SYNOPTIC DENDROCLIMATOLOGY: OVERVIEW AND OUTLOOK

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ABSTRACT. The fields of synoptic climatology and dendroclimatology have maintained an interconnected and parallel development. In this paper we suggest that this mutual advancement should continue as *synoptic dendroclimatology,* a subfield that uses dated tree rings to study and reconstruct present and past climate from the viewpoint of the atmospheric circulation. Eigenvector-based analyses and the use of circulation indices are prime examples of the ways in which tree growth has been related to the circulation. However, analyses that define a direct process-based connection between the large-scale circulation and local ring-width variation are a critical missing link. We propose that standard dendroclimatic reconstructions be enhanced by companion analyses that identify the climate's constituent weather components and the way in which these components are related to tree rings through the circulation at all scales. Three examples of this approach are presented: anomalous circulation patterns associated with frost-ring formation, storm tracks that can be differentiated using tree-ring information in India, and "response circulation patterns" for trees in Oregon and New Mexico.

INTRODUCTION

Since its inception, dendrochronology has had a vital link with climatology and climatic variability. Our paper examines this link from the perspective of *synoptic climatology,* a subfield of climatology that studies the relationships between the atmospheric circulation and the surface environment of a region (Yarnal 1993). In our review of research involving tree rings and atmospheric circulation, we have found several parallels between synoptic climatology and *dendroclimatology,* a subfield of dendrochronology that uses dated tree rings to reconstruct and study past and present climate (Fritts 1976). Although reconstructions of single climate variables such as precipitation and temperature have commanded a primary emphasis in dendroclimatology, several researchers have sought ways of calibrating and analyzing the relationship between atmospheric circulation processes and tree-growth response. Continuing advances in both synoptic climatology and dendroclimatology, longer records of circulation data and a growing interest in the variability of past and future climates together indicate great potential for continued progress. We suggest that researchers in both areas might gain new insights by focusing their efforts under the aegis of a subfield that we call *synoptic dendroclimatology.* In the following sections we present an overview of the evolution of this line of research in tree-ring analysis, introduce our definition of "synoptic dendroclimatology," discuss critical research questions that synoptic dendroclimatology may be able to resolve, and report on the feasibility of some methodologies we are developing to link atmospheric circulation with tree rings.

OVERVIEW OF PREVIOUS WORK

Synoptic climatology and dendroclimatology had their beginnings as formal scientific endeavors in the first half of the twentieth century. Following the computer revolution and the development of sophisticated analytical routines, both subfields experienced a period of definition, rapid growth and advancement in the 1960s and 1970s. Interest was catalyzed by the publication of compendium volumes outlining the state of the art in each discipline: *Synoptic Climatology, Methods and Applications* by R. G. Barry and A. H. Perry (1973) and *Tree Rings and Climate* by H. C. Fritts (1976). At this time the two subfields were already interconnected. Barry and Perry (1973) cited LaMarche and Fritts (1971) and Fritts *et al.* (1971) as illustrations of the application of eigenvector analysis to the linkage of spatial patterns of tree growth with monthly precipitation eigenvectors and seasonal pressure fields. Fritts (1976) included a discussion of synoptic climatology (citing Barry and Perry 1973) in his overview of dendroclimatology. Some two decades later, Harman and Winkler (1991) reviewed the subfield of synoptic climatology and Yarnal (1993) presented an updated overview and "primer" of the current state of the discipline. At about the same time, Fritts (1991) summarized his years of research directed toward using grids of tree-ring data to reconstruct grids of sea-level pressure and other climatic parameters.

As the synoptic climatology and dendroclimatology subfields developed, they remained interconnected. Methodological approaches popular in synoptic climatology were echoed in dendroclimatology, the latter field advancing at an equal pace due to the strong interdisciplinary research component it has always maintained. Table 1 summarizes the evolution over the last three decades of dendroclimatological research related specifically to atmospheric circulation. The table contains a list of references (through 1993) addressing tree rings and atmospheric circulation, selected from the bibliographic database maintained by Henri Grissino-Mayer at the University of Arizona's Laboratory of Tree-Ring Research. The table is not exhaustive in its listing of circulation-related dendroclimatological papers, but attempts to highlight examples of key papers that introduced a particular methodology or first addressed a problem with a specific type of circulation-based approach common to synoptic climatology. An overview of the parallel development of these two subfields follows.

Synoptic Climatology and Dendroclimatology

The basis of synoptic climatology is the relationship between the atmospheric circulation and local or regional climate-related processes or responses. Several definitions of synoptic climatology have been offered:

> The study of the relationship between the atmospheric circulation and local or regional climates. (Barry and Perry 1973)
>
> The study of climate from the viewpoint of its constituent weather components or events and the way in which these components are related to atmospheric circulation at all scales. (Harman and Winkler 1991)
>
> The study of the relationship between the atmospheric circulation and the surface environment. (Yarnal 1993)

Both Barry and Perry (1973) and Harman and Winkler (1991) emphasized the link between the atmospheric circulation and a region's weather elements, while Yarnal (1993) broadened the definition to include any aspect of the surface environment that responds to climatic variability driven by the atmospheric circulation. According to Yarnal (1993), all synoptic-climatological studies involve some classification of the circulation. The classification methodologies vary and include: eigenvector-based differentiation of circulation map-patterns or regionalizations; specifying the circulation pattern through circulation indices; manual synoptic typing (typically based on weather maps); defining the circulation patterns associated with specific events; correlating a pressure field with variability in a time series at a single locality; and producing composite map patterns that are linked to certain environmental criteria.

Dendroclimatology was originally defined as "a subfield of dendrochronology that uses dated tree rings to reconstruct and study past and present climate" (Fritts 1976). The meaning of the term has expanded to encompass a whole suite of approaches that link climate and tree rings. Fritts also specified a related area of research that he called *dendroclimatography,* defined as a field "in which the spatial variations in tree rings are employed to reconstruct and map the spatial variations in past cli-

TABLE 1. Overview of Studies Linking Dendroclimatology with Atmospheric Circulation

Reference	Eigenvector-based		Index-based		Event/Weather-based		Circulation Map-based	
	Eigen-vector-based maps/ groups	Pressure fields, recon-structed grids	Indexing *e.g.,* SOI, ENSO NAO	Position of circu-lation feature *e.g.,* STH	Event-based analysis, extreme events	Storm tracks, frontal position, air mass	Com-positing	Correla-tion field maps
Fritts 1965	■	■						
Fritts *et al.* 1971	■	■						
LaMarche and Fritts 1971	■	■						
Blasing and Fritts 1976	■	■						
Douglas 1976			■				■	
LaMarche and Hirschboeck 1984					■			
Lough and Fritts 1985			■					
Briffa *et al.* 1986	■	■						
Lough and Fritts 1987	■	■			■			
Wu and Lough 1987	■	■						
Baillie and Munro 1988					■			
Scott *et al.* 1988						■		
Lough and Fritts 1990	■	■	■					
Michaelsen 1989			■					
Kelly *et al.* 1989							■	
Stahle 1990			■		■	■	■	
Swetnam and Betancourt 1990			■					
Stockton 1990			■		■			
Villalba 1990	■		■	■				
Fritts 1991	■	■						
D'Arrigo and Jacoby 1991, 1992	■		■					
Villalba *et al.* 1992	■							
Bradley and Jones, eds. 1992 *Climate Since A.D. 1500*	multiple refs	multiple refs	multiple refs					
D'Arrigo, Jacoby and Cook 1992			■					
Diaz and Markgraf, eds. 1992 *El Niño: Historical and Paleoclimatic Aspects of the Southern Oscillation*			multiple refs					
Harrington, ed. 1992 *The Year Without a Summer? World Climate in 1816*					multiple refs			
Johnson and Young 1992						■		
Hughes and Brown 1992					■		■	
Stahle and Cleaveland 1992				■			■	
Meko *et al.* 1993	■		■					
Woodhouse 1993			■					
This paper				■	■	■	■	■

mate" (Fritts 1976: 436). Much of what is called dendroclimatology today involves the mapping of climate patterns; hence dendroclimatography and dendroclimatology are rarely seen as distinct fields. However, within dendroclimatology there is a unique tract of research that focuses directly on atmospheric circulation processes rather than on the spatial or temporal patterns of temperature and precipitation. In our review of these tree-ring/circulation studies, we discovered that all of the synoptic climatological methodologies mentioned above have been incorporated in dendroclimatological tree-ring studies to varying degrees.

Eigenvector-Based Approaches

Since the 1960s, eigenvector-based approaches have dominated synoptic climatological methodologies due to their ability to reduce large grids of complex data into a manageable set of simplified, orthogonal components of circulation information. The eigenvector-based methods are so widely used that we will not describe them in detail here. A comprehensive overview of this approach as used in synoptic climatology can be found in Yarnal (1993). Table 1 shows that eigenvector-based methods also have played a prominent role in dendroclimatological circulation studies. The most common strategy, pioneered by H. C. Fritts and his colleagues in the 1960s and 1970s, employs grids of tree-ring data that are calibrated to atmospheric pressure fields (*e.g.*, Fritts *et al.* 1971, Briffa *et al.* 1986). Fritt's 1991 work, *Reconstructing Large-Scale Climatic Patterns from Tree-Ring Data*, provides an excellent summary of the rationale and results of this approach to reconstructing pressure fields. Eigenvector methods also have been used extensively to identify significant patterns and relationships in other types of climate indicators and in spatial patterns of tree-growth (*e.g.*, Villalba, Holmes, and Boninsegna 1992; Meko *et al.* 1993). The widespread use of these methods has shown that whenever large grids of tree-ring or climate data are involved, eigenvector-based approaches are well-suited for circulation/tree-ring analyses.

Indexing

Another standard methodology in synoptic climatology is the use of circulation indices. A circulation index is a series of values that describes a climatic condition and the variations in that condition over time. An index usually synthesizes some key aspect of circulation into a single time series. It may describe contrasting effects, teleconnections or mechanisms that work together to produce an overall effect. An index often specifies the behavior of atmospheric pressure in significant "centers of action" of the global circulation. Indices provide efficient means to quantify the seasonal or interannual variability of the circulation without having to process large amounts of data. The widely used Southern Oscillation Index (SOI) is an example of such an index. Based on pressure vacillations between the east and west Pacific, it is associated with fluctuations in a suite of other factors, including sea surface temperature, wind direction, and precipitation in the tropical Pacific region. Hence, the index encompasses all these processes indirectly (Rasmussen and Carpenter 1982).

Table 1 reveals that indices of the circulation (usually the SOI) have been frequently employed to identify a link between tree growth and the atmospheric circulation. Indices usually describe synoptic to continental-scale circulation patterns, which are then linked to variations in regional climates when correlation with the index time series is strong. Variations in climate at these scales may also be reflected in tree-ring width patterns, in much the same way as local climate is influenced by variations in large-scale circulation features. The SOI has particular utility because numerous studies have demonstrated the importance of El Niño/Southern Oscillation (ENSO) events as aspects of the circulation that have a major impact on climate/tree-growth variations in certain sensitive regions (see Diaz and Markgraf 1992).

Although relationships between sea surface temperatures, air-sea interactions and ring-width variations in the western United States were being explored as early as the 1970s (Douglas 1976), studies examining the link between the SOI and tree rings proliferated following the unprecedented 1982/83 ENSO event, (*e.g.*, Lough and Fritts 1985, 1990; Michaelsen 1989; Swetnam and Betancourt

1990; Meko 1992, Stahle and Cleaveland 1993). These studies investigated the relationship between tree growth and the SOI in an attempt to understand the *long-term* behavior of the Southern Oscillation and how it has influenced tree growth in mid-latitude climates. Such long-term assessments of the variability of the SOI have proved invaluable for climatologists interested in global change.

Although the feasibility of using dendrochronological techniques to reconstruct the SOI from tree-ring chronologies has been demonstrated (*e.g.*, Michaelsen 1989), much work still needs to be done to enhance these SOI reconstructions. Areas with strong SOI signals have not yet been fully explored, and many tree-ring chronologies in areas where climate is sensitive to the index need to be updated. For example, Stahle and Cleaveland (1993) suggest additional sampling in the Sierra Occidental and Sierra Oriental in Mexico, areas with strong climatic responses to variations in the SOI. The success of tree-growth/SOI studies has promoted the expansion of this line of research and the exploration of other circulation indices in dendroclimatology. These include the North Atlantic Oscillation index (NAO) (Stockton 1990; D'Arrigo, Jacoby and Cook 1992; D'Arrigo *et al.* 1994), the Pacific North American index (PNA) (Stahle 1990), and, in the Southern Hemisphere, the Central Zonal Circulation Index (ICZC) and the Austral Zonal Circulation Index (ICZA) (Villalba 1990).

One other type of indexing has been successfully used in dendroclimatic studies. Spatial aspects of the circulation often can be evaluated by using the latitudinal position of a key pressure feature, such as the subtropical high, as an index. Villalba (1990) and Boninsegna (1992) have used this technique effectively. They found that tree-ring width variability in chronologies from the Andes region in Argentina and Chile is strongly associated with the latitude of the subtropical anticyclone belt off the coast of South America. In the Northern Hemisphere, the latitudes and strength of key pressure features also have been shown to be important. For example, Stahle and Cleaveland (1992) linked reconstructed spring rainfall regimes in the southeastern United States to the expansion and migration of the North Atlantic subtropical anticyclone.

Manual Typing Schemes

Manual typing schemes have been central to synoptic climatology since its early days. This approach, in which an investigator subjectively groups climatic data and/or weather map patterns into predetermined categories, is highly labor intensive, yet infinitely flexible (Yarnal 1993). Manual classifications can use diverse and unusual kinds of data in assorted combinations to explore the relationship between the circulation and an environmental response. A drawback to this approach is its subjectivity, which does not allow exact duplication of the scheme in the way that automated approaches do. Yet subjectivity also plays a role in the computer-assisted schemes, *e.g.*, as decisions are made at each stage of a multivariate eigenvector-based suite of analyses. Although the manual classifications lack efficiency and objectivity, they offer the researcher control at every step of the investigation and the ability to attune the classification to variations and processes in the physical world that are relevant to the circulation/environment relationship being examined.

The use of manual typing schemes has been explored but not used extensively by dendroclimatologists, who have traditionally opted for more automated classification techniques. In an unpublished feasibility study undertaken in the 1970s, Fritts examined the relationship between reconstructed pressure fields and the manual circulation classification scheme of B. L. Dzerdzeevskii. Tree-ring data sets also have been related to a manual classification of wet and dry indices, based on documentary evidence in China dating back to the mid-15th century (Wu and Lough 1987; Lough, Fritts and Wu 1987). The more common way in which the manual approach has been used in dendroclimatic studies is in combination with some automated procedure directed toward the analysis of a specific type of event. This approach is discussed in the following section.

Event-based Analyses

Although climatic processes proceed without interruption and therefore are usually represented as a continuous time series, extremes in this continuum are of particular interest. For example, although the SOI is a variable calculated as a continuous time series, extreme positive or negative values of the index are indicative of discontinuous ENSO "events" that occur at certain points in the time series and have an identifiable beginning and end. Like ENSO, other types of circulation-related extreme climatic events have been shown to have an important influence on the patterns of tree-growth anomalies as revealed in tree rings. These may be of relatively long duration, such as a prolonged drought lasting many years (Stockton 1990), or they may be of short duration, such as a severe freeze occurring on one to two days during the growing season (LaMarche and Hirschboeck 1984; Stahle 1990). They may also be associated with extreme precipitation leading to a flood event (Hupp 1987; McCord 1990) or severe weather such as a tropical storm or hurricane. Under appropriate site conditions, such events may be recorded by a tree in the form of a scar, false ring, frost ring or anomalous growth response. Hence, extreme events such as droughts, freezes and floods can all be dated using dendrochronological techniques and some measure of their severity usually can be assessed.

A complete synoptic climatology of the patterns and process associated with such extreme events recorded in tree rings has not yet been fully developed but several studies have provided important results. Drought variability in different regions has been successfully linked with circulation indices such as the SOI (Cleaveland and Duvick 1992) and the North Atlantic Oscillation, NAO, (Stockton 1990). Floods and extremely wet years as detected in tree rings have also been related to atmospheric circulation through indices such as the SOI.

The occurrence of unusual cooling during the growing season—exemplified by the weather and climate of 1816, "the year without a summer"—has spawned another important area of event-based analysis in which many dendroclimatologists have participated: an interest in the climatic effectiveness of explosive volcanic eruptions (*e.g.*, LaMarche and Hirschboeck 1984; Lough and Fritts 1987; Baillie and Munro 1988; several authors in Harrington 1992). These studies have addressed, either directly or by implication, the post-eruption circulation patterns and climate that can be detected through tree-growth responses in different parts of the world.

Several studies of tree growth response to climatic events have been based on the evaluation of weather map features such as storm tracks, frontal positions, and air mass frequency. These analyses have focused on the events that bring the "weather" to the trees at a given site using various indicators of atmospheric circulation. For example, Scott *et al.*'s (1988) study of white spruce (*Picea glauca*) and tamarack (*Larix laricina*) from Churchill, Manitoba, Canada demonstrated that treeline regions are sensitive to shifts in the Arctic Front. Johnson and Young (1992) examined the impact of coastal tracking hurricanes and northeasters on barrier island populations of loblolly pine (*Pinus taeda*) in a comparative analysis of ring widths and storm occurrence.

One of the more comprehensive applications of a synoptic climatological approach to analyze extreme events recorded in tree-rings is that of Stahle (1990). In his study of frost-damaged trees in the southcentral United States, Stahle compiled detailed information to identify the weather, climate and circulation patterns associated with frost injury to trees during severe false spring events. These events were also linked to ENSO variability using the SOI, and their relationship to another circulation index, the Pacific/North American (PNA) pattern (Wallace and Gutzler 1981; Leathers, Yarnal and Palecki, 1991) was examined. Stahle found that the false spring episodes included both climatological and meteorological signals. The consistent registration of specific weather conditions associated with frost ring occurrence led him to propose the feasibility of "dendrometeorology."

Many more analyses of the anomalous atmospheric circulation patterns and weather features that are associated with extreme events need to be conducted, primarily because of their severity and their impact on human activity. In addition, because very short-lived extreme events occur at a different timescale than that which forms an annual growth ring, they represent processes occurring within a nested set of spatial and temporal scales and can give insight into both large-scale mean circulation patterns and short-term local surface responses.

Correlation Fields

Correlation fields (Fig. 1A) are an efficient means to specify the centers of circulation or anomalous flow direction that co-vary with the time series of some environmental variable at a given location.

The correlation field technique is a way of displaying the spatial relationship between a time series of observations at a single station and a corresponding spatial array of time series observations in a grid of sea-level pressure or geopotential heights. By plotting the correlation coefficients in map form at each respective grid point location, a correlation pattern will emerge that displays geographically where a strong direct or inverse relationship exists between the grid point observations and the single station observations. There is a physical meaning to the correlation field such that the grid point pattern of correlations can be interpreted as a circulation map, where positive and negative areas on the map reflect anomalous anticyclonic and cyclonic flow, respectively. The pattern then resembles a circulation composite map or a circulation anomaly map by revealing the dominant areas of mean high and low geopotential heights or pressure that are linked with variability at the surface site. To date, correlation fields have not been used in dendroclimatology to link tree-ring chronologies in a region or single locality with a grid of geopotential heights. We will present a feasibility study of this procedure later in our paper.

Composite Maps

Compositing (Fig. 1B) is an approach that uses *a priori* decisions based on environmental criteria to select a set of maps and average them, therefore representing the key synoptic features of a specific situation (*e.g.*, drought years, severe freezes, high ring-width index years). Like manual typing, this method is extremely flexible, can incorporate complex criteria, and is not limited to pressure surfaces. Composites can be made of pressure fields, storm tracks, frontal positions, ridge and trough axes, key isotherms, air masses and many other physical aspects of weather and climate. When averaging data fields from different months or seasons, composites of standardized anomalies from the long-term mean provide a useful way of viewing variation in the patterns that is independent of the seasonal cycle. Composites can be used in conjunction with correlation fields to validate whether the statistical surface of correlation coefficients produced by a correlation-field analysis bears a resemblance to the patterns on actual pressure fields. Compositing also allows identification of nonlinear responses that will be lost in correlation mapping.

Compositing has been used in a variety of dendroclimatic studies and often is applied in event-based analyses. Mean sea-level pressure patterns associated with regional drought have been identified through pressure map composites (Hughes and Brown 1992). This same compositing methodology has been used to analyze extreme high and low rainfall regimes reconstructed from tree rings (Stahle and Cleaveland 1992) and to contrast the climatic conditions resulting in increasing or decreasing tree-growth "signature" years over a large region (Kelly *et al.* 1989). As noted earlier, Stahle (1990) used compositing to define the circulation patterns associated with frost injury to trees during severe false spring events.

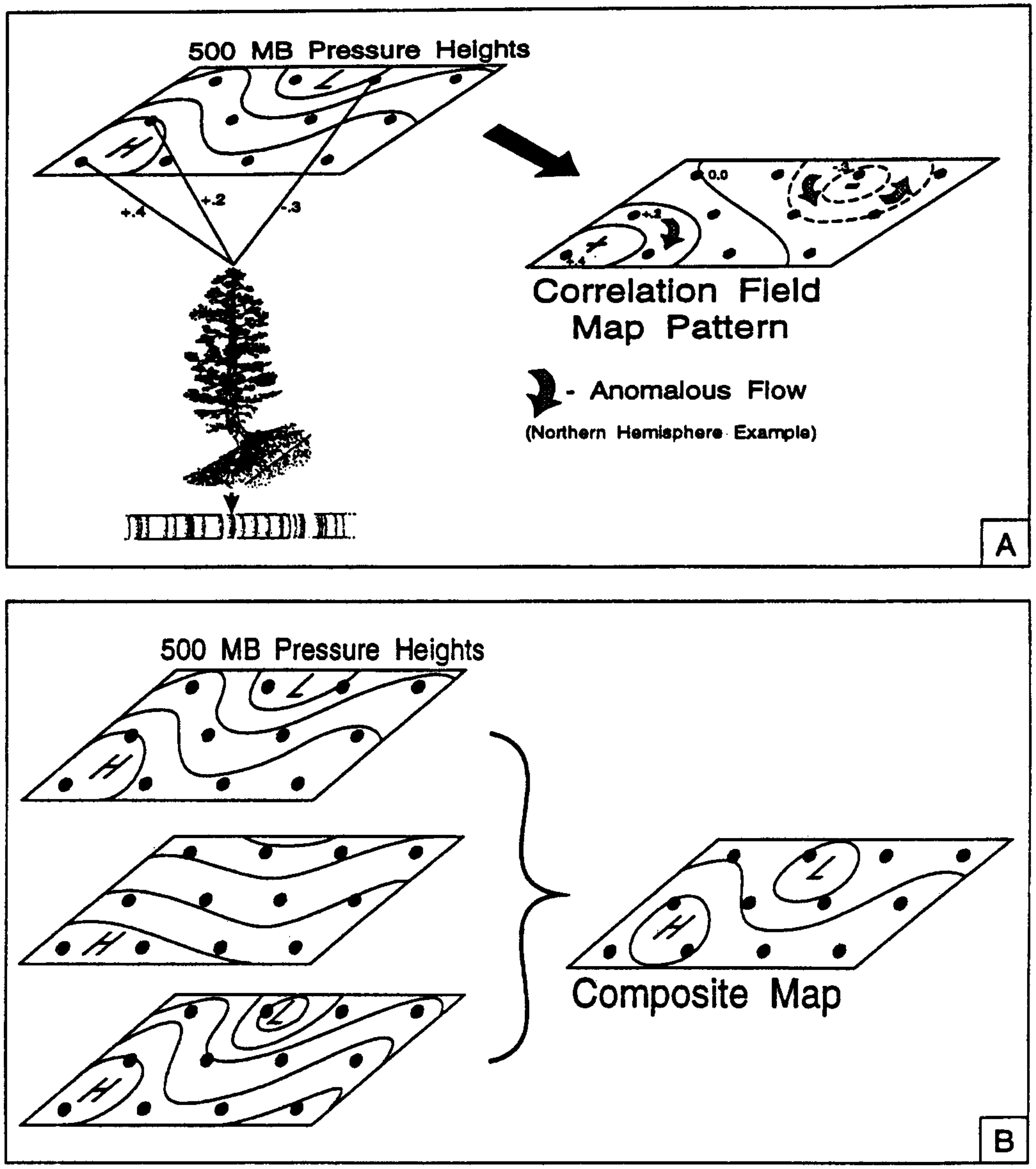

Fig. 1. Schematic diagrams illustrating two circulation map-based approaches used to link the circulation with the surface environment. A. Correlation field technique showing how a grid of correlation coefficients reflects the circulation pattern; B. composite mapping technique.

Summary of Previous Work

Table 1 reveals that dendroclimatologists studying the relationship between atmospheric circulation and tree growth have concentrated their efforts mainly on either eigenvector-based methodologies or indexing. This has no doubt occurred for the same reasons that these methods are popular among synoptic climatologists: their ability to decompose large grids of complex data into a manageable set of components or a simple index. Much emphasis has been placed on the use and/or reconstruction of gridded surface pressure fields and linkages with the SOI. However, Table 1 also shows that dendroclimatologists have applied a variety of other methodologies in addition to the eigenvector- and index-based approaches.

According to Harman and Winkler (1991) and Yarnal (1993) one aspect of research that has been underdeveloped in synoptic climatology is a systematic approach that examines and seeks to understand the "cascade" of processes linking the circulation to an environmental response through climate and weather components occurring at all scales. Often a black-box approach based on statistical models has been employed to link the atmosphere and the surface environment. Such a strategy does not address nonlinearities, feedbacks and the dynamic processes occurring throughout the atmosphere at all scales. Harman and Winkler (1991) suggest that for synoptic climatology to advance and become increasingly fruitful as a discipline it must seek to: 1) develop an understanding of causative interactions, 2) identify process-based explanations of behavior in a climatic parameter (in addition to description of the behavior), and 3) better incorporate the principles of physical meteorology and dynamic climatology into all aspects of the research. The study of processes that are driven by the large-scale circulation to effect a local or regional climatic response is therefore an area in need of more research in synoptic climatology. This same critique can be applied to dendroclimatology.

Many of the studies we have reviewed above used spatial and temporal indicators of atmospheric features such as storm tracks, frontal position, or latitude of a semipermanent pressure feature as the climatic variable linked to tree growth. This approach also can be combined with compositing and indexing. The advantage of such studies is that they define a direct process-based connection between the large-scale circulation and ring-width variation at a local site. It is this critical link that often has been missing in some of the eigenvector-based analyses that define large-scale patterns from grids of tree-ring data. A process explanation also is sometimes lacking in some of the index/teleconnection studies. We suggest that one of the best ways to enhance the eigenvector and indexing approaches is to develop companion analyses that can identify the series of telescoping linkages from larger to smaller scales of circulation and relate these processes to local and regional tree-growth response to climate. In the following section we outline this vision of "synoptic dendroclimatology" and illustrate it with three feasibility studies of how it might be applied.

THE POTENTIAL OF SYNOPTIC DENDROCLIMATOLOGY

Our newly proposed definition of *synoptic dendroclimatology* is based on Fritts (1976) and Harman and Winkler (1991):

> Synoptic dendroclimatology is a subfield of dendrochronology that uses dated tree rings to study and reconstruct present and past climate from the viewpoint of the climate's constituent weather components or events and the way in which these components are related to atmospheric circulation at all scales.

We believe that greater attention to climate's constituent weather components or events and the scales at which these components operate will improve our ability to interpret and evaluate the reconstructions of climate that are central to dendroclimatology. In particular, we suggest that some approaches—*e.g.*, compositing, manual typing, and circulation indices derived from positions of storm tracks, fronts, or pressure features—have been underutilized by dendroclimatologists in their analyses, reconstructions and interpretations of past climate.

A typical dendroclimatic study involves reconstruction of a time series of annual or seasonal precipitation and temperature. The climatology inherent in the interannual variability of the reconstructed series is discussed in terms of wet years, dry years, or whether there is evidence of low frequency variation (*e.g.*, a possible Little Ice Age or Medieval Warm Period signal). Often, spectral analysis is used to identify periodicities in the series that might suggest some ultimate geophysical forcing for the variability observed. The synoptic climatology of the storms, air masses, fronts and pressure patterns that are the direct cause of the observed variability are either not addressed or are discussed in only a limited manner. This is largely because detailed regional or local synoptic climatologies have not been developed for the chronology sites. Important knowledge about the long term-variability of the meteorological and climatological *processes* that produce temperature and precipitation fluctuations may be embedded in the hundreds of climate reconstructions now in existence. Uncovering some of this information may be as simple as developing companion analyses that focus on the synoptic circulation processes that operate in a given region.

A more comprehensive synoptic climatological perspective may also enhance the quality of our dendroclimatic databases by providing a physical basis for developing specific circulation-linked sampling strategies (similar to sampling efforts for the detection of other climatic variables). One current example of this is the development of new chronologies attuned specifically to the detection and reconstruction of a strong ENSO signal. Lough and Fritts (1990) and Meko (1992) have suggested that chronology development be pursued in areas with climatic conditions that are influenced in opposite directions by the SOI. Two such contrasting regions are northern Mexico/southern United States and northwestern United States/southwestern Canada. If tree-growth patterns in both regions reflect variations in the SOI, they can be used together to better define spatial variations in the influence of SOI on climate. The spatial extent of SOI influence and the gradient of response between one SOI teleconnection center and another also can be examined with tree-ring chronologies. A network of chronologies having similar relationships to climate may delineate a gradient of response to a particular circulation feature—from regions of strong, to transitional, to nonexistent response. An illustration of this approach is found in Woodhouse (1993). She was interested in determining whether or not an ENSO signal could be detected in ring patterns of trees at high elevations in the central Colorado Front Range, an area in which the influence of SOI is not well understood. She found that ENSO events have an inconsistent, but in some years, important influence on tree growth, which in this area is primarily limited by winter/spring moisture conditions. Her study serves as an example of how tree-ring analysis—coupled with climatically informed site selection—can be used to better understand spatial and temporal variations in synoptic-scale patterns of circulation.

Our vision of synoptic dendroclimatology includes the continued use of the standard approaches already in wide use by dendroclimatologists (such as eigenvectors and indexing), but encourages their enhancement through a more physically based understanding of the circulation processes involved. For example, nonlinear tree-growth responses may be blurred by using linear regression techniques and orthogonal solutions that may not necessarily have direct physical interpretations. Synoptic dendrolimatology might well provide process-based reasons to seek alternative techniques such as fuzzy regression or nonorthogonal eigenvector analyses. Similarly, alternative or entirely new circulation indices could be carefully and creatively constructed and used in conjunction with a tree-ring sampling strategy tailored to regions of greatest sensitivity to the circulation patterns of interest. Such an approach may enable the reconstruction of long records of different types of synoptic patterns or indices that would complement existing reconstructions of the SOI. We also advocate a more vigorous use of other synoptic climatological approaches that have not yet been applied extensively in tree-ring analyses. To illustrate some of these, we will close our paper with brief descriptions of three studies that we are conducting as part of ongoing research linking atmospheric circulation and tree rings.

Feasibility of Examining Telescoping Temporal Scales: Frost Rings and Atmospheric Circulation

The application of synoptic climatology to tree-ring analysis has tended to address the circulation/tree-growth relationship at two disparate timescales: 1) the "event scale" that records a response to an extreme, short-term event that is linked to weather or an anomalous climate pattern, or 2) the "year-to-decade" timescale that reflects much longer-period climatic variation. The most useful timescale for synoptic climatological analysis is weeks-to-months, a period that is not typically differentiated by tree rings. Yet in anomalous (and hence climatically important) years, there is an inherent persistence or recurrence of key circulation patterns that may manifest itself at progressively longer or shorter telescoping (or cascading) timescales. Furthermore, extreme climatological events often display a "signature" in the circulation pattern that is detectable at both short and long timescales.

The circulation patterns associated with widespread frost-ring formation in trees illustrate the cascade of atmospheric patterns and processes that connects the large-scale circulation with a local or regional tree-ring response. The typical synoptic signature for a mid-latitude frost ring in North America event is a deep mid-tropospheric trough that conveys Arctic air masses to lower latitudes and often is associated with blocking activity in the hemispheric-wide circulation. In 1965 frost damage was observed in subalpine bristlecone pine in widely separated localities in the western United States (LaMarche and Hirschboeck 1984). The damage was caused by a freeze that took place on 17–19 September while a deep trough was situated over western United States. Figure 2 shows this circulation event depicted at two different timescales—monthly (Fig. 2A) and daily (Fig 2C)—in simple mapped patterns of the 700 mb and 500 mb pressure height fields. Also shown is the 500 mb chart for the day just before the beginning of the anomalous cold wave (Fig. 2B). Prior to the freeze

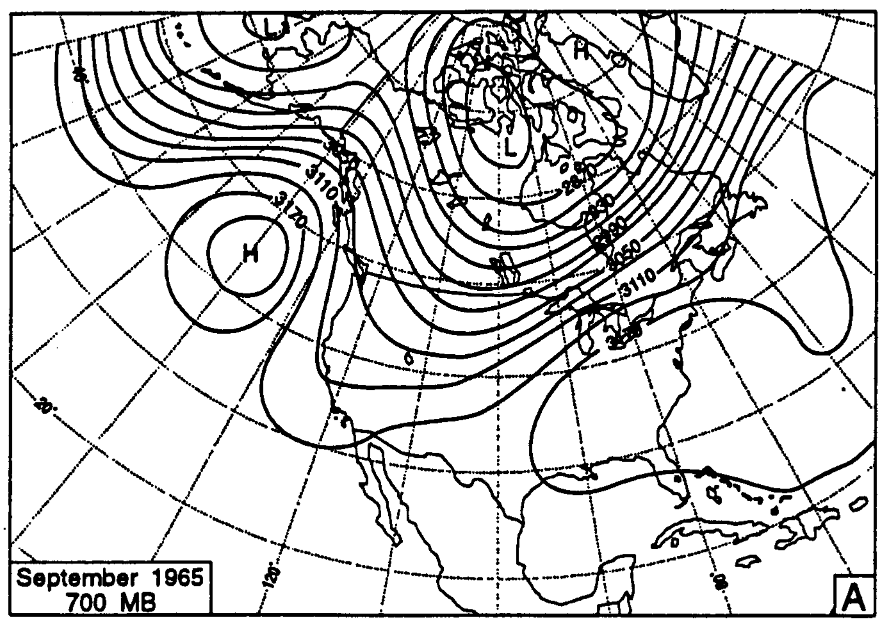

Fig. 2A. The mean monthly circulation pattern for September 1965. Units are geopotential heights in meters above sea level.

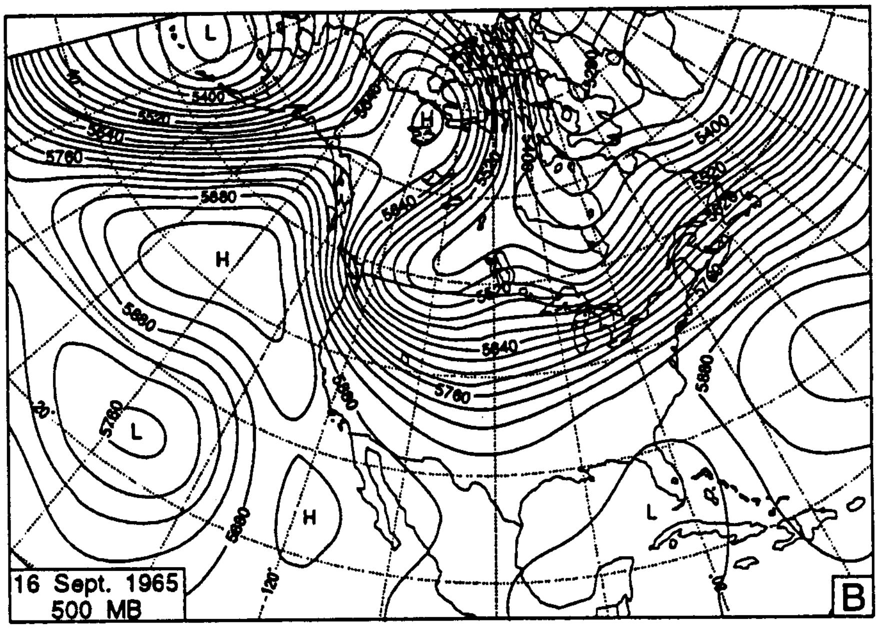

Fig. 2B. The daily pattern for 16 September 1965, just before the severe cold wave began

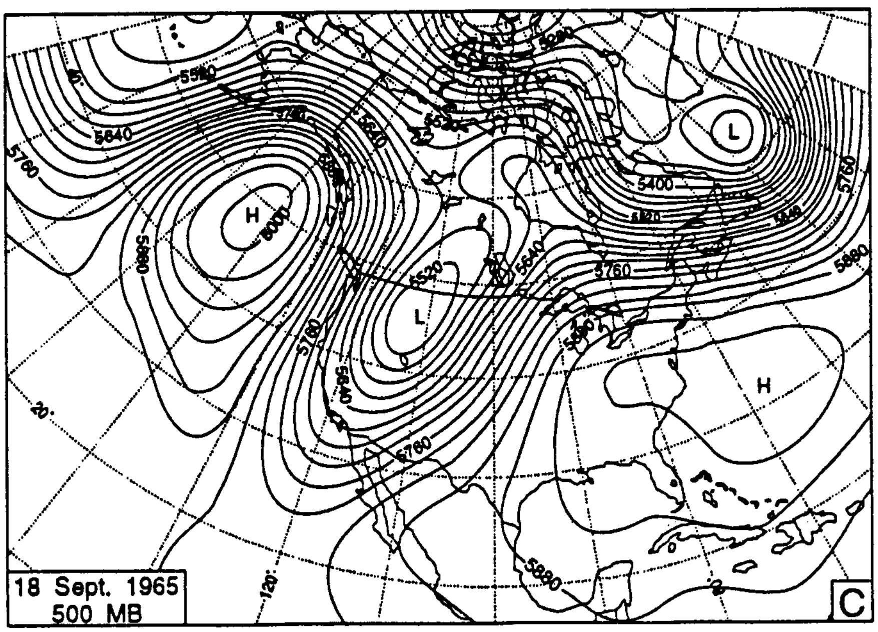

Fig. 2C. The daily pattern for 18 September 1965, the second day of the freeze event

event, the circulation had a more zonal pattern, but on 16 September a strong ridge began to develop over the Gulf of Alaska and an abrupt shift to a highly meridional pattern occurred. The circulation then "locked in" to the pattern depicted in Figure 2C and persisted.

A comparison of Figures 2A and 2C shows that the circulation as mapped on both the monthly and daily timescales is very similar. This raises an important question: is such persistence in pattern related to the dynamics of large-scale, long-wave planetary circulation or merely an artifact of numerical averaging? This single example from our ongoing study of extremes that can be detected at several timescales suggests that the key to developing a viable synoptic dendroclimatology will be to identify episodes with strong linkages across telescoping timescales and to evaluate the existence or persistence of specific atmospheric circulation patterns prevalent during these episodes. Because frost rings represent short-lived events recorded in an annual growth ring that also contains climate information for a much longer period, they provide an excellent research base from which to evaluate anomalous circulations and extremes at varying timescales.

Feasibility of Using Event-based Analyses: Flooding and Storm Tracks in India

This study illustrates the usefulness of event-based synoptic climatology and compositing to refine a research question. Our original purpose was to use teak (*Tectona grandis*) from the Upper Narmada River Basin in central India to reconstruct precipitation and evaluate the flood hydroclimatology of a highly seasonal streamflow regime driven by a monsoonal climate. Historical information on flood years is available for the Narmada going back about 200 yr, but the gaged climate and discharge record is too short to use with this information. Hence, we wanted to reconstruct rainfall. A cursory analysis of flooding in the basin showed that annual or seasonal regional rainfall totals were not always useful for distinguishing between flood years and low flow years. More flooding tended to occur in wet years, but extreme floods were also recorded in dry years. Such is often the case when trying to assess hydrologic extremes, but the nature of monsoonal rainfall in central India seemed to compound this problem. Through a synoptic climatological study, we found that flooding on the Narmada River seems to result from either of two scenarios: 1) several low-pressure systems track successively over the upper catchment, saturating the ground and setting the stage for a flood to happen, or 2) a single major storm occurs with either an extreme rainfall intensity, or a track that is oriented along the axis of the basin and superimposes rainfall on the downstream-moving flood wave. The latter single-storm flood scenario has occurred in both unusually wet and drought seasons.

The key to understanding the Narmada's flood/climate regime clearly is related to the trajectory of storms over the basin. Our research emphasis shifted, therefore, to an event-based analysis of the storm tracks moving across the basin. We composited storm tracks for the monsoon months having the five highest and five lowest precipitation totals at Mandla, a climate station located in the upper basin close to our tree-ring site. The categorization of years based on high and low annual rainfall totals at a single key site produced notably different composites of storm track patterns. At the onset of the monsoon season (Fig 3A and 3B), June experienced a much lower number of low pressure systems during the driest five years than the wettest. The storms in the wet years were concentrated in a relatively narrow region. In contrast, no superposition of successive storm tracks occurred in the dry years. These differences between wet and dry periods at the beginning of the rainy season were found to be related to the date of onset of the monsoon and the position of the monsoon trough.

During the full monsoon season (June–September, Fig. 3C and 3D), the number of low-pressure systems that formed in the region of the Indian subcontinent was not significantly different between the wettest and driest years, but the regions covered by the storm tracks *were* very different. The tracks during the wettest years were concentrated in a narrow band that stretched across central and northwest India, while those in the driest years were more diffuse. If categorization of different storm-track patterns in this part of India can be done so effectively using the record of a single climate station, it is feasible that a nearby rainfall-sensitive tree ring-width chronology could be used to perform

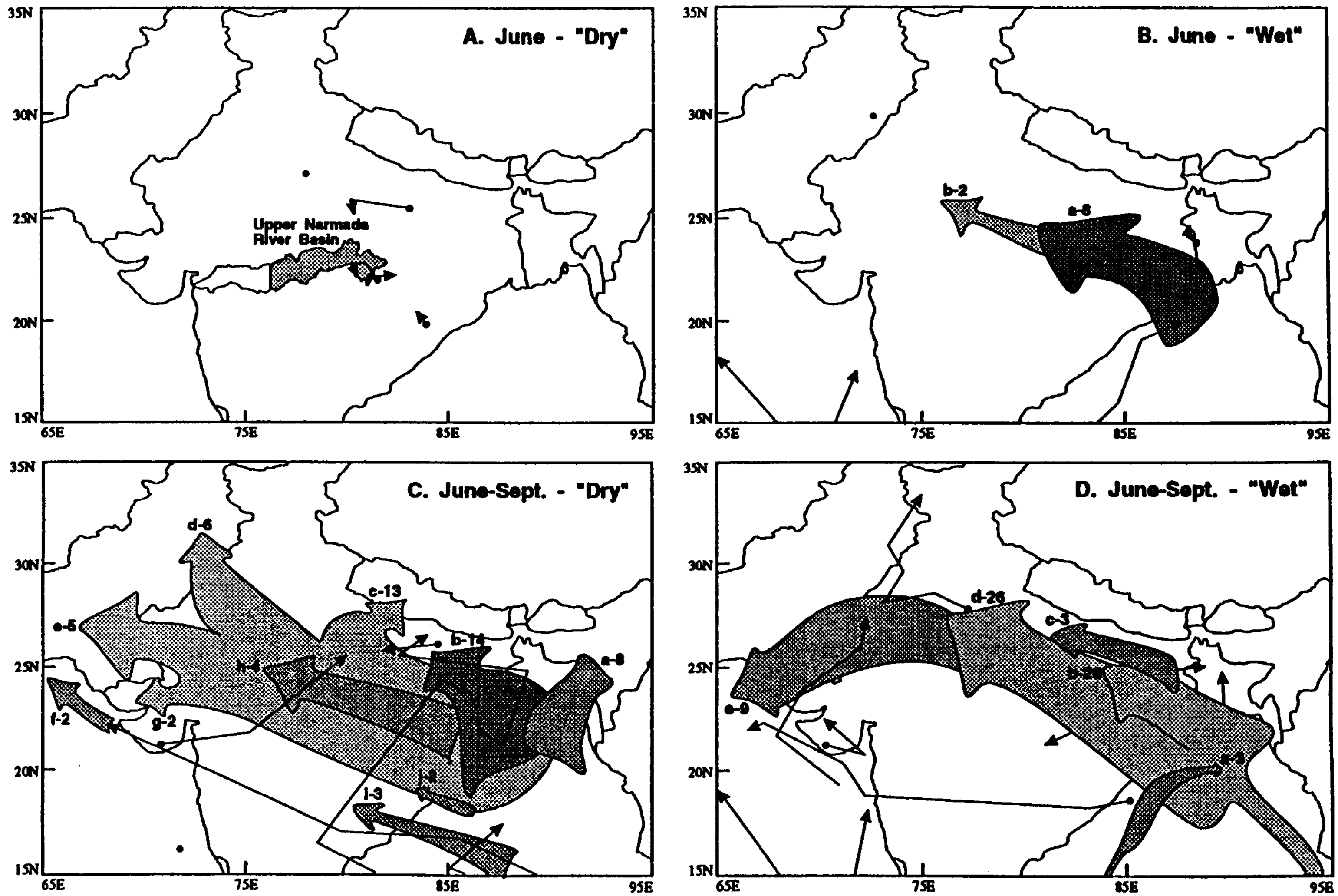

Fig. 3. Storm tracks for the periods having the five lowest ("Dry") and five highest ("Wet") monsoon precipitation totals at Mandla, India (22°36′N, 80°23′E). Shaded arrows represent several tracks with roughly the same orientation and are labeled with a letter and an indication of the number of tracks represented (*e.g.*, c-13). • = point of storm origin. Storm tracks are from Mooley and Shukla (1987) and are based on the period 1901–1970. A. Five driest Junes; B. five wettest Junes; C. five driest June–September monsoon seasons; D. five wettest June–September monsoon seasons.

a similar categorization for a much longer period. The synoptic dendroclimatic information gleaned from tree rings can then put flood events into context by answering the question: did the flood occur in a month or season characterized by a great number of successively occurring storm tracks, or did it result from a storm that had an unusual track or exceptionally high rainfall intensity?

Feasibility of Using Correlation Fields and Composites: Circulation Response Patterns

In our last illustration of the potential of synoptic dendroclimatology, we use the correlation field and composite map approaches. Compositing has been used by other researchers to reveal the circulation patterns dominant in "signature" years of tree growth, but we are not aware of any studies involving correlation fields and tree-ring indices. A major distinction between the two approaches is that a single correlation field is produced to represent the circulation/tree-growth relationship for the *entire* period of record as a whole, not just selected years. This concept is not unlike that of a "spatial response function"—linking ring-width variations to circulation instead of temperature or precipitation. Through this process a function (the correlation field) expresses the relative effects of several climatic factors (the geopotential height gridpoints) on ring width.

We explored the feasibility of constructing "circulation response patterns" for two different tree-ring localities having response functions that indicated a sensitivity to winter climate. Figure 4A depicts the winter correlation field (based on 500 mb geopotential heights) for a tree-ring chronology from western juniper (*Juniperus occidentalis*) in central Oregon (Frederick's Butte). Figures 4B and 4C represent corresponding winter composite anomaly maps for the five years with the highest and lowest ring-width indices, respectively. Figure 4D depicts the winter correlation field for a regional average chronology from stands of ponderosa pine (*Pinus ponderosa*) in the Jemez Mountain area in northern New Mexico (Swetnam and Lynch 1993). Figures 4E and 4F show the corresponding winter high and low growth composites. The series of maps reveals that high and low tree growth at the two localities are associated with two totally different large-scale prior-winter circulation patterns. In Oregon, growth is enhanced by lower-than-normal 500 mb pressure heights over the Gulf of Alaska. This pattern entrains anomalous southwesterly flow into central Oregon from the Pacific Ocean. The pattern is aided by a strong ridge of high pressure to the south. The composite winter map for high-growth years depicts essentially the same pattern, showing that the extremes in the record are not responding to a different or rare circulation pattern. The composite for low growth years shows an inverse of the correlation field pattern, with lower-than-normal 500 mb pressure situated off Southern California, reflecting a southerly displaced storm track.

The correlation and composite maps for northern New Mexico depict a circulation pattern that is almost the inverse of the Oregon site. High growth is correlated with a belt of North Pacific Ocean lower-than-normal 500 mb heights that spills over into the Southwest (Fig. 4D). The high growth composite map displays an even more intense 500 mb low off Baja California as the contributor of anomalous flow from the tropical eastern North Pacific Ocean (Fig. 4E). Low growth years are dominated by the inverse of this pattern, a strong ridge over the lower Southwest (Fig. F). This simple analysis indicates that the concept of "circulation response patterns," which are developed for key seasons related to tree growth, may be an effective method to link tree-ring chronologies to circulation patterns.

Summary and Conclusions

In our overview of synoptic climatology and dendroclimatology we found that the two subfields have had parallel development and maintain a strong interconnection, each field enhancing the other with new insights and approaches. We suggest that this mutual advancement continue as a subfield

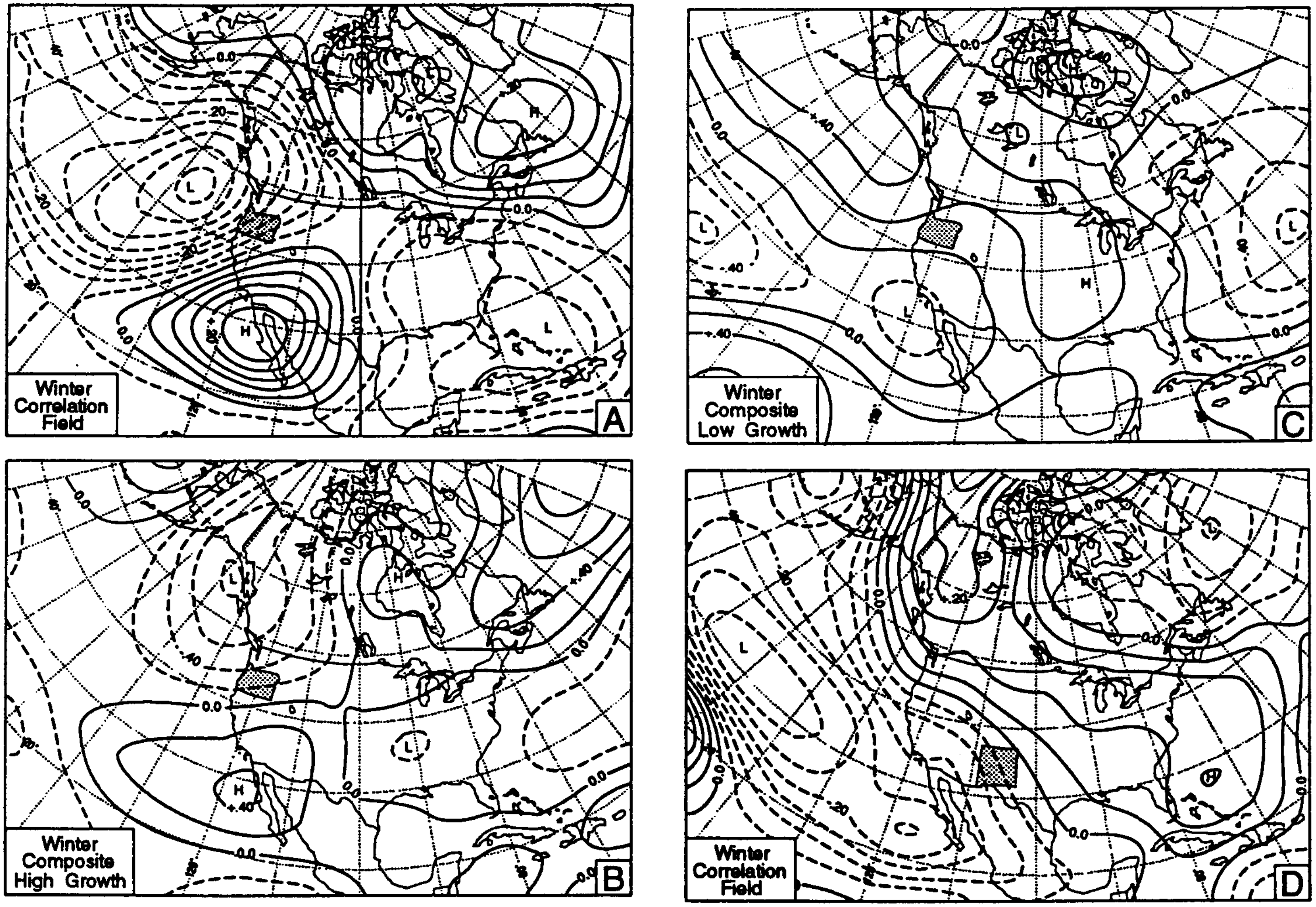

Fig. 4. "Circulation response patterns" (based on 500 mb geopotential height) for two different tree-ring localities having a sensitivity to winter climate. A. Winter (Dec.–Feb.) correlation field for a tree-ring chronology in central Oregon. Units are correlation coefficients (based on period 1947–1982)); B. composite anomaly map of the five winters with the highest ring-width indices in the chronology. Units are standardized anomalies; C. as in B, but for the five winters with the lowest ring-width indices in the chronology; D. correlation field as in A, but for an average chronology of seven sites in northern New Mexico (based on period 1947–1986).

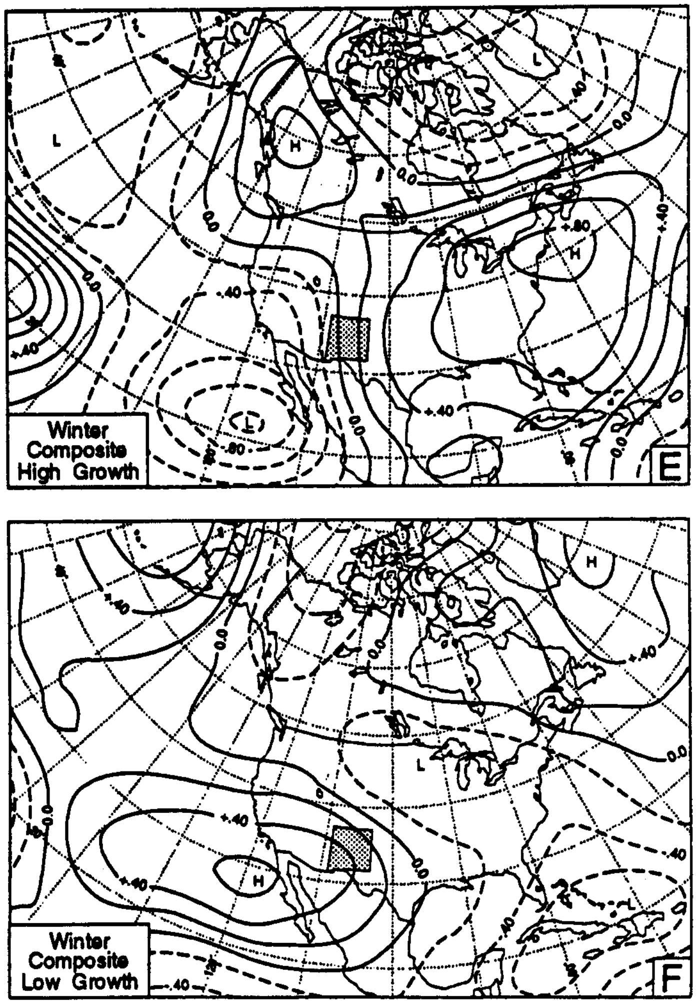

Fig. 4. E. Composite for high-growth years, as in B; F. composite for low-growth years, as in C.

that we call synoptic dendroclimatology. The goal of this subdiscipline is to use dated tree rings to study and reconstruct present and past climate from the viewpoint of the climate's constituent weather components and the way in which these components are related to atmospheric circulation at all scales. Researchers using this approach will seek to define a direct process-based connection between the large-scale circulation and ring-width variation at a local site. It is this critical link that often has been missing in many of the standard dendroclimatic analyses and climate reconstructions. One way to bridge this gap is to develop companion analyses that can identify the cascade of linkages from larger to smaller scales of circulation and relate these processes to local and regional tree-growth response to climate. Our three feasibility studies demonstrate that it is possible to relate components of the circulation to tree-ring chronologies in diverse ways that are tailored to the specific research question at hand. We believe that greater attention to climate's constituent synoptic weather components and the scales at which these components operate will improve our ability to interpret and evaluate the reconstructions of climate that are central to dendroclimatology. Furthermore, the value of this approach may extent well beyond dendroclimatology. With a process-based understanding as the unifying thread, we should be able to combine and integrate many different proxy climate data sources and gain an even better understanding of the nature of past climate variations.

Acknowledgments

Dave Meko and Tom Swetnam kindly provided tree-ring data for the Frederick's Butte, Oregon and Jemez Mountain, New Mexico chronologies, respectively. Janice Lough contributed exceptionally thoughtful review comments and suggestions. This research was funded in part by the Department of Energy, Western Regional Center (WESTGEC) of the National Institute for Global Environmental Change (NIGEC) Grant #92-020.

References

Baillie, M. G. L. and Munro, M. A. R. 1988 Irish tree rings, Santorini and volcanic dust veils. *Nature* 332: 344–346.

Barry, R. G. and Perry, A. H. 1973 *Synoptic Climatology, Methods and Applications*. London, Methuen: 555 p.

Blasing, T. J. and Fritts, H. C. 1976 Reconstructing past climatic anomalies in the North Pacific and Western North America from tree-ring data. *Quaternary Research* 6: 563–579.

Boninsegna, J. A. 1992 South American dendroclimatological records. *In* Bradley, R. S. and Jones, P. D., eds., *Climate Since A.D. 1500*. London, Routledge: 446–462.

Bradley, R. S. and Jones, P. D., eds. 1992 *Climate Since A.D. 1500*. London, Routledge: 679 p.

Briffa, K. R., Jones, P. D., Wigley, T. M. L., Pilcher, J. R. and Baillie, M. G. 1986 Climate reconstruction from tree rings: Part 2, spatial reconstruction of summer mean sea-level pressure patterns over Great Britain. *Journal of Climatology* 6: 1–15.

Cleaveland, M. K. and Duvick, D. N. 1992 Iowa climate reconstructed from tree rings, 1640–1982. *Water Resources Research* 28 (10): 2607–2615.

D'Arrigo, R. D., Cook, E. R., Jacoby, G. C. and Briffa, K. R. 1994 NAO and sea surface temperature signals in tree-ring records from the North Atlantic sector. *Quaternary Science Reviews* 12: 431–440.

D'Arrigo, R. D. and Jacoby, G. C. 1991 A 1000-year record of winter precipitation from northwestern New Mexico, USA: A reconstruction from tree-rings and its relation to El Niño and the Southern Oscillation. *The Holocene* 1(2): 95–101.

____1992 A tree-ring reconstruction of New Mexico winter precipitation and its relation to El Niño/Southern Oscillation events. *In* Diaz, H. F. and Markgraf, V., eds., *El Niño: Historical and Paleoclimatic Aspects of the Southern Oscillation*. Cambridge, Cambridge University Press: 243–257.

D'Arrigo, R. D., Jacoby, G. C. and Cook, E. R. 1992 Impact of recent North Atlantic anomalies on surrounding land areas based on dendroclimatic evidence. *Geophysical Research Letters* 19(23): 2321–2324.

Diaz, H. F. and Markgraf, V., eds. 1992 *El Niño: Historical and Paleoclimatic Aspects of the Southern Oscillation*. Cambridge, Cambridge University Press: 476 p.

Douglas, A. V. (ms.) 1976 Past air-sea interactions over the eastern North Pacific Ocean as revealed by tree-ring data. Ph.D. dissertation, University of Arizona, Tucson, Arizona: 196 p.

Fritts, H. C. 1965 Tree-ring evidence for climatic changes in western North America. *Monthly Weather Review* 93 (7): 421–443.

____1976 *Tree Rings and Climate*. London, Academic Press: 567 p.

____1991. *Reconstructing Large-Scale Climatic Patterns from Tree-Ring Data*. Tucson, Arizona, The University of Arizona Press: 286 p.

Fritts, H. C., Blasing, T. J., Hayden, B. P. and Kutzbach, J. E. 1971 Multivariate techniques for specifying tree-growth and climate relationships and for reconstructing anomalies of paleoclimate. *Journal of Applied Meteorology* 10: 845–864.

Harman, J. R. and Winkler, J. A. 1991 Synoptic climatology: Themes, applications and prospects. *Physical Geography* 12: 220–230.

Harrington, C. R., ed., 1992 *The Year Without a Summer? World Climate in 1816*. Ottawa, Canadian Museum of Nature: 576 p.

Hughes, M. K. and Brown, P. M. 1992 Drought frequency in central California since 101 B.C. recorded in giant sequoia tree rings. *Climate Dynamics* 6: 161–167.

Hupp, C. R. 1987 Botanical evidence of floods and paleoflood history. *In* Singh, V. P., ed., *Regional Flood Frequency Analysis*. Dordrecht, D. Reidel: 355–369.

Johnson, S. R. and Young, D. R. 1992 Variation in tree ring width in relation to storm activity for Mid-Atlantic barrier island populations of *Pinus taeda*. *Journal of Coastal Research* 8(1): 99–104.

Kelly, P. M., Munro, M. A. R., Hughes, M. K. and Goodess, C. M. 1989 Climate and signature years in west European oaks. *Nature* 340(6228): 57–60.

LaMarche, V. C., Jr., and Fritts, H. C. 1971 Anomaly patterns of climate over the western United States, 1700–1930, derived from principal component analysis of tree-ring data. *Monthly Weather Review* 99(2): 138–142.

LaMarche, V. C., Jr. and Hirschboeck, K. K. 1984. Frost rings in trees as records of major volcanic eruptions. *Nature* 307: 121–128.

Leathers, D. J., Yarnal, Brent and Palecki, M. A. 1991 The Pacific/North American teleconnection pattern and United States climate. Part I: Regional temperature and precipitation associations. *Journal of Climate* 4: 517–528.

Lough, J. M. and Fritts, H. C. 1985 The Southern Oscillation and tree rings: 1600–1961. *Journal of Climate and Applied Meteorology* 24: 952–966.

____1987 An assessment of the possible effects of volcanic eruptions on North American climate using tree-ring data, 1602 to 1900 A.D. *Climatic Change* 10: 219–239.

____1990 Historical aspects of El-Niño/Southern Oscillation – Information from tree rings. *In* Glynn, P. W., ed., *Global Ecological Consequences of the 1982–83 El-Niño–Southern Oscillation*. Elsevier Oceanography Series 52. Amsterdam, Elsevier: 285–321.

Lough, J. M., Fritts, H. C. and Wu, Xiangding 1987. Relationships between the climates of China and North America over the past four centuries: A comparison of proxy records. *In* Duzheng, Y., Congbin, F., Jiping, C. and Yoshino, M., eds., *The Climate of China and Global Climate*. Beijing, China Open Press: 89–105.

McCord, V. A. S. (ms.) 1990 Augmenting flood frequency estimates using flood-scarred trees. Ph.D. dissertation, The University of Arizona, Tucson, Arizona: 182 p.

Meko, D. M. 1992 Spectral properties of tree-ring data in the United States Southwest as related to El Niño/Southern Oscillation. *In* Diaz, H.F. and Markgraf, V., eds., *El Niño: Historical and Paleoclimatic Aspects of the Southern Oscillation*. Cambridge: Cambridge University Press: 227–241.

Meko, D., Cook, E. R., Stahle, D. W., Stockton, C. W. and Hughes, M. K. 1993 Spatial patterns of tree-growth anomalies in the United States and Southeastern Canada. *Journal of Climate* 6(9): 1773–1786.

Michaelsen, J. 1989 Long-period fluctuations in El Niño amplitude and frequency reconstructed from tree-rings. *In* Peterson, D. H., ed., *Aspects of Climate Variability in the Pacific and Western Americas*. Geophysical Monographs 55. Washington, D.C., American Geophysical Union: 69–74.

Mooley, D. A. and Shukla, J. (ms.) 1987 Characteristics of the westward-moving summer monsoon low pressure systems over the Indian region and their relationship with the monsoon rainfall. Submitted to the Center for Ocean-Land-Atmosphere Interactions: 203 p.

Rasmussen, E. M. and Carpenter, T. H. 1982 The relationship between eastern equatorial Pacific sea surface temperature and rainfall over India and Sri Lanka. *Monthly Weather Review* 111: 517–528.

Scott, P. A., Fayle, D. C. F., Bentley, C. V. and Hansell, R. I. C. 1988 Large-scale changes in atmospheric circulation interpreted from patterns of tree growth at Churchill, Manitoba, Canada. *Arctic and Alpine Research* 20(2): 199–211.

Stahle, D. W. (ms.) 1990 The tree-ring record of false spring in the southcentral USA. Ph.D. dissertation, Arizona State University, Tempe, Arizona: 272 p.

Stahle, D. W. and Cleaveland, M. K. 1992 Reconstruction and analysis of spring rainfall over the southeastern U.S. for the past 1000 years. *Bulletin of the American Meteorological Society* 73(12): 1947–1961.

____1993 Southern Oscillation extremes reconstructed from tree rings of the Sierra Madre Occidental and Southern Great Plains. *Journal of Climate* 6: 129–140.

Stockton, C. W. 1990 Climatic, hydrologic and water supply inferences from tree rings. *Civil Engineering Practice* 5(1): 37–51.

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

Swetnam, T. W. and Lynch, A. M. 1993 Multicentury, regional-scale patterns of western spruce budworm outbreaks. *Ecological Monographs* 63(4): 399–424.

Villalba, R. 1990 Latitude of the surface high-pressure belt over western South America during the last 500 years as inferred from tree-ring analysis. *In* Rabassa, J., ed., *Quaternary of South America and Antarctic Peninsula*. Rotterdam, A.A. Balkema: 273–303.

Villalba, R., Holmes, R. L. and Boninsegna, J. A. 1992 Spatial patterns of climate and tree growth variations in subtropical northwestern Argentina. *Journal of Biogeography* 19: 631–649.

Wallace, J. M. and Gutzler, D. S. 1981 Teleconnections in the geopotential height field during the Northern Hemisphere winter. *Monthly Weather Review* 109: 784–812.

Woodhouse, C.A. 1993 Tree-growth response to ENSO events in the central Colorado Front Range. *Physical Geography* 14: 417–435.

Wu, Xiangding and Lough, J. M. 1987 Estimating North Pacific summer sea-level pressure back to 1600 using proxy climate records from China and North America. *Advances in Atmospheric Sciences* 4(1): 74–84.

Yarnal, Brent 1993 *Synoptic Climatology in Environmental Analysis, A Primer*. London, Belhaven Press: 195 p.