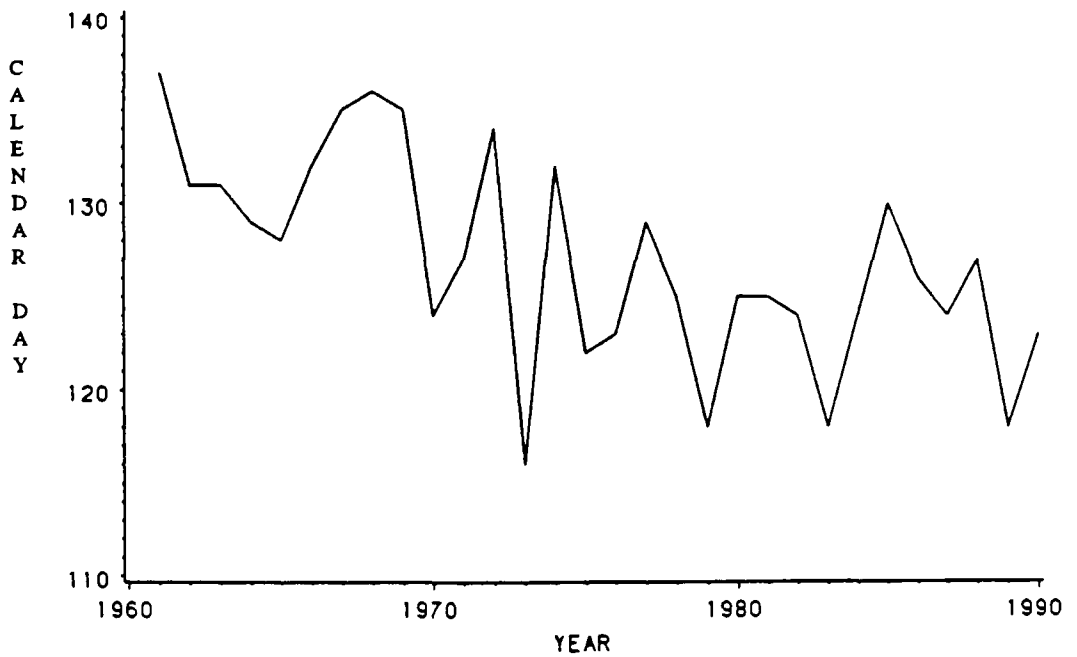


Figure 28. Mean date of last spring snowfall, 1961-1990.

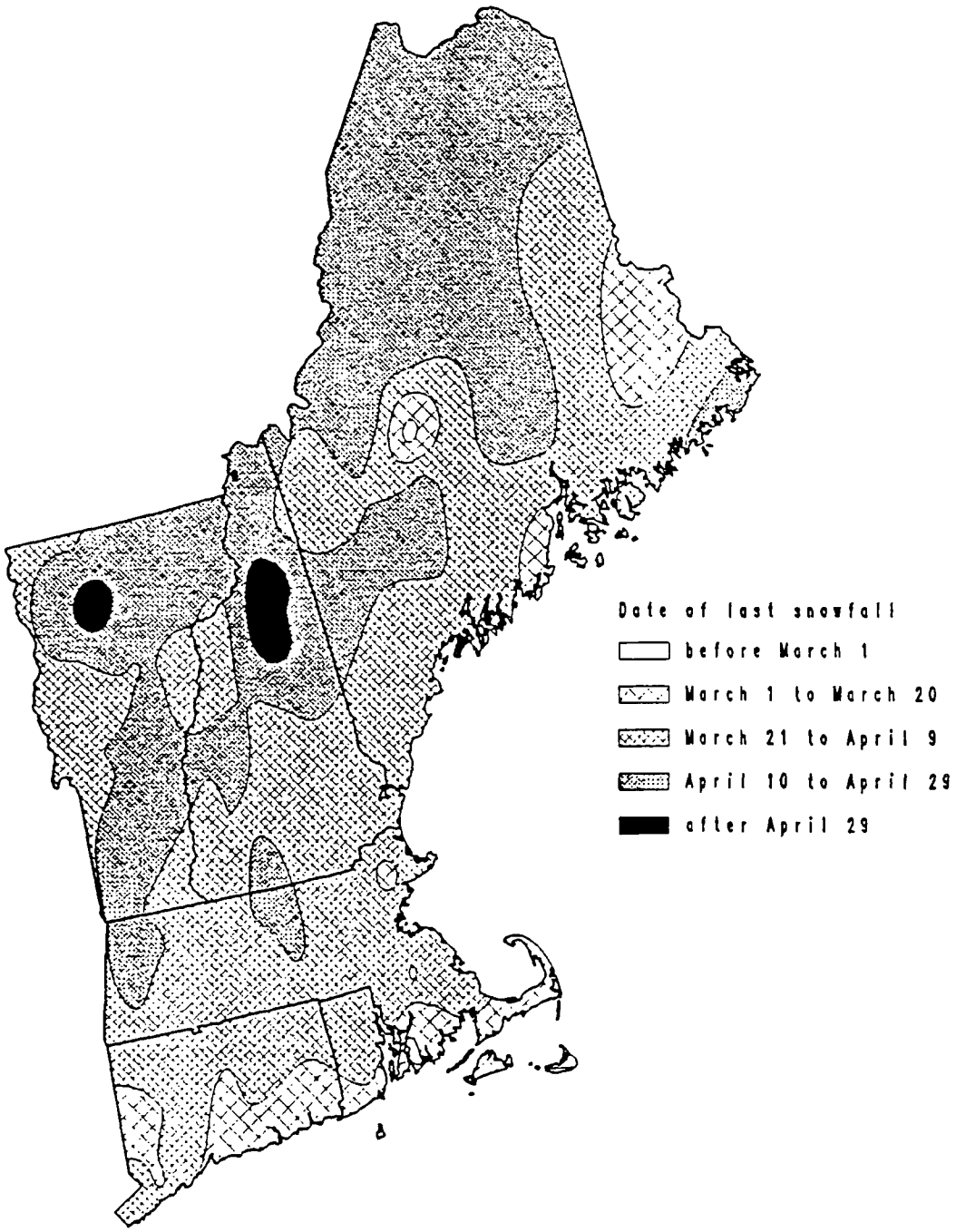
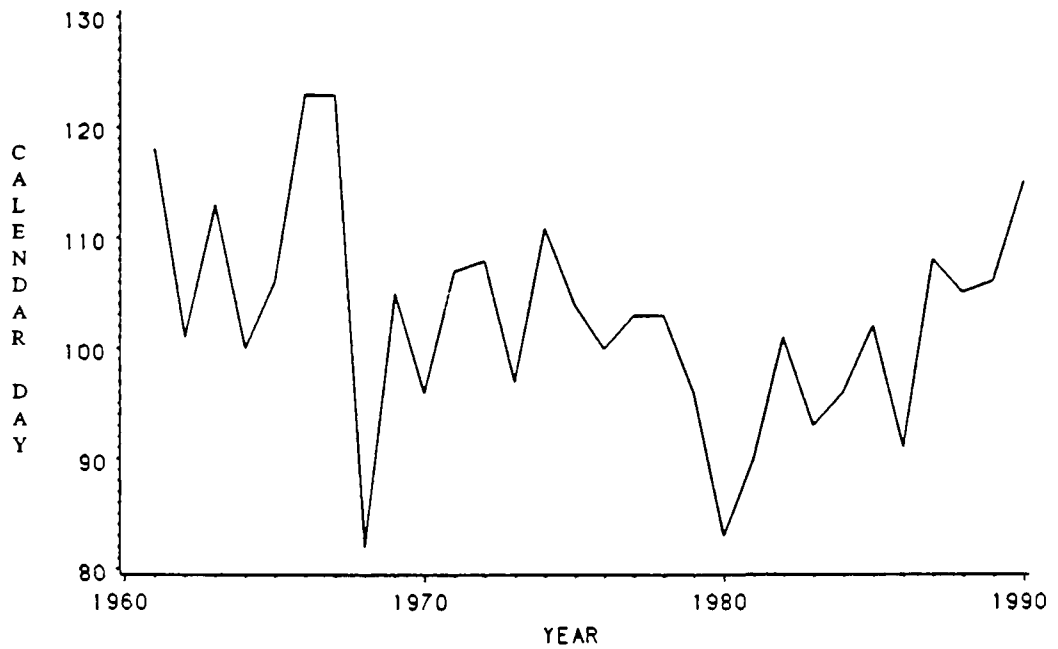


Figure 29 contains an area-weighted time series of last spring snowfall dates. Although the earlier record (1961-1980) is difficult to interpret, there is a marked date increase (later in spring) in the decade of the 1980s. This, in combination with regional freeze data (Figure 27) suggests that during the 1980s the risk of damage associated with late spring snowfall events may have increased. Late spring hard freeze events that might delay bud initiation occur earlier in the spring (Figure 27), while snowfall events occur later (Figure 29). Note that the term "risk" is used here. Given the present dataset, it cannot be stated with certainty that the number of damaging snow events has increased. It does not contain the information needed to verify the moisture content of the snow. In the future, newly developed snowfall data sets, used in combination with synoptic meteorological map analysis could be used to more carefully define such events.

Figure 29. Area weighted timeseries of last spring snowfall dates in New England, 1961-1990.



III.C. Most Recent Decade (1981-1990)

In contrast to the 30-year climatology, a 10-year study is used to emphasize short-term variability of climate stress. This also represents more closely the regional response time of forest ecosystems to chronic climatological stress. Since detectable ecosystem health and productivity response times are relatively slow, substantial data sets will be required before true ecological trend analyses over relatively small areas can be performed. Under the present EMAP Forests four year sampling design, it is estimated that detection of regional and national trends in response indicators on the order of 1% per year is expected within 10-15 years (Hunsaker and Carpenter, 1990).

The period 1981 to 1990 has been chosen to illustrate regional climate fluctuations within a decade which approximates the time interval since the last USDA Forest Inventory Analysis (FIA) Survey (see table below).

DATES OF LAST FIA SURVEY	
Connecticut	1984
Maine	1982
Massachusetts	1984
New Hampshire	1983
Rhode Island	1984
Vermont	1983

Table 9 summarizes the characteristics of the regional stress regime for which sample climatologies covering the period 1981-1990 have been developed. A comparison of Tables 8 and 9 shows a greater emphasis on spatial characterization in the decadal analysis (Table 9) than in the baseline study. Since temperature and precipitation have been addressed extensively in the baseline discussion, they are omitted from the decade analysis. As is the case throughout all these example climatologies, no effective means of wind event magnitude and areal extent characterization has been identified.

Table 9. Elements of a New England disturbance regime climatology for which decadal examples have been developed.

CLIMATE VARIABLE	FREQUENCY	MAGNITUDE	SIZE
Tornadoes	intra-annual	X	X
Wind	intra-annual		
Tropical Cyclone	X	X	X
Drought	X	X	X
Temperature			
Precipitation			
Growing Degree Days	X	X	X
Late Spring Freeze	X	X	X
Late spring Snowfall	X	X	X

III.C.1. Severe Weather and Tropical Cyclones

The most recent decade has been relatively quiet in terms of large scale windthrow events. There has been a total of 58 tornado events reported. The annual mean number of reported events dropped from a 30-year value of 9 to only 6 per year. Seventy-five percent of these storms were of strength F-2 or less. Only two tornadoes of strength F-3 or greater were reported. Annually, the average area impacted by tornadic events was only 1.6 km^2.

The number of damaging wind events has shown a marked increase in the last decade. It is not clear if this represents a physical trend or if it reflects changes in reporting techniques. There have been 832 damaging wind reports in the last decade. The decade average of 83 events each year is nearly double that of the last 30 years. Incompleteness of data records prevents any generalization of peak gusts or area impacted by these storms.

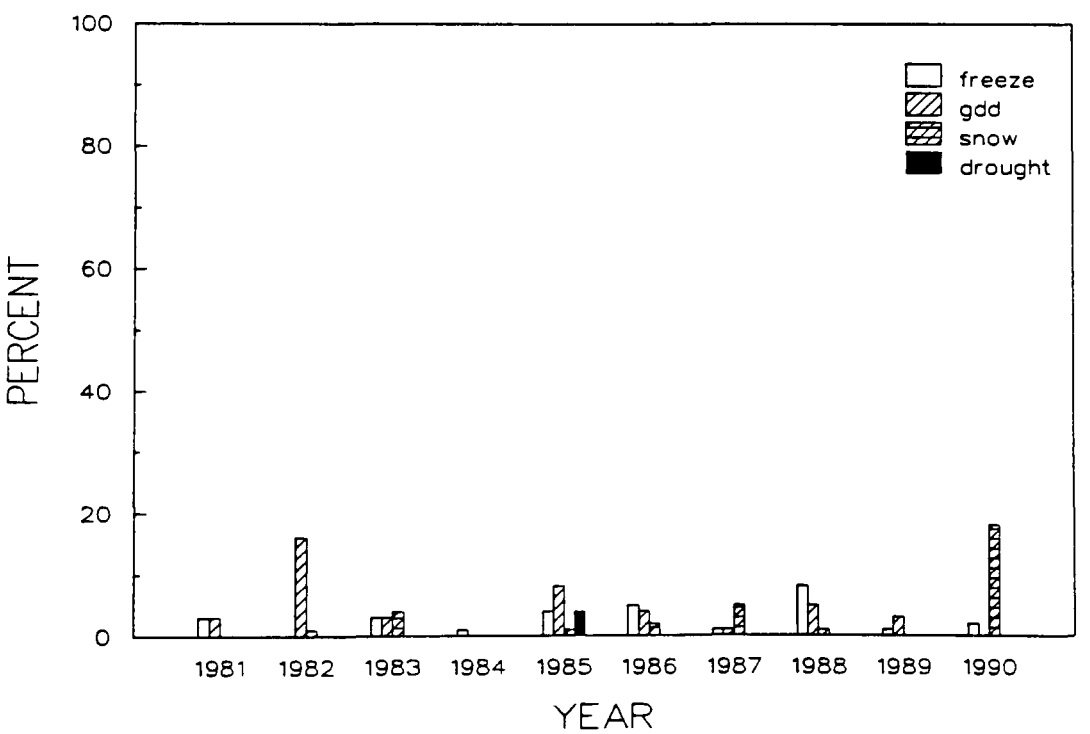
Only two tropical cyclone-spawned storm systems passed through New England in the last decade (Table 8). Both were classified as extra-tropical storms. The larger of the two, Gloria, passed through Connecticut, Massachusetts, Maine and New Hampshire in 1985.

In summary, the most recent decade has generally lacked large-scale windthrow events such as tornadoes and well-developed tropical cyclones. A significant increase in the number of damaging wind events (most often described as downburst type events associated with dissipating severe weather) is suggested by the data, but verification of this increase has not been performed. Research by Canham and Loucks (1984) for downburst events in Wisconsin suggests that forest damage from individual events should be on the order of 1 km^2 or less.

III.C.2 Combined Stress (Disturbance) Analysis

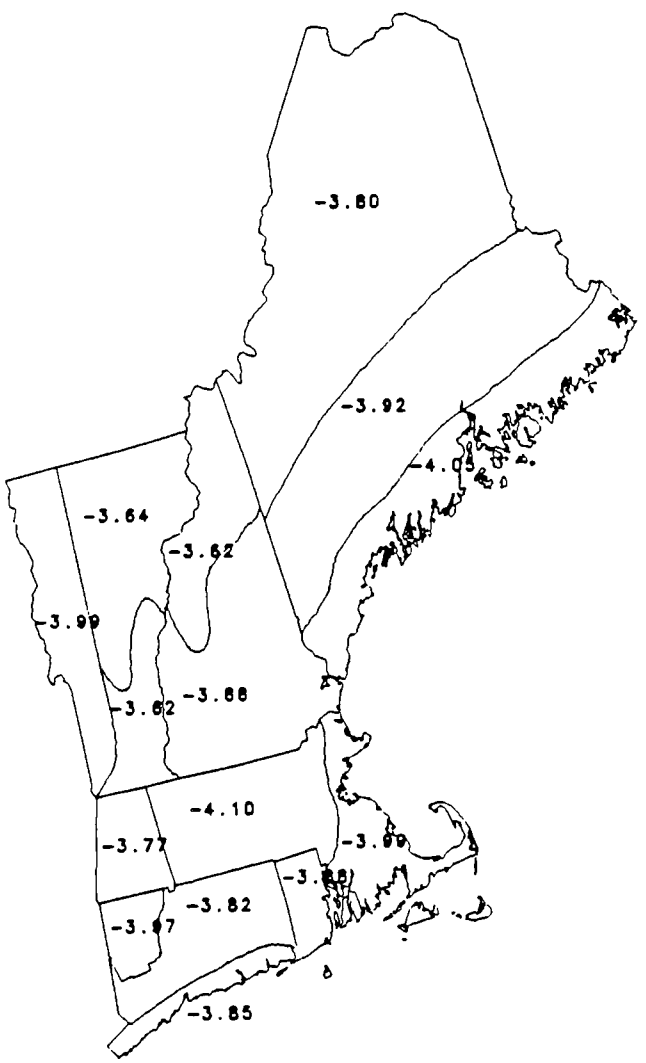
Figure 30 contains a decadal summary of drought, GDD sums, spring freezes and warm spring snowfall events in terms of the percent of total area impacted. Small GDD totals, spring freeze and snowfall dates are included if, based on the entire climate record for a station, the current value is expected to occur fewer than once in 20 years. Although more extreme conditions such as a 100 year freeze are suggested as appropriate by Figure 3a, the relatively short period of record available does not support the direct calculation of these values. Such rare events might be statistically estimated through the use of extreme value theory in future studies (Mearns, et al., 1984; Katz and Brown, 1991).

Figure 30. Percent of New England region impacted by climate stress, 1981-1990.



In order to determine a comparable drought return period, a frequency analysis was performed using the minimum PDSI value reported in each CD during each October through September calendar year. Figure 31 presents the PDSI values expected in each CD once in every 20 calendar years. These values range from -3.62 to -4.10. To simplify calculations, a value of -4.0 was used to declare a forest growth year to have suffered under drought stress.

Figure 31. Monthly PDSI values for New England with a 1 in 20 year chance of occurrence, 1895-1990.

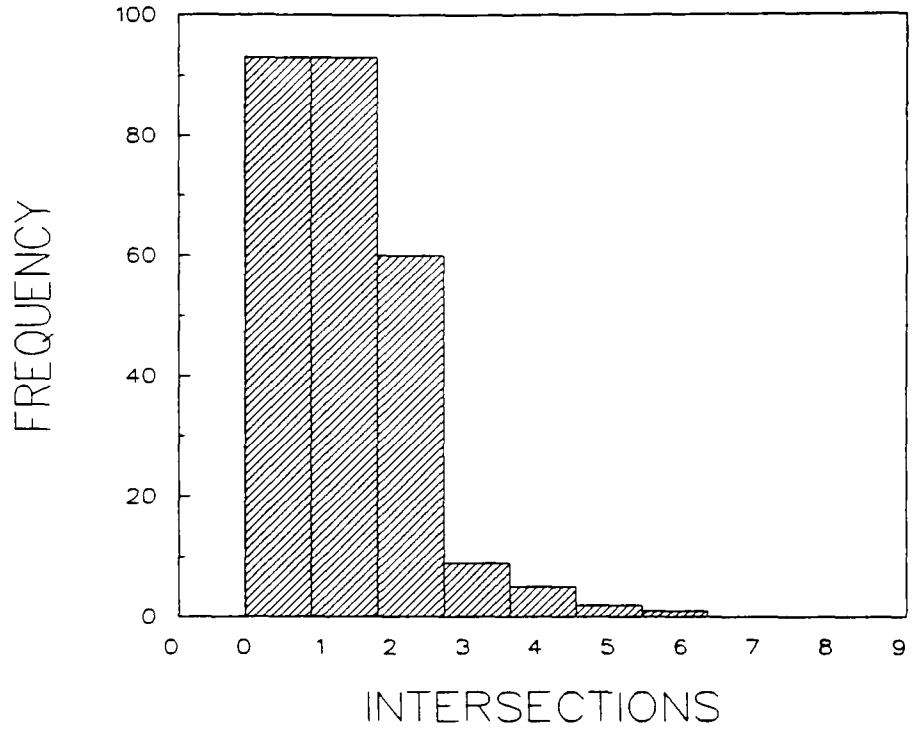


The purposes of Figure 30 are 1) to facilitate visual identification of short-term trends in forest related climate variables; 2) to identify the frequency and size of regional-scale climate events; and 3) to identify associations of stressful climate conditions. This figure does not quantify the amount of forest damage or forest response to these stresses. The impact of environmental stress will vary with ecological system (although all of these measures reflect local conditions) and combinations of stresses may result in threshold behavior (discontinuities) or non-linear increases in damage. This figure represents a consistent intensity of stress across stressors and permits, for this decade, some generalizations of size/frequency relationships.

Figure 30 indicates that one drought event occurred (PDSI during at least one month equal to or less than -4.00) in the New England region during the last decade. Late spring freezes were associated with at least a few sampling locations during nine of the ten years. The freeze event of largest spatial extent occurred in 1988 and impacted 8% of the region. Late spring freezes and unfavorably cool growing conditions throughout the year (small GDD totals) were not clearly associated. The most widespread GDD event was reported in 1982 and affected 16% of the New England region. The most extensive late spring snowfall event of the last decade occurred in 1990 and impacted 20% of New England. Thus, for the decade of the 1980s, at the level of stress represented by a 20 year return period, the largest scale events (spatially) were late spring snowfall and low GDD totals.

Next, this stress information is related to the NEFHM program sampling network. Figure 32 shows the distribution of the number of event "intersections" with NEFHM sampling hexagons over the decade. A hexagon intersection is said to occur when a disturbance event is identified in the climatological record associated with a particular NEFHM sampling hexagon. The maximum possible number of intersections for each hexagon is 40 (drought, freeze, snow and GDD for each of ten years). The areas of interest are the "tails" of the distribution. Hexagons counts located at the lower tail (zero intersections) represent areas experiencing few climate disturbances (as defined by our four events and 20-year return period). Using the earlier conceptual description of climate-ecosystem interactions, these are areas that might be expected to persist or show slow or little change. Dramatic changes in forest status or health in these areas are likely associated with something other than the climatological stresses examined here.

Figure 32. Distribution of hexagon and climate event intersections, 1981-1990.

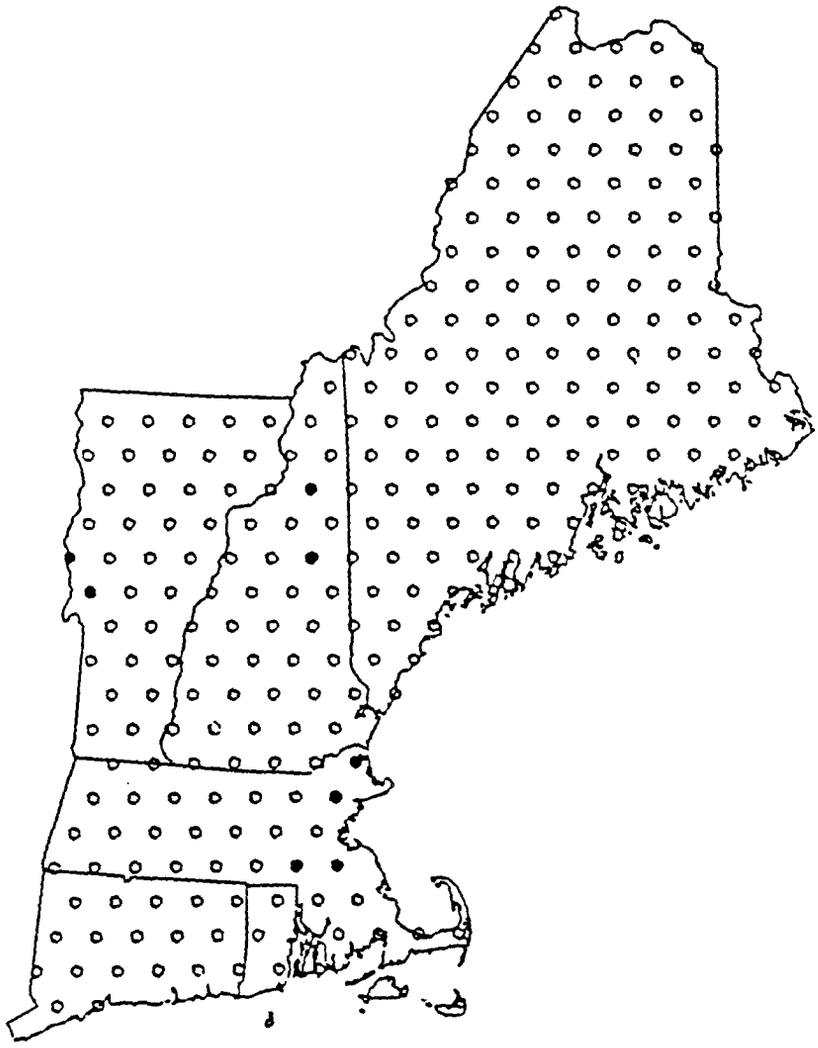


Hexagons in the upper tail represent areas subject to a relatively larger number of stresses. Evidence of ecosystem response to these factors could take the form of changes in ecosystem structure or characteristics or changes in overall system health (resistance to pest and disease injury). The present stress analysis, however, is not complete. Disturbance persistence should be included as well. Under the present system, a region that experiences stresses that are few in number but persistent would not be highlighted. The estimation of drought persistence is straightforward and has been demonstrated in the background study. Late spring freeze persistence could also be easily defined. The development of a definition of persistence for GDD and late spring snowfall is more difficult.

Figure 33 contains the location of hexagons reporting 4 or more event intersections. This is equivalent to the upper 3% of the frequency distribution shown in Figure 32. Five cooperative

weather network stations define the three intersection areas of Figure 33. Three of these five stations define the Massachusetts area, indicating this is likely to be a climatologically active region. Further investigation shows the Vermont area becomes more firmly defined when the next lower intersection frequency category is added to the map. Alternatively, the third area which is located in New Hampshire remains poorly defined, even when hexagons with lower intersection frequencies are added. This suggests "noisy" weather data or local-scale phenomena rather than a pattern of regionally important climatological disturbances.

Figure 33. Location of hexagons reporting four or more intersections with climate disturbances, 1981-1990.



III.C.3. Summary

The results of the 1981-1990 analysis suggest that this was a relatively quiet period with no significant mesoscale disturbances (tropical cyclones), few tornadoes and only small scale (area) disturbances throughout the region. By way of comparison, a similar regional hexagon analysis was performed for the decade of the 1960's. This is a period of particular interest because high elevation red spruce decline is suggested to have been triggered by a combination of climate and pollution stresses during this time (Johnson et al., 1988). Figure 34 contains the same data presentation as Figure 30. It is immediately apparent that this is a more active climatological period. Three consecutive large scale drought years dominate the figure from 1964 into 1966. Late snowfall events also are more frequent and impact a larger area than during the 1980's. Nearly one-third of New England was impacted by a late spring freeze in 1961 and 20% was impacted in 1969. GDD totals do not appear to be of major importance in the 1960's. Figure 35 contains the distribution of hexagon/climate stress intersections. Hexagons with four or more intersections represent 31% of the 1961-1970 sample as compared to 3% of 1981-1990 hexagons. The bulk of these sites is concentrated in the Northern three New England states (Figure 36).

Figure 34. Percentage of New England region impacted by climate stress, 1961-1970.

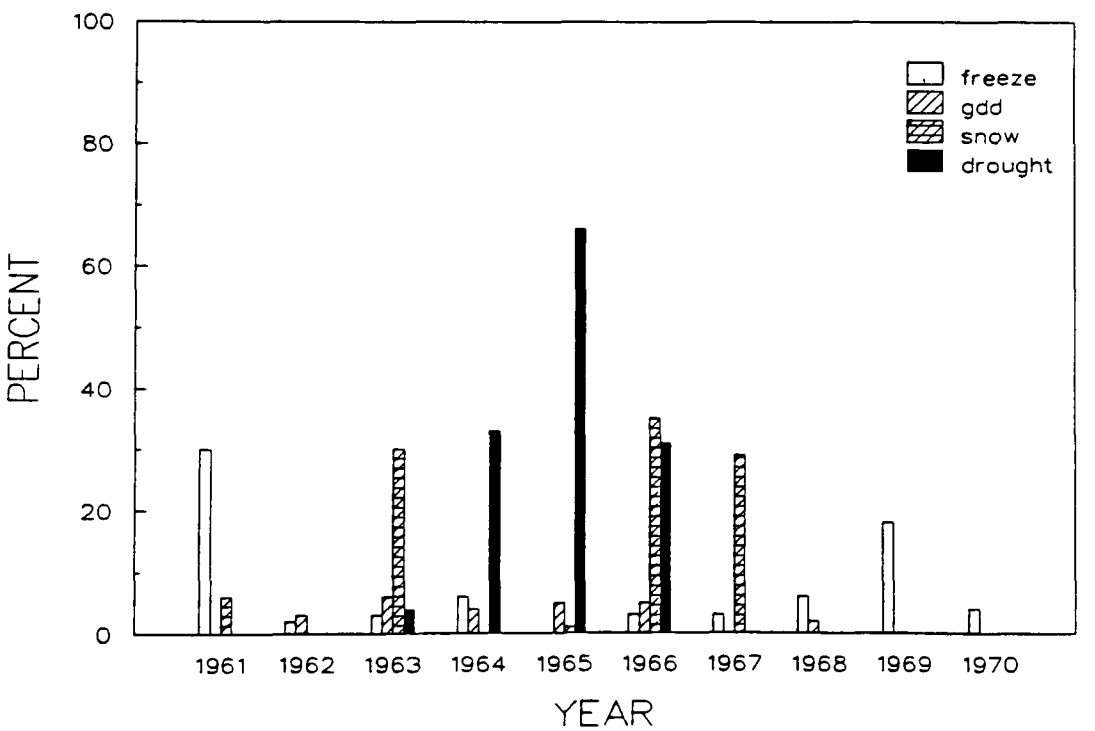


Figure 35. Distribution of hexagon and climate event intersections, 1961-1970.

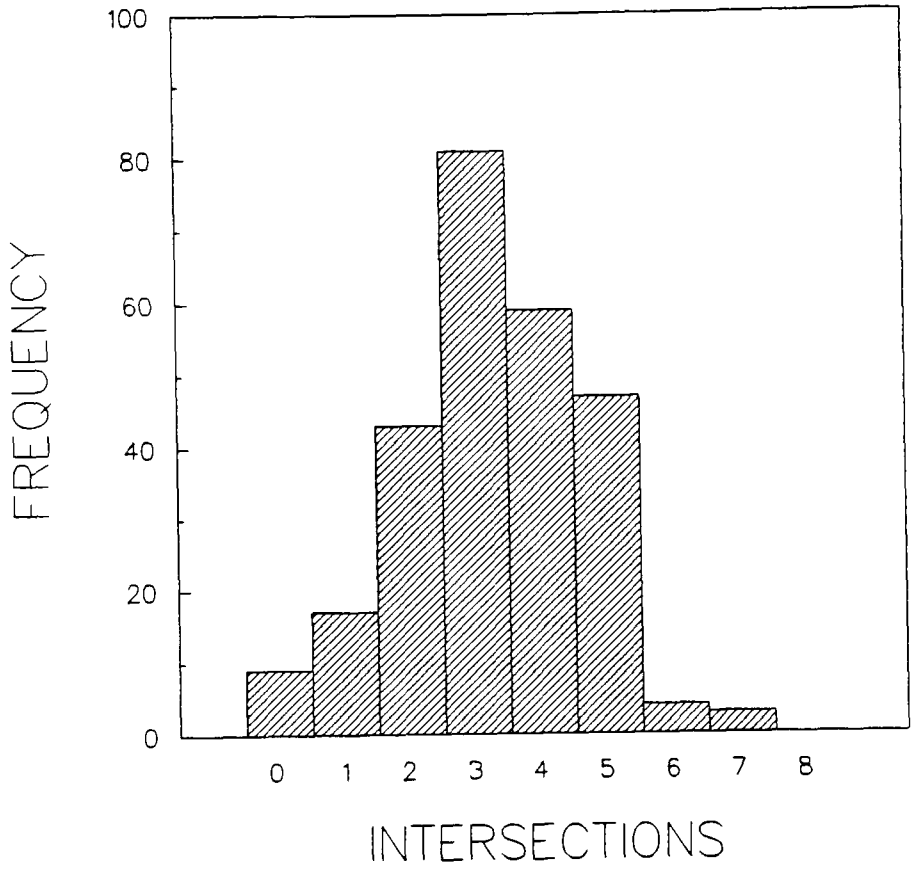
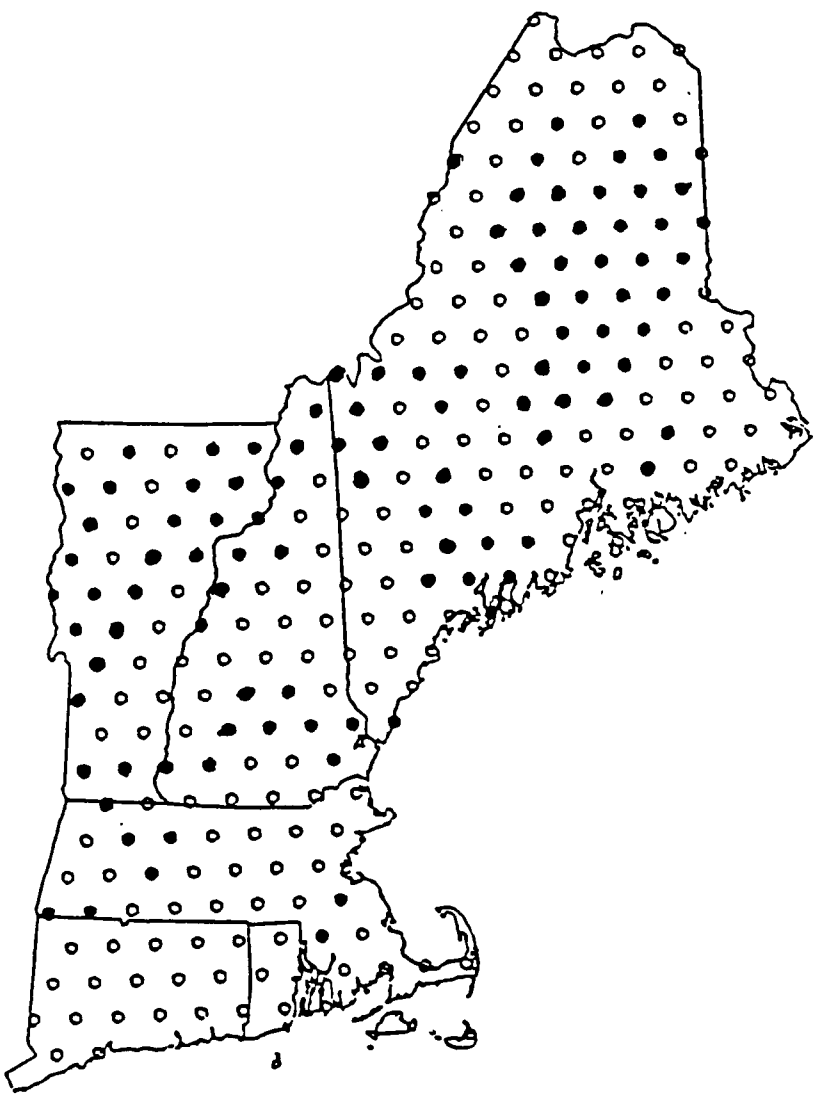


Figure 36. Location of hexagons reporting four or more intersections with climate disturbances, 1961-1970.



Johnson et al. (1988) attribute red spruce declines in the White, Green and Adirondack Mountains to a series of cold winters in 1961, 1962 and 1963. Although there is agreement that this is a likely source of decline at higher elevations, there is some disagreement concerning the interpretation of tree-ring patterns and mortality elsewhere (Van Deusen et al., 1991). The time series in Figure 34 does suggest unusual winter conditions in 1961 and 1963, but also indicates that these conditions were followed by severe drought and continued unfavorable winter conditions in 1966, 1967 and 1969. Johnson et al. (1988) found conflicting evidence of the association of PDSI with ring width, but drought as an additional source of stress cannot be entirely discounted. Zahner et al. (1989) found PDSI very useful in evaluating tree-ring chronologies in conifers of the Southeast.

Johnson et al. (1988) found close relationships between cold early winters prior to the growing season and warm late summers of the previous years to red spruce ring chronologies. Such unusually late warm conditions could easily be associated with the multiple year drought of 1964-1966. As yet there is no physiological explanation for these relationships other than perhaps the new shoot material doesn't harden-off properly when the late summer is too warm. In the future, if tree-ring chronologies are to be used to track changes in disturbance regime by EMAP and the NEFHM program; then an index of late summer temperatures and the distribution of wintertime temperature minima should be added to the stress climatology.

Associative studies such as these and modeling activities linking climate and ecosystem behavior in the northeastern United States are anticipated in the future. Recent climate/forest modeling activities are discussed in a special issue of Agriculture and Forest Meteorology. The April, 1990 issue is devoted to the Second Uppsala workshop on Modeling Forest growth Processes. A meeting summary and review is presented by Perttu (1990).

Examples of forest modeling and associative studies for climate change applications are discussed in Solomon et al.(1984), Pastor and Post (1988), Joyce et al. (1990), Overpeck et al. (1990), Fritts and Swetnam (1989) and IPCC (1990). Although a relatively large body of research literature exists, the need for more basic and applications research is identified by both the IGBP and the U.S. Department of Agriculture Forest Service (IGBP, 1990; USDA Forest Service, 1990).

III.D. Most Recent Year (1990)

Summaries of climatological conditions in the most recent past are primarily used to aid in the interpretation of the current year's sampling program. An example is found in Brooks et al. (c, in press). These products and analyses, in combination with supplemental field observations, can be useful for the identification of areas in need of special studies to identify unknown sources of stress or mortality. Table 10 indicates those disturbance regime characteristics summarized for the most recent sample collection period (1990). With the exception of wind and tropical cyclone events, all identified disturbances are characterized for 1990 in terms of their frequency, magnitude and size.

Table 10. Elements of a 1990 New England disturbance regime climatology.

CLIMATE VARIABLE	FREQUENCY	MAGNITUDE	SIZE
Tornadoes	X	X	X
Wind	X		
Tropical Cyclone	none reported	none reported	none reported
Drought	X	X	X
Temperature	X	X	X
Precipitation	X	X	X
Growing Degree Days	X	X	X
Late Spring Freeze	X	X	X
Late spring Snowfall	X	X	X

III.D.1. October 1989 through September 1990 Weather

Record warmth was reported during November 1990. This was followed by a blizzard with sustained hurricane force winds and gusts of 45 ms^{-1} in Maine during November. Winter weather impacted Maine again during December, when the worst blizzard since 1987 struck the Presque Isle area. Many Vermont stations reported "the coldest December on record." Ice accumulations of from 1.27 cm to 1.9 cm on trees and powerlines in Connecticut and Massachusetts made a February ice storm the most serious since 1984.

Severe weather was reported in May and June. Two weak tornadoes were reported in Massachusetts during May. A small tornado, three funnel clouds and 15 damaging wind events were reported during June. Flooding was reported in New Hampshire and Vermont throughout July and August. The heaviest 24-hour rainfall in 50 years was reported in Massachusetts during August.

III.D.2. Historical Comparison

There were fewer than average tornadoes during 1990. Those that were reported occurred earlier in the summer than usual. The spring and summer wind events were in keeping with the past climatology of the area, but the large number of reports associated with a September storm outbreak was unusual. Peak wind gusts of 45 ms^{-1} in November, over 34 ms^{-1} in June and over 31 ms^{-1} in August were unusually strong. Figures 37-39 illustrate 1990 departures from average temperature and precipitation conditions. Figure 30 tells us that GDD, last spring frosts date and PDSI conditions were not unusual over a significant portion of New England during 1990.

Mean annual 1990 New England temperatures follow the typical south to north gradient evident in the long-term area record (Brooks et al, c, in press). Slightly cooler than normal conditions prevailed in southern Vermont and southeastern Maine, with slightly warmer than average conditions elsewhere. Annual maximum temperatures were near, or slightly cooler than, the 30-year average (Figure 37). Annual minimum temperatures were below the 30-year average for much of Maine and near to slightly above average for the remainder of New England (Figure 38). This is in keeping with the unusually cold winter conditions noted in the weather summary.

An irregular pattern of precipitation was reported across New England during 1990. With the exception of north-central and southern coastal Maine, the region reported near-normal or wet conditions. Some areas reported 25.4 to 38.1 cm of rain in excess of their average annual totals (Figure 39).

Figure 30 indicates a fairly large portion of New England experienced a late season (spring) snowfall event in 1990. This event occurred on May 22 and 23 and was centered in northern Maine. A few stations in Vermont and New Hampshire were impacted as well. Frozen precipitation associated with this storm tended to be light, with the exception of Squapan Dam, Maine, which reported accumulations of 5 cm.

Figure 37. 1990 annual maximum temperature departure from 30-year average conditions.

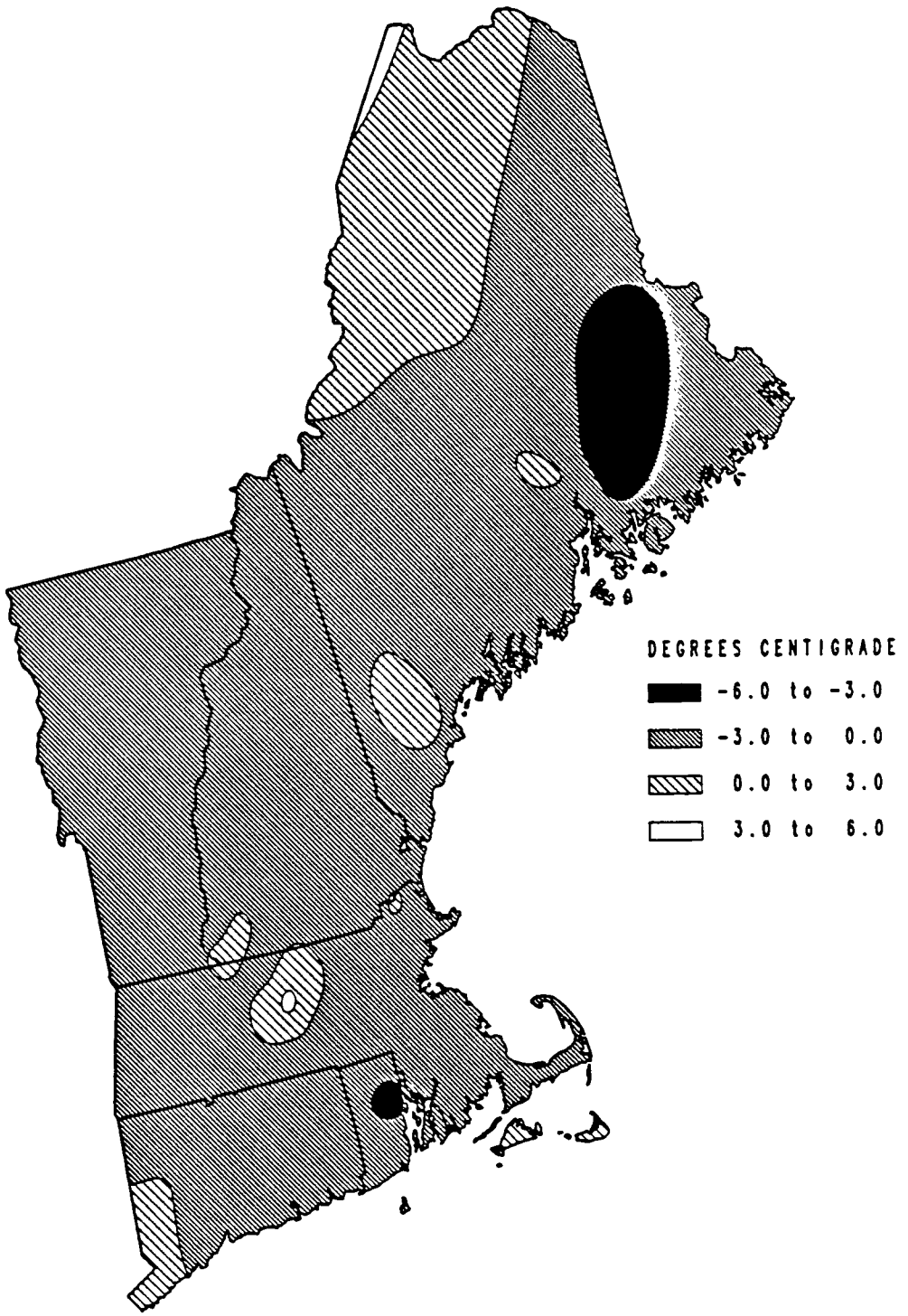


Figure 38. 1990 annual minimum temperature departure from 30-year average conditions.

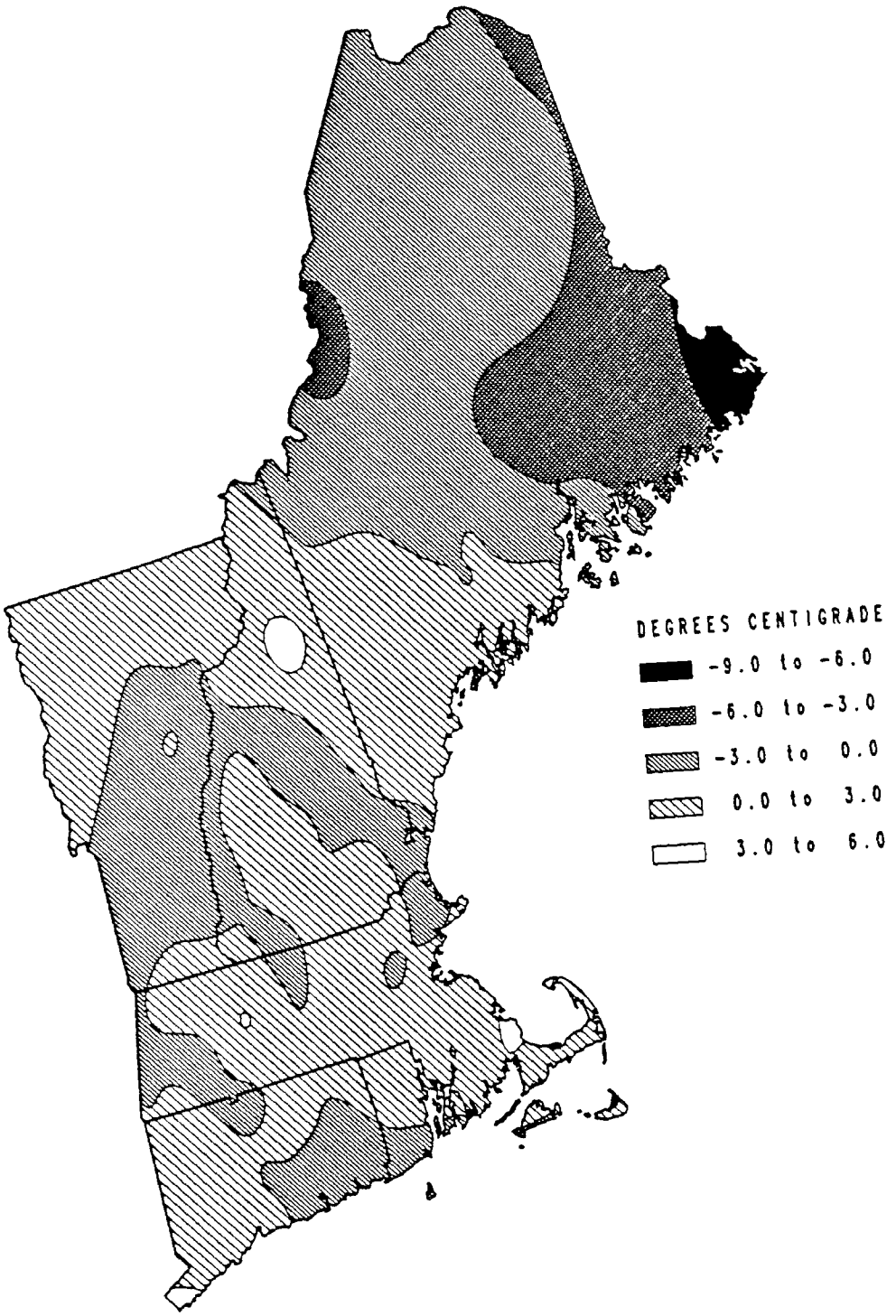
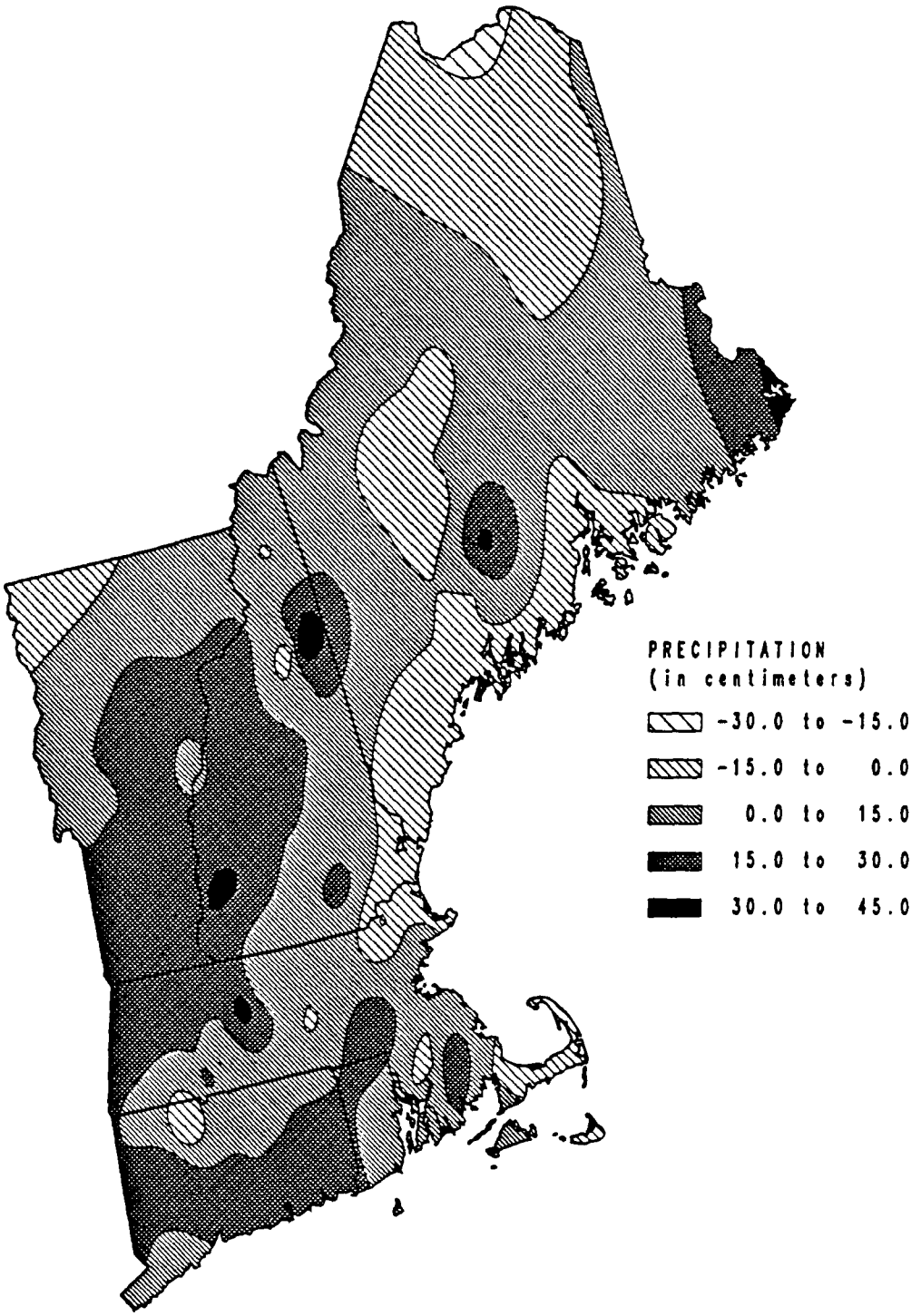


Figure 39. 1990 annual precipitation departure from 30-year average conditions.



III.D. Summary and Comparison with Monitored Data

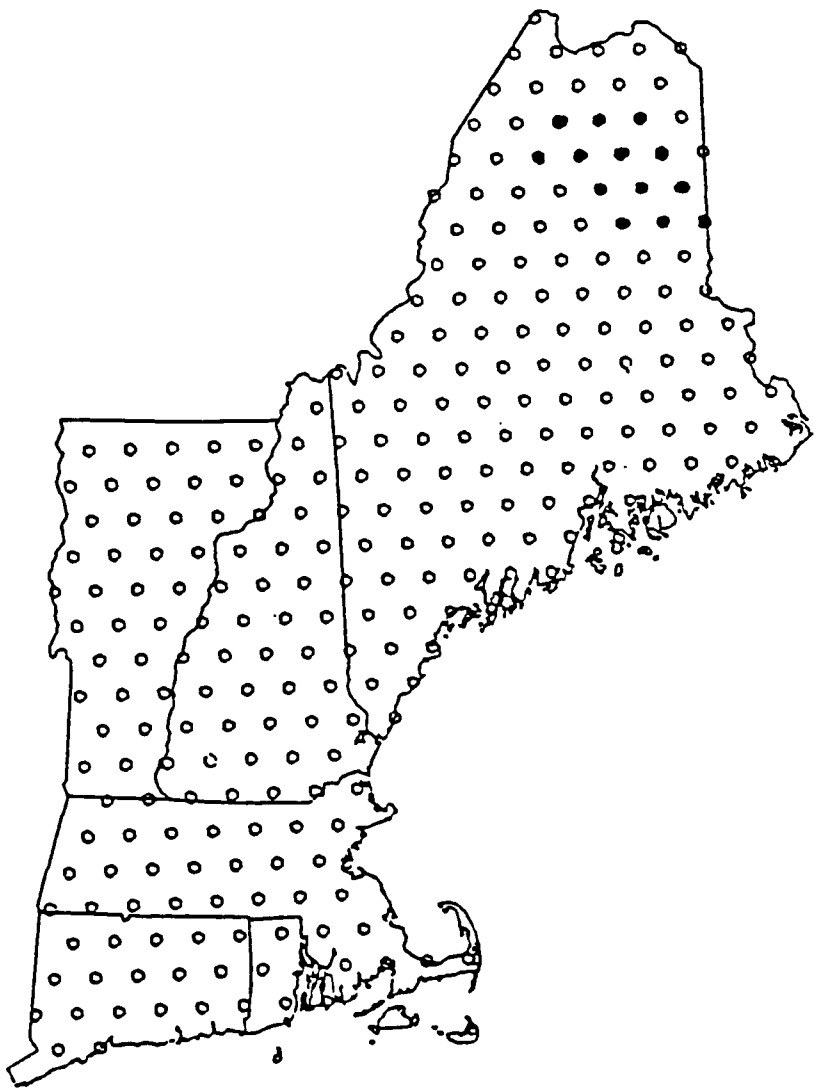
With only a few local exceptions, 1990 brought to a quiet close a notably uneventful disturbance decade. The negative trend in severe weather and tropical storm activity discussed in the decade summary continued through 1990. No significant drought stress was noted. Conditions generally favorable to forest growth prevailed as is borne out by Brooks et al. (c, in press). Isolated cases of winter freeze damage were reported, but no locations were given. This could coincide with extremely cold winter conditions reported in Maine and Vermont.

Brooks et al. (c, in press) note an area of moderate to severe crown dieback in Maine cedars, particularly in Aroostook County. No explanation was immediately available. Although many other factors could be involved, a cursory check of weather records for that area suggests three possibilities. First, the Presque Isle area of Aroostook County reported record 24-hour snowfall in December of 1989 (76 cm) accompanied by sustained winds of 13 ms^{-1} and peak gusts of 21 ms^{-1}. Although evergreens in this region are well adapted to such events, the early December blizzard was extreme by any standard.

Second, Figure 30 indicates an unusual late spring snowfall event during 1990. Further investigation shows that the event centered on Aroostook County. The county is represented by three precipitation stations, Caribou, Fort Kent and Squapan Dam. Temperature conditions were warm enough to suggest this was a warm snow event. Records for Caribou and Fort Kent indicate this was snow mixed with rain, but frozen precipitation accounted for only a trace of that recorded and there was no snow accumulation. Squapan Dam, on the other hand, reported 5 cm of accumulated frozen precipitation from this storm which lasted from May 22 to 23 and produced a total water equivalent (rain and melted snow or ice) of 3.1 cm. Figure 40 illustrates the locations of hexagons represented by the Squapan Dam observation.

Finally, a severe storm passed through the area during August of 1990 with winds in excess of 26 ms^{-1}. This event would be a factor only if sampling in this area was done late in the summer. Since more detailed information concerning the location of crown damage within the county is unavailable at this time, these three sources of forest disturbance are only suggestions and cannot be directly associated with the sample observations.

Figure 40. Potential forest sampling hexagons represented by precipitation recorded at Squapan Dam, Maine.



IV. Report Summary and Future Work

Forest response research has established that climate plays an important role in forest ecosystems, influencing both persistence and recurrence characteristics of the landscape (Chapter I). Forests act as environmental integrators of both natural and anthropogenic disturbances. New monitoring programs such as EPA EMAP and the USDA FHM program hope to capture forest response to changes in these stresses, but their observations cannot be correctly interpreted without an ability to discern between natural climate variability and signals of permanent climatological change. Likewise, changes in ecosystem health and productivity can not be accurately attributed to changes in societal behavior unless the ecosystem response to natural disturbance can be better understood and predictively modeled.

Pickett and White (1985) propose the foundation for a theory of natural disturbance. One conclusion is that, "in order to develop a theory of disturbance composed of unambiguous, testable hypotheses and capable of making sound mechanistic predictions, the relevant variables of disturbance must be established. These include at least magnitude, frequency, size and dispersion." Existing climatological products that are designed to appeal to a general audience provide valuable background information. If, however, we are to correctly interpret and model forest/climate interactions as proposed by Pickett and White, we must be certain to focus on the most pertinent aspects of the environment. This includes making sure that researchers are provided with the climate conditions being integrated by and inducing changes in the communities under study (Chapter II).

This research addresses several critical climate impact issues. First, while existing historical networks may be adequate for landscape or regional analyses, local geographic influences critical to the development of accurate predictive models (a stated goal of the FHM) may be lost or misinterpreted by using nonrepresentative climate observations. Ecosystem monitoring and modeling programs that anticipate the availability of climatological observations suitable for assessment and research applications may be disappointed by reality. The availability and characteristics of climatological data and information pertinent to the research issue to be addressed should figure prominently in the early stages of any ecological monitoring program. Too often it is included as an afterthought. With many of today's critical issues focusing on the presence, absence, change and detection of climatological and anthropogenic influences on the biosphere, this oversight could be very costly in terms of knowledge lost as well as dollars expended.

Next, although there are usually far more climate data available for analysis than for ecosystem status and health, there

are serious quality control and representation problems. Some of these issues are currently being addressed by the atmospheric science community, but true, uniform quality control of cooperatively observed weather conditions is a formidable task. The ecological research community must be made as aware as possible of particularly risky areas. Alternatives should be provided where possible.

Finally, new data analysis technologies such as GIS offer unique opportunities to integrate previously intractable multi-media research issues. With increased flexibility comes new challenges to research problem definition. One issue illustrated in this research is the problem of graphically representing an inherently temporal process (climate\forest interactions and dynamics) in a spatial setting (regional analysis). The discussion of data biases and weighting scheme error illustrates that the best solution to these problems is yet to be determined.

Remotely sensed and new ground-based monitoring programs increase analysis opportunities. For example, Quattrochi and Pelletier (1991) suggest that remote sensing technology can be used to detect and record successional or cyclical ecosystemic changes in response to disturbance, to identify the location and spatial extent of stress response or disturbance events and to estimate the magnitude of disturbance and level of stress response. To realize this potential, there is first the need to establish the new data in the assessment process. Even if remotely sensed data provides improved characterization of spatial and temporal variability of the climate, comparative relationships between historic data sources and new sources must be established before they are routinely incorporated into ecological assessment products.

Pickett and White conclude that the development of disturbance theory requires an explicit statement of the parameters of systems that can respond to disturbance. Predictions must be made in terms of the variables of disturbance and the response parameters. The research summarized here represents a first step in this process, i.e., the presentation of the magnitude, frequency, size and dispersion of known climate disturbance phenomena. The next step is to explicitly link observations of forest status and behavior with the unified climatological disturbance data base to identify and more precisely define forest response parameters. This has been done in a cursory fashion in Chapter III, but a long process of research, integration and application remains before the role of climate/forest interactions in the overall earth system can be fully understood and predicted.

This point is illustrated by Appendix A, which contains an outline of research opportunities suggested by this report. They are not ranked but have been stratified into four categories. These areas represent: (1) the development of new climate analyses (climatologies), (2) fundamental program design issues, (3)

acquisition of new data, and (4) applied climatological research. This report illustrates the volume of research and applications studies that can be applied to operational monitoring programs such as EMAP and FHM. Appendix A suggests there is far more that can and should be done to expand the use and value of climate data and information to these programs.

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APPENDIX A

FUTURE WORK

Additional Climatologies

1. Ozone or other pollution episodes could, over time, impact forest growth and productivity. Ozone climatologies are needed for use with pollution indicator species monitoring data.

2. Climatologies of other temperature related disturbances:
   a. heat waves (evaporative stress and heat shock)
   b. frequency, intensity and duration of cold winter temperatures (winterkill and tree-ring chronologies)
   c. warm August temperatures (tree-ring chronologies)

3. Climatologies of other precipitation variables:
   a. Fall precipitation greater than or equal to 1.25 cm (correlated with growth)
   b. Spring precipitation greater than or equal to 1.25 cm (correlated with growth)

4. Statistical definition of drought areas not necessarily based on climate divisions. This would help to target special forest health studies and is of interest to tree-ring scientists.

5. Climatology of wet-spell or flooding events. The extreme positive end of the PDSI scale could be considered as an indicator of wide-spread soil saturation. It would not be adequate for local or short-term flooding events. If this is critical, alternative methods of estimation will need to be identified.

6. Climatology of spring or fall freeze duration (within and between 24-hour periods) and pre-freeze conditions (winter hardiness).

7. A fire weather climatology. Because of the influence of forest management, this is a difficult issue, but is critical for climate trend/climate change assessment research. Much work has been done by USDA Forest Service scientists already, so this may only involve determining how best to apply the information in an EMAP/FHM setting.

8. Expansion of the spring hard freeze and snowfall climatologies to late fall events.

Program Design

1. Investigation of the implications of the proximity of weather data for FHM data analysis: i.e., are the stations we have selected adequate in time and space? No comparison of climate site descriptors to sample site descriptors has been made. Selection criteria is based only on distance from sampling site and quality of record. If interpolation is needed, which methods are the most appropriate? This may vary with the climate variable to be interpolated.

2. Examination and resolution of any differences between EMAP monitoring and climate GIS designs.

3. Exploration of potential interactions between climate and air pollution and deposition activities.

Database Development

1. Extraction from data record of "modeling" of snow and ice disturbance events. A model is needed because of inaccuracies in the snow/ice record for most NWS cooperative observer locations. Ice storms in particular can result in substantial areas of crown damage, defoliation and mortality.

2. Acquisition of digitized tropical cyclone paths. Since these paths are remotely sensed, this information may help to fill-in severe storm observations in sparsely populated areas. Since the resolution of the paths is known, error bars can be placed around the central path to establish potential impact area estimates.

3. Calculation of PDSI by station. Once this database has been developed, it can be manipulated in a variety of ways, including support for tree-ring chronology studies and the spatial drought climatology described above.

4. Acquisition of Canadian weather data to supplement data-sparse northern border areas. This has been started, but has not progressed very far.

5. Acquisition of a lightning strike database. Data are available from networks operated by Bureau of Land Management (BLM), National Severe Storms Laboratory (NSSL) and the State University of New York at Albany (SUNYA).

6. Acquisition of the Robinson quality controlled snowfall database from NCDC. These data would be used to better define heavy (wet) snowfall events and to then generate more meaningful return period climatologies.

Applied Research

1. Investigate the application or integration of remotely sensed weather data to quantitative summaries used by landscape ecologists that also use remotely sensed land surface data.

2. Explicitly examine the way in which disturbance climatologies have been used and may be used in tree-ring chronology studies. This would be done specifically with trend detection and source analysis in mind.

3. Develop and complete definition of disturbance phenomena in three-dimensional (3-D) space (size, intensity and duration) for given disturbance frequencies. For instance, what does a 100 year drought look like in terms of intensity, size and impact area and duration (where area is defined by percent of total area involved)? Perform an historical study to determine spatial and temporal variability of the 3-D space. Investigate ways of detecting trends or changes in the character of the 3-D space. Develop a 3-D time series such as Figure 30 summarizing regional characteristics. This study would also relate to spatial pattern analysis of drought described earlier.

4. Explore the use of extreme value distributions to estimate return periods beyond the cooperative (30-year) data record. This has been done in the literature for temperature and precipitation variables, but not necessarily for all those identified as critical to forest health.

5. Explore the development of interactive/multiple disturbance climatologies such as moisture stress and Southern Pine Beetle infestation and damage severity or similar relationships for Gypsy moth in the northeast.

APPENDIX B

EMAP BIBLIOGRAPHIC RESOURCE LIST
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