Climate Impacts to Forest Ecosystem Processes: Douglas-fir Growth in Northwestern U.S. Mountain Landscapes and Area Burned by Wildfire in Western U.S. Ecoprovinces

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Abstract

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Jeremy S. Littell

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Climate plays an important role in the structure and function of forest ecosystems on seasonal to evolutionary time scales and on local to planetary spatial scales. The supply of water and thermal energy can both facilitate and limit the rates of important processes throughout the ecological hierarchy. In this dissertation, I demonstrate a combination of appropriate scale and gradient-based inquiry for two studies of climate impacts to ecosystem processes in the western U.S.A: the area burned by fire in western ecoprovinces and the growth of Douglas-fir (*Pseudotsuga menziesii*) in northwestern mountain landscapes. First, I present relationships between the area burned by fire and climate for the period 1916-2003 in the western U.S.A. I use a novel reconstruction technique to backcast late-20th century datasets and show that the area burned by wildfire in the West was significantly controlled by climate for the full period. Persistent, ecosystem-specific correlations between climate variables and area burned are grouped by vegetation type for 16 ecoprovinces across the West. For the period 1977-2003, between 33 and 87 percent (mean 64 percent) of the variability in ecoprovince area burned could be explained by a few significant climate variables. For the period 1916-2003, between 25 percent and 57 percent (mean 39 percent) of the total variability could be accounted for with climate. In both cases, precipitation variables were more important than temperature. The relationship between the mean and the variance for area burned exhibits a gamma distribution for independent data sets and different spatial scales of fire data. Second, I developed a network of Douglas-fir tree-ring chronologies from the western Olympic Peninsula in Washington to the eastern Rocky Mountain Front in Montana. Annual radial growth in 60-65% of the plots across the entire region is significantly correlated with variables describing precipitation, drought or water balance during the late summer prior to growth and the early summer the year of growth. Few plots are significantly positively correlated with cool-season temperature or negatively correlated with snowpack. Water availability is therefore more commonly limiting to Douglas-fir growth than factors influencing the length of the growing season.

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To my field crews in the summers of 2003 and 2004, there is no other word but burly. You went above (the uphill total, for recon and sampling, is about 37,000 vertical meters) and beyond (840 kilometers) and you did it cheerfully and accurately, whatever the weather or the terrain. Your strong wills will not be forgotten: Mike Tjoelker, Michael Case, Melissa Hornbein, Sean Hill, Sarah Gobbs, Spencer Wood, Carson Sprenger, and Alex Karpoff. I owe Mike Tjoelker especially for his unwavering assistance in the tree-ring lab; remember that not ALL those rings were mine.

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Seattle, WA
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DEDICATION

This dissertation is dedicated to three people, each of whom contributed to the
foundation I relied upon, and at times, dug into deeply, during the last four years.

First, to my wife Allene Whitney, who shared the hazards and rewards of my research
while also negotiating, with grace and skill, a medical residency and fellowship.
It appears that the silver bus still starts up and totters down the road when it’s needed.
I am grateful.
One way or the other, all bleeding eventually stops, right?

Next, to my father, Jim Littell, who encouraged me, by example, to develop the tools of
a scientist: curiosity, skepticism, analytical precision, and objectivity. I do not still have
the microscope, the telescope, or the precision compass,
but I rely on the other tools daily.
Might as well do it right the first time.

Finally, to my mother Susan Littell Fox, who encouraged me to read widely, pay
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very, very determined.
It took me awhile, but I’m getting there.

CHAPTER 1:

COMPLEXITY AND CLIMATE MEDIATION OF ECOSYSTEM PROCESSES: BARRIERS TO CLIMATE IMPACTS RESEARCH IN FOREST ECOSYSTEMS

Introduction: Climate Impacts to Ecological Processes

Climate plays an important role in the structure and function of forest ecosystems on seasonal to evolutionary time scales and on local to planetary spatial scales. The supply of water and thermal energy can both facilitate and limit the rates of important processes throughout the ecological hierarchy. From plant photosynthesis (and, integrated over space and time, ecosystem productivity) to community assembly and disassociation to variation in landscape pattern, climate acts on the physiological processes, life history outcomes, environmental structures, and disturbances that produce characteristic ecological patterns. The impacts of climate change on a particular ecosystem, process, or species are the summation of these effects in the context of complicated, interacting factors characteristic of ecology. Adapting to and, when possible, mitigating the impacts of climate change on ecosystems is the purview of ecosystem management.

If it is possible to manage ecosystems, the success and long-term viability of management efforts are directly dependent on predictions of ecological responses to future climate change and characterization of the uncertainty of those predictions. Because ecosystem management is a multi-scale, multi-agency, multi-objective endeavor, synthesis of scientific results over space, time, and management objective is necessary to develop a scientific basis for decision making, but the complexity of such synthesis is daunting. In this introductory chapter, I describe some barriers to effective prediction and synthesis of the impacts of climate change to forest ecosystem processes. I then identify some concepts to dissolve or circumvent those barriers. Finally, I briefly describe the resulting conceptual model and its implementation in two studies of climate impacts to ecosystem processes in the West that form the core of this dissertation.

Barriers to Ecosystem Management: Complexity, Prediction, and Uncertainty

The goal of ecosystem management is to ensure the sustainability of ecosystem services. Ecosystem services (such as native species habitat, water supply, and timber) are derived from multiple levels of ecological hierarchy, and effective strategies for sustaining them depend on synthesizing diverse research and data to make predictions about the effects of future climate change across the those levels. However, such synthesis is difficult because the complexity of predicting future climate and associated forest ecosystem responses results in substantial uncertainty. This is especially true for forecasts of ecological responses many years to decades in the future. Unfortunately, these are precisely the time scales that parallel the operational horizons of public agencies charged with land management. The consequences of poor planning or poorly-integrated scientific findings may be benign or severe given the unknown sensitivities and potentially long-term impacts associated with climate.

The key to minimizing these consequences is maximizing predictive capability and minimizing uncertainty. Predictive uncertainty in climate impacts science can arise from several sources. Future climate predictions from global or regional climate models have a range of uncertainty associated with ranges of assumptions about forcing factors (such as anthropogenic greenhouse gas emission, human population, or natural feedback responses to warming that has already occurred) as well as uncertainty that arises from incomplete understanding of the natural dynamics of the climate system (for example, the sensitivity of the climate system to the combined natural and human perturbations). Forecasts of ecological responses to future climate therefore also have a range of uncertainty, dependent on the uncertainty in the climate models, as well as uncertainty associated with the ecological responses in question.

In this chapter, I am chiefly concerned with the mechanisms that lead to this latter source of uncertainty and developing conceptual models of climate impacts to forest ecosystems that minimize it. I posit that the predictive uncertainty in climate impacts to ecological processes comes from two primary sources that can be effectively mitigated.

First, there is often a scale mismatch between the ecological process we would like to predict and the climatic mechanisms we view as drivers of the process. The multi-scale nature of climate presents a barrier to ecological prediction because plants necessarily experience local climates, but local climate is a function of a hierarchical set of processes and influences from global to local. There is a disconnect between the hemispheric and planetary scales at which characteristics of the climate system operate, the continental and regional scales at which physiography and topography mediate regional climate, and the scales at which plants directly respond to local climate. This is because the controls on both climate and plant processes (such as growth) are scale-dependent and translations of climate observations from one scale to another do not always neatly covary with translations of ecological observations from one scale to another. Climate is neither completely deterministic nor completely stochastic with respect to ecosystems. There is therefore an important problem in climate change biology that stems directly from the scale mismatch between climate and its impacts on ecosystems. We have a need, driven by forecasting and prediction applications for ecosystem management, to integrate observations and measurements across scales, but the data we have was not sampled or analyzed with the intent to impute across the scales necessary to bridge the gap between the scale of sampling and the scale of prediction. Preemptively accounting for the multi-scale nature of climate and ecological response in observational sampling design could reduce predictive uncertainty substantially and bridge the gap between correlative and predictive approaches. Alternatively, constraining these sources of uncertainty for the purposes of synthesis of existing research may also be possible.

Second, ecological processes are characteristically complex, both independently and because of the hierarchical nature of climate. Ecological processes do not lend themselves easily to synthesis across scales precisely because they are complex. Forest ecosystems can be defined as “complex” because they are often characterized by scale-dependence, non-linear responses, thresholds, and time lags. The scales at which we can make strong, quantitative predictions about climate impacts to forest ecosystem processes have, with some exceptions, focused on the highly local and the highly general. Often, it is possible to make very detailed local measurements repeatedly or to make global measurements of a process for short periods, but in between, the interplay between local-to-regional controls on the process in question results in difficulty measuring and analyzing responses to climate. Non-linear responses also complicate prediction because a small change in a variable can sometimes produce a large change in the observed response. Therefore, unless the full spectrum of a process can be observed, extrapolation from a linear relationship can be hazardous if a threshold (step-function) or non-linear relationship describes the process over a larger domain. Time lags are also important in predicting ecosystem responses to climate change because the main impacts of a change in a variable can be delayed or spread out over longer time periods. Historical changes can have long-persisting impacts, and the inertia in ecosystems renders prediction difficult because systems are sometimes buffered against a change we would otherwise predict because of a historical artifact, such as the presence or absence of a species or a chance disturbance. The uncertainty associated with such complexity must be minimized for future predictions of climate impacts to have credibility and utility in ecosystem management. By recognizing *a priori* the complex nature of ecological processes and adapting research approaches to complex sources of uncertainty, more robust and widely applicable predictions of climate impacts may be possible.

If a goal of climate impacts science is to provide scientific information for ecosystem management, then it is necessary to address the barriers to prediction, estimating uncertainty, and synthesis in research approaches. The most important barriers are:

- For purposes of climate impacts to ecological processes, the climate system is multi scale
- Processes likely to be important for ecosystem management are meso-scale, yet ecological studies tend to occur at very local scales or very broad scales
- Ecological processes tend to be complex

These barriers can be addressed in a three-fold approach to sampling (or, in the case of synthetic studies, re-scaling via combinations of models and observations) the observational data required to answer the question of interest. First, the influence of climate on the process of interest must necessarily be measured at an appropriate scale, and the spatially nested influences on the local manifestation of climate must be considered at appropriate time scales. For example, despite the quasi-predictive utility of persistent ocean/atmosphere interactions (such as El Nino or the Pacific Decadal Oscillation), from a climate impacts perspective, it is much more profitable to focus on the causal mechanisms relating climate and ecosystem processes because these allow future forecasting in response to either climate derived from climate models or climate derived from modes of decadal climate variability as well as their combinations. Second, by sampling and analyzing climate impacts along the full range of climate conditions to which a process of interest is subjected, non-linear and threshold relationships can be discovered if they exist. Such processes provide good leverage on prediction when they exist, so sampling in a manner that can detect them is paramount. Third, by sampling along gradients of limiting factors at multiple scales associated with controls on local climate, the hierarchical nature of climate impacts to ecosystem processes can be partitioned into appropriate scales of influence and, hence, prediction.

In each of the following chapters, I investigate the impacts of climate on an ecosystem process using these concepts. In Chapter 2, I demonstrate the combination of appropriate scale and gradient-based inquiry in a synthetic study of fire and climate that relies on a meso-scale reconstruction of area burned from two datasets. I develop seasonal climate indices from constituent climate divisions and relate them to the annual area burned by fire for 16 vegetation-based ecoprovinces in the western U.S. These ecoprovinces span the full range of climatic and vegetation conditions in the western U.S. and provide a unique opportunity to assess the role of climate in controlling wildfire are at large spatial scales and in different vegetation types. In Chapter 3, I show how these concepts can be used from the inception of a research project to generate sampling methodology that is capable of true multi-scale climate impacts research. To understand the climatic controls on Douglas-fir growth across the northwestern U.S., I rely on a combination of nested gradient sampling that allows correlations between two scales of 20th century climate estimates and a gradient-based network of tree-ring chronologies. Finally, in Chapter 4, I evaluate the benefits (and hazards) of both the synthetic approach (fire study) and the multi-scale sampling approach (tree-growth study) for studying climate impacts to forest ecosystems in the western U.S.

CHAPTER 2:
CLIMATE AND AREA BURNED BY FIRE IN ECOPROVINCES OF THE WESTERN U.S., 1916-2003

Summary

In this chapter, I present relationships between the area burned by fire and climate for the period 1916-2003 in the western U.S.A. I use a novel reconstruction technique to backcast late-20th century datasets and show that the area burned by wildfire in the American West was significantly controlled by climate for the full period. Persistent, ecosystem-specific correlations between climate variables and area burned are grouped by vegetation type for 16 ecoprovinces across the West. Most mountainous ecoprovinces exhibit strong log-linear year-of-fire relationships with anomalously low precipitation, low PDSI, and high temperature. Many grass/shrub dominated ecoprovinces have stronger positive relationships with antecedent precipitation/PDSI. Some ecoprovince reconstructions are sensitive to different climate variables for the 1977-2003 period than the 1916-2003 period, indicating that correlations between some climate variables in wildfire area burned (WFAB) are not stationary through the whole 20th century. For the period 1977-2003, between 33 and 87 percent (mean 64 percent) of the variability in ecoprovince WFAB could be explained by a few significant climate variables. For the period 1916-2003, the relationships are weaker, but between 25 percent and 57 percent (mean 39 percent) of the total variability could be accounted for with climate. I also found that the relationship between the mean and the variance for WFAB repeatedly exhibits a gamma distribution for independent data sets and different spatial scales of fire data. This relationship provided significant leverage in reconstructing WFAB in more southerly and more arid ecoprovinces. I hypothesize that the log of the variance is universally proportional to the mean squared for WFAB, and that the mechanism leading to the gamma distribution is connected to the climate-vegetation interactions that lead to fuel drying and production. These results suggest that, despite the influence of fire suppression efforts, WFAB is still substantially controlled by climate and that some ecoprovinces have stronger climate controls on WFAB than others. At ecoprovince scales, seasonal climate is sufficient to explain a significant fraction of the variance in

WFAB, although the specific climate mechanisms vary with ecosystem vegetation in the ecoprovinces. The importance of antecedent climate (especially summer drought in forested ecosystems and higher antecedent winter precipitation in shrub and grassland ecosystems) indicates that the observed fire-climate relationships represent climatically-driven contingencies that precondition large areas of homogeneous low fuel moisture. The implications for future planning and management in natural resource and ecosystem management are that future WFAB will likely depend on ecosystem-specific, seasonal variation in climate-fire sensitivities and potentially on shifts in characteristic mean-variance relationships for ecoprovinces. The impacts of future climate change on WFAB are likely to be ecoprovince specific.

Introduction

The area burned annually by wildfire in the western United States (U.S.) influences policy decisions and future land-use agendas of public land management agencies. Capped by a string of years with large areas burned between 2000 and 2004 (National Interagency Fire Center 2005), the nation-wide area burned on federal agency lands gradually increased since the mid 1970s (Agee 1997). Suppression costs incurred by all agencies have approached or exceeded one billion dollars (U.S.) in recent years (Calkin et al. 2005, NIFC 2005). These trends have led to speculation that fire suppression caused increasing fire area by producing unprecedented fuel accumulations across the West. However, this assumption is complicated by the fact that fires and fire regimes are products of interacting factors other than suppression operating at multiple spatial and temporal scales (Keeley et al. 1999, Johnson et al. 2001, Bridge et al. 2005, Cumming 2005). Indeed, from an ecological standpoint, the annual area burned by fire across the western U.S. has little meaning, because a diversity of natural fire regimes, vegetation types, and fire severities produces a broad range of ecological responses to a given area burned. It is therefore difficult to assign terms such as ‘unprecedented’, ‘catastrophic’, or ‘unnatural’ to fire years based on area burned without a meticulous accounting of the ecological severity (*sensu* Romme 1980, Agee 1993) and ecosystem context (vegetation type, natural fire regime, fire suppression history, and impact on ecosystem services) of each fire contributing to the annual total.

The importance of attributing causal mechanisms to the increase in fire area burned during the latter 20th century is underscored by the size of recent fires, the cost associated with suppressing them, and the ecological effects that federal land managers face in responding to climate change, future fires, and their impacts to natural resources. If the predominant factor driving area burned is fire hazard associated with fuel structure, the role of climate must be understood in order to weight the importance of mitigation (e.g., fuels) and adaptation (e.g., to the less tractable impacts of climate).

Considerable research has focused on mechanisms forcing interannual variability in wildland fire area burned (WFAB) in the conterminous Western states. While the decline and subsequent increase in annual West-wide WFAB fits timelines of supposedly more effective fire suppression and ubiquitous fuel accumulation (Agee 1993, Pyne 1997), the combined influence of climate, vegetation, land use, and land management is likely a strong contributor to total variation in WFAB, with regional and local differences in the relative influence of these factors producing the aggregated response (Stephens 2005). It is also likely that not all ecosystems with increasing WFAB trends have increased fuel accumulation caused by fire exclusion, especially when the time frame of effective fire exclusion approximates or is less than the range of return intervals characteristic of fire regimes (Johnson et al. 2001, Shoennagel et al. 2004).

Fire history evidence from diverse climate regimes and forest types suggests fire regimes prior to Euro-American settlement, fire suppression and fire exclusion were strongly related to climate (Swetnam 1990, Larsen 1996, Barrett et al. 1997, Swetnam and Betancourt 1998, Veblen et al. 2000, Brown and Sheppard 2001, Heyerdahl et al. 2002, Taylor and Skinner 2003, Weisberg and Swanson 2003, Brown et al. 2005, Hessl et al. 2005). These pre-settlement fire histories demonstrate a strong correlation between low precipitation and years of widespread fire, consistent with a regional depletion of soil moisture that leads to low foliar moisture and the potential for widespread fire (Swetnam and Betancourt 1998). Some fire histories in the American Southwest also demonstrate a lagged relationship with above-average antecedent precipitation (Swetnam and

Betancourt 1998) and/or cooler temperatures (Veblen et al. 2000) the year(s) prior to years of widespread fire. It has been suggested that the observed relationship is caused by anomalously low temperatures and high precipitation that mitigate the climatic constraints on fine fuel production (Knapp 1995, Swetnam and Betancourt 1998), resulting in higher fine-fuel continuity that leads to an increased potential for widespread fire if subsequent years are dry. Years of widespread fire in fire histories appear positively related to increased antecedent precipitation (Swetnam and Betancourt 1998) but it is often difficult, especially in ecosystems that are not likely to be fuel limited, to determine if this is a real climate forcing on fire activity, an artifact of low sample size, the autocorrelated nature of climate reconstructions, or a combination of several factors.

During the late 20th century, WFAB on federal lands (U.S. Department of Agriculture Forest Service (USFS), U.S. Department of Interior Bureau of Land Management (BLM), National Park Service (NPS), and Bureau of Indian Affairs (BIA)), was related to monthly Palmer Drought Severity Index (PDSI), and the sign and magnitude of the relationships were quite consistent with those in the fire history record (Westerling et al. 2003). The additional temporal precision allowed by monthly observed climate and WFAB records also suggested region-specific, seasonal mechanisms stemming from latitudinal and altitudinal differences in ecosystem structure and the onset of the fire season (Westerling et al. 2003), and these relationships were strong enough to produce PDSI-based forecasts of WFAB. These relationships were then hindcast (Westerling and Swetnam 2004) using reconstructed PDSI. However, the lack of complete digitzed data for all agencies prior to 1980 hindered climate-specific analyses extending further back in the 20th century.

WFAB data from a variety of sources have been aggregated annually since 1916 at the state level, first from U.S. Forest Service and Department of Interior “Smokey Bear” reports and later from archived information at the National Interagency Fire Management Integrated Database. These records, while spatially and ecologically imprecise, span much of the 20th century, and have allowed analyses of longer-term WFAB-climate relationships. McKenzie et al. (2004) constructed linear regression models of the state-level WFAB as a function of summer (JJA) temperature and precipitation in 11 western states: Arizona (AZ), California (CA), Colorado (CO), Idaho (ID), Montana (MT), New Mexico (NM), Nevada (NV), Oregon (OR), Utah (UT), Washington (WA), and Wyoming (WY). These relationships were strong enough to develop hypotheses about the future area burned for each state given future climate scenarios, and made significant progress towards a mechanistic understanding of the independent and combined role of precipitation and temperature in years of large WFAB.

Synoptic climatology during the fire season is ultimately the proximate driver of fire weather and, along with topography, fuels, and general ecological structure affects the area burned by a given fire event. The role of atmospheric patterns in large fires has been well described in both Canada (Flannigan and Harrington 1988, Johnson and Wowchuck 1993, Skinner et al. 1999, Skinner et al. 2002) and the U.S. (Schroeder 1957, Schaefer 1969, Gedalof et al. 2005). The role of seasonal to interannual climate variation has received less attention, but the importance of extreme fire weather and ignitions associated with brief events is often contingent on climatic factors operating at longer time scales that influence fuel moisture and availability. In this paper, I focus more on the seasonal mechanistic relationships between precipitation, temperature, drought, and the annual area burned by fire.

Previous research has frequently focused on the relatively short-term operational time scale of fires (Gedalof et al. 2005). In this paper I focus on larger scale, longer time frame capacity for climate to precondition different ecosystem types for large WFAB. I use a novel reconstruction technique to relate the WFAB databases described above – one from Westerling et al. (2003) and one from McKenzie et al. (2004) – to reconstruct the area burned in each of 16 Bailey's ecoprovinces (Bailey 1995) (most of the western U.S.) for the period 1916-2003. I also relate the variation in these WFAB time series to their climatic influences. My approach considers the capacity of seasonality, ecosystem vegetation type, and coarse physiography to produce different results in the relationship between climate and fire by using ecoprovinces (Bailey 1995) to partition the fire response to seasonal climate (Westerling et al. 2002). This approach extends previous work by examining the relative role of precipitation, temperature, and drought as well as extending the time period of the climate-fire analysis to most of the 20th century.

My working ecological hypothesis is that the relationship between climate and fire is mediated by vegetation structure and sensitivity to moisture at the broad scales of ecoprovinces (e.g. Westerling et al. 2002); the area burned by fire in any given year is indirectly related to climate by climatic influence on fuels (e.g., Carcaillet et al. 2001). Evidence of this would be different ecoprovince WFAB sensitivities to climate that parallel the dominant, and/or distribution of, vegetation structure in an ecoprovince. Testing this hypothesis would lead to an ecosystem-specific set of climate-fire-vegetation relationships useful to land managers faced with mitigating the vulnerability of ecosystem services. Adapting to climate change will require decisions that increasingly depend on the nature of climate and fire relationships.

Methods

Study Area

I focused on the ecoprovinces in 11 Western states (AZ, CA, CO, ID, MT, OR, NM, NV, UT, WA, WY), because they contain much of the public land for which ecologically specific climate-fire relationships would be useful. Ecoprovinces (Bailey 1995, Figure 2.1) represent coarse aggregations of biophysical constraints on modern ecological assemblages, and are subsets of Köppen-Trewartha domains and divisions based on subregional vegetation characteristics with more specific climatic features. Twenty ecoprovinces are contained within the 11 states, and 19 of these are considered in this paper (Table 2.1). The Black Hills ecoprovince has a very small proportion of its area in WY and is not considered further. Western ecoprovinces are classified within Bailey's Humid Temperate and Dry domains, with representative ecoprovinces in the Humid Temperate Marine and Mediterranean divisions and Tropical/Subtropical Steppe, Tropical/Subtropical Desert, Temperate Steppe, and Temperate Desert divisions (Bailey 1995).

The mountainous terrain of the western U.S. results in mountain ecoprovinces that retain the characteristic climate regime of the surrounding lowlands but with important altitudinal zonation. Each ecoprovince therefore has a distinct suite of climate characteristics and resulting vegetation structure and composition. Mountainous

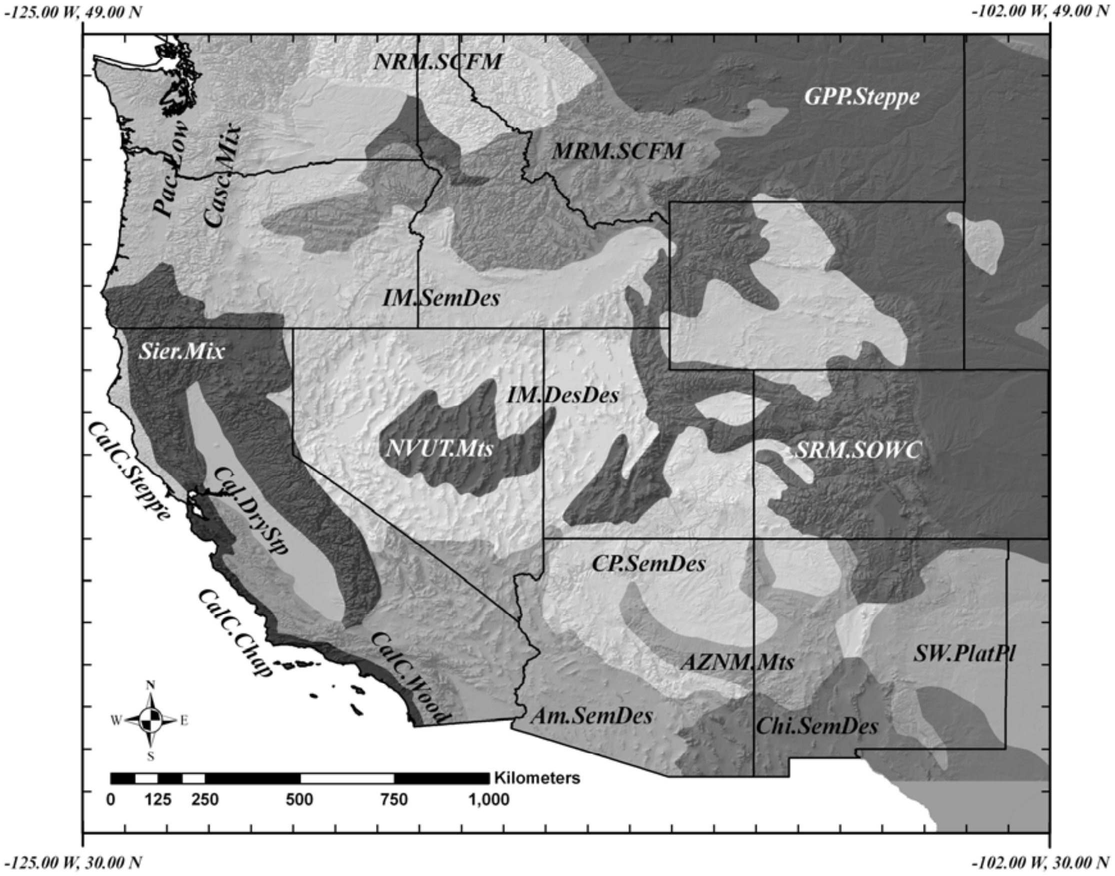

FIGURE 2.1. Ecoprovinces of the Western United States.

TABLE 2.1 Ecoprovince Area Burned Statistics 1980-2000. Calculated from gridded fire data in Westerling et al. (2003). Ecoprovinces are arranged by annual province fraction area burned.

Ecoprovince	Bailey Code	Abbreviation	1980-2000 area burned Analysis area (ha x 10^7)	Ann. mean (ha x 10^4)	Peak fire season	Prop. Ecoprov. Ann. mean (x 10^{-3})
Pacific Lowland Mixed	242	Pac.Low	0.38	0.01	Sep.-Oct.	0.02
Cal. Coastal Steppe	263	CalC.Steppe	0.12	0.02	Apr; Jul; Oct.	0.18
Ariz.-New Mex. Mts. Semi-Desert	M313	AZNM.Mts	1.30*	0.93	May – Jul.	0.72
American Semi-Desert and Desert	322	AM.SemDes	2.27	1.74	Apr.-Aug.	0.77
Cal. Dry Steppe	262	Cal.DryStp	0.50	0.42	Jul.-Sep.	0.85
Southwest Plateau / Plains Steppe	315	SW.PlatPl	0.25*	0.22	Feb-Apr.; Jun.	0.89
Colo. Plateau Semi-Desert	313	CP.SemDes	1.95	1.76	Apr.-Aug.	0.90
Great Plains-Palouse Dry Steppe	331	GPP.Steppe	3.52*	3.31	Jun.-Sep.	0.94
Cascade Mixed Forest	M242	Casc.Mix	1.38	1.95	Jul.-Aug.	1.41
Northern Rocky Mt. Forest	M333	NRM.SCFM	0.99	1.39	Jun. – Oct.	1.41
Chihuahuan Semi-Desert	321	Chi.SemDes	1.37*	2.14	May. – Jul.	1.57
South. Rocky Mt. Steppe-Forest	M331	SRM.SOWC	2.65	5.47	Jun. – Sep.	2.06
Nev.-Utah Mountains-Semi-Desert	M341	NVUT.Mts	1.13	2.39	Jun. – Aug.	2.11
Middle Rocky Mt. Steppe-Forest	M332	MRM.SCFM	2.12	8.28	Jun. - Sep.	3.91
Cal. Coast. Chaparral Forest/Shrub	261	CalC.Chap	0.27	1.07	Jul.; Sep. – Nov.	4.01
Sierran Steppe-Mixed Forest	M261	Sier.Mix	1.77	7.22	Jun. – Oct.	4.08
Intermountain Semi-Desert / Desert	341	IM.DesDes	2.77	11.46	Jun. – Sep.	4.13
Intermountain Semi-Desert	342	IM.SemDes	4.12	21.23	Jun. – Oct.	5.15
Cal. Coastal Range	M262	CalC.Wood	0.64	4.90	Apr. – Nov.	7.60

*Partial ecoprovince in analysis; some ecoprovinces exceed borders of 11 Western states from which fire data was taken.

ecoprovinces tend to have heterogeneous vegetation along an altitudinal gradient from lower elevation grasslands-shrublands / forest ecotones in valleys up through continuous montane and subalpine forest, and, in some cases, into alpine tundra. Broadly speaking, the more northern and higher elevation ecoprovinces have higher proportions of forest, and the more southern and lower elevation ecoprovinces have higher proportions of grassland and shrubland. These differences represent subregional mechanisms behind fire-regime sensitivity to climate that derive from vegetation characteristics limiting fire at seasonal and longer time scales (fuel moisture, fuel continuity) and that are different for, e.g., grasslands and forests. Aggregating vegetation types at the ecoprovince level should give a broad perspective on the sensitivity of modern fire-vegetation relationships to climate.

Primary Fire Data and Pre-treatment

I used three separate WFAB datasets for this study. First, I obtained annual area burned data for combined federal, state, and private lands (Smokey Bear reports 1916-1982, combined Department of Interior (DOI)/ United States Forest Service (USFS) reports 1983-1989 from Don Long/Dennis Simmerman, USFS Rocky Mountain Research Station-Missoula; 1990-1997 USFS fire statistics from Janice Peterson, Mount Baker-Snoqualmie National Forest; 1998-2003 USFS fire statistics from Marian Villasenor, USFS WO Fire and Aviation Management, Planning and Budget). I used an **adjusted 1916-2003 state-level time series**, corrected for the area-reporting observation bias associated with the changes in public lands administered by the USFS and DOI over the period of the 20th century (Westerling and Littell, in prep). Second, I used the **1980-2000 gridded** dataset used by Westerling et al. (2003), which includes area burned on all managed lands at 1° latitude x 1° longitude spatial resolution. Finally, Westerling (unpublished data) developed a similar product, a **1980-2003 large-fire** dataset derived from a partially complete large-fire dataset and pre-aggregated into ecoprovinces (Bailey 1995). The second and third datasets are the same areal coverage, but allowed us to update my analyses to include data from 2001-2003, a period that includes large fire activity in much of the western U.S. The duplication is also necessary because state-level data from CO, ID, MT, and NM were missing from the third dataset at the time of this analysis.

My goal was to use relationships between the long-term (1916-2003), state-level WFAB dataset and the shorter 1980-2000 gridded and 1980-2003 large-fire datasets to reconstruct a full-length (1916-2003) record of WFAB for each ecoprovince in the 11 Western states. For the 1980-2000 WFAB dataset, I projected the 1° x 1° cells onto a map of ecoprovinces and assigned each grid cell an ecoprovince membership based on simple areal majority. For the 1980-2003 WFAB dataset, fire events from the large fire database (Westerling, in prep.) were assigned to each ecoprovince and annually totaled to produce ecoprovince time series. From these, I produced annual WFAB totals in each ecoprovince for the period 1980-2000/2003 (two time series for each province).

Reconstructing Ecoprovince Area Burned: Regression Methods

I compared two regression approaches to relate the 1980-2000/2003 ecoprovince-level WFAB to the state WFAB for the same time period. The first approach assumes that the WFAB ecoprovince and state data are both distributed log-normally and are linearly related; it produces a classical least-squares linear model that predicts ecoprovince WFAB from multiple constituent state WFAB for the training period (**log-log model**). This model is then used to reconstruct the ecoprovince WFAB given the longer, state-level WFAB data. The second approach extends the log-linear assumption to include knowledge of the relationship between the mean and variance of the observed data and produces a maximum-likelihood general linear model that takes advantage of an observed gamma distribution relationship between the mean and variance of the fire area burned data (**gamma model,** Figure 2.2). This approach assumes the area burned data are still Gaussian, but as the mean increases, the variance increases non-linearly. I applied both modeling approaches to estimates of ecoprovince area burned for both the 1980-2000 grid-based and 1980-2003 large fire datasets, resulting in four candidate models for each ecoprovince.

All regressions were performed in the S+ environment (version 6.1 for Windows, Insightful Corp. 2000). For the log-log and gamma ecoprovince models, all states (and

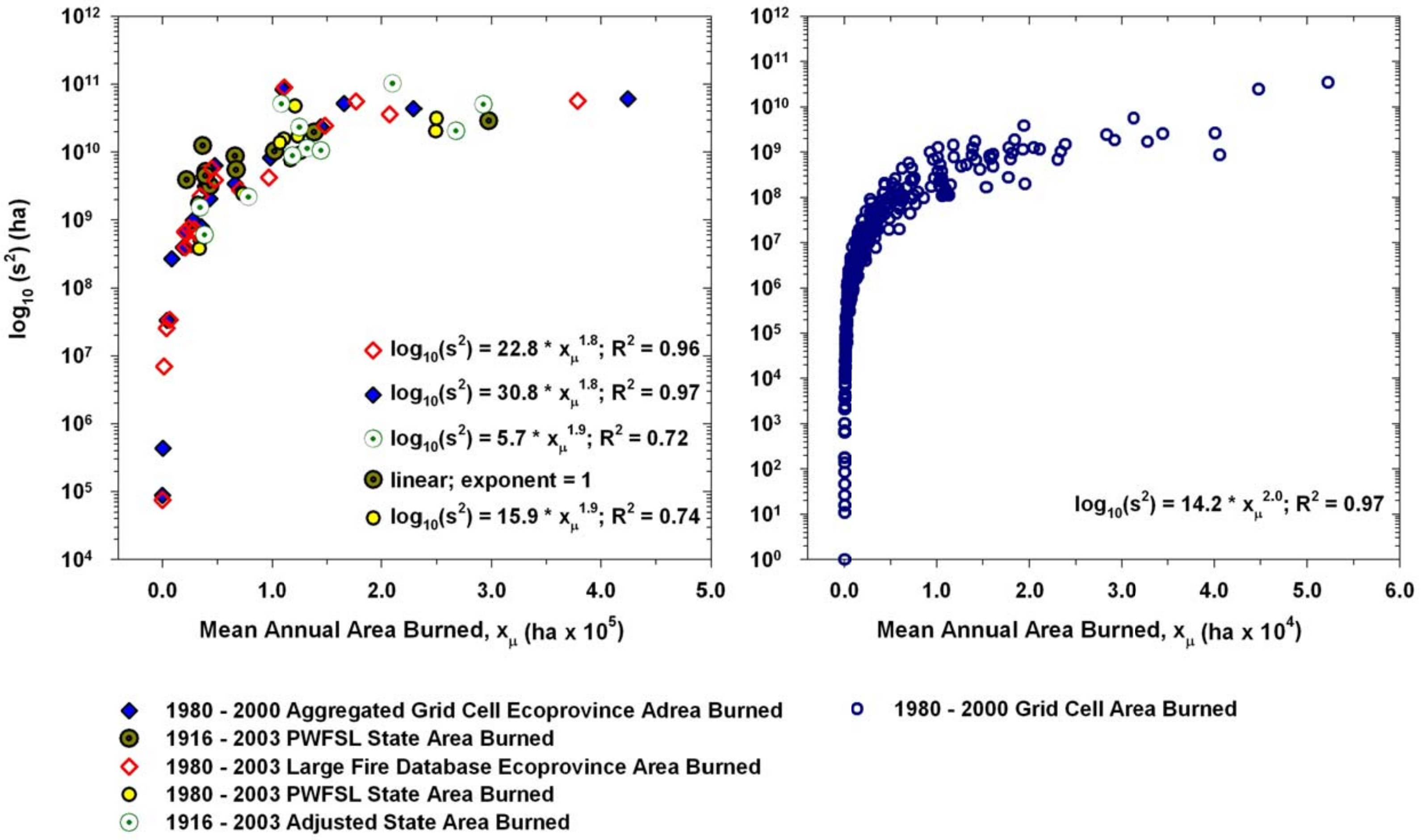

FIGURE 2.2. Relationship Between the Mean and Variance in Annual WFAB. For states and ecoprovinces (left) and lat/long gridcells (right) in the western U.S. The log of the variance is proportional to the mean squared in all datasets used for reconstruction, implying some advantage in regression-based reconstruction methods.

their interactions) with area contributing to the ecoprovince targeted for reconstruction were considered possible predictors (Figure 2.2). Both log-log and gamma strategies relied on iteratively entering and removing candidate state predictors and their interactions into the regression model. Log-log model (gamma model) predictors were considered for retention if the p-value associated with *t* was less than (greater than) 0.1. I considered all possible interaction terms (full model) and non-significant state predictors were retained if they contributed to significant interaction terms. I accepted a final model when the Akaike Information Criterion (AIC) could not be minimized further by removing or adding terms. To simultaneously cross-validate and compare the four candidate models for each ecoprovince, I calculated the predicted residual sum of squares (P.R.E.S.S.) root mean square error (RMSE) and accepted the model with the lowest P.R.E.S.S. RMSE as the reconstruction model. The P.R.E.S.S. approach to cross-validation calculates the average prediction error by iteratively leaving out each observation and re-assessing the model fit. I then used the best model to produce estimates of the 1916-2003 area burned for each ecoprovince by projecting the observed state WFAB values onto the fitted model.

Climate Data and Pre-treatment

I obtained monthly state climate-division precipitation (PPT), temperature (T), and Palmer Drought Severity Index (PDSI) data from the National Climatic Data Center (NCDC, online, accessed 02-Jun-04, Karl et al. 1986). For each ecoprovinces, I used the raw climate-division data to develop 15 seasonal climate variables I hypothesized to be likely predictors of fire area burned at the large scales of ecoprovinces: Annual (hydrological year, or Oct.-Sept.), Winter (ONDJFM), Spring (MAM), Growing Season (MJJAS), and Summer (JAS) PPT, T, and PDSI. Annual and winter variables include months (OND) from the year immediately prior to the fire year in question. Climate division areas vary greatly, and climate division boundaries are not consistent with ecoprovince boundaries, so I used an area-weighted principal components analysis (PCA) to produce a 1910-2003 time series, aggregated at the ecoprovince level, for each of the 15 climate variables. Each time series is the leading principal component derived from a

PCA on the covariance matrix produced by square-root area-weighting each climate division time series contributing to the ecoprovince (Preisendorfer 1988). This allows the desired emphasis on the common variance without the potential biased variability from mixing smaller and larger climate divisions by simply averaging the time series.

Relating Climate and Fire

I evaluated the autocorrelation in each ecoprovince climate time series and used an AIC minimization criterion to determine the best order autoregressive model (up to third order) for pre-whitening the annualized, seasonal climate time series. I used a log10 transformation for the ecoprovince fire time series due to the highly non-linear nature of the fire data; these time series did not consistently exhibit strong (lag 1, $r < 0.25$) autocorrelation. I first focused on the period 1977-2003 to describe the climate/fire relationships for ecoprovinces during the same period covered by previous studies. This period is also indicated by a continent-wide increase in mean temperature and the post-1977 changes in the influence of the Pacific Ocean on western North American climate (Trenberth 1990, Hare and Mantua 2000). The 1977 regime shift represents a significant restructuring of ocean-atmosphere relationships in the Pacific Ocean and the transition from a cool phase of the Pacific Decadal Oscillation to a warm phase (Mantua et al. 1997). I then investigated the feasibility of constructing diagnostic climate models for the full 1916-2003 period for all ecoprovinces. This period encompasses more climatic variability and provides a good basis for evaluating more recent relationships.

To broadly categorize the correlation patterns between climate and fire for each ecoprovince as well as the set of ecoprovinces comprising the western U.S., I used simple Pearson correlation analyses between each ecoprovince seasonal (year of, lag 1 and lag2) climate time series and the annual WFAB time series for that ecoprovince. My objective was to interpret common signals in climate- fire patterns, so I approached this analysis diagnostically, without correcting for the probability values associated with conducting many independent correlation analyses. I did this for both the 1977-2003 and 1916-2003 periods.

To evaluate the potentially complex interaction of different seasonal variables given ecoprovince vegetation type, I also sought diagnostic linear least-squares multiple regression models relating each ecoprovince WFAB time series (response) to a suite of pre-whitened, annualized seasonal PPT, T, and PDSI predictors. Except for the inclusion of lag climate variables, the methods for producing candidate predictive models mirror the criteria used for the ecoprovince WFAB reconstruction. I included lagged versions (up to two years) of the climate variables in my search for candidate predictors. This potentially results in an undesirably large ratio of predictors to observations, especially for the 1977-2003 models. I assumed that climate in the year-of-fire was the most proximate influence on fuel moisture and built forward-selection models of fire using the year-of-fire predictors first. However, the sensitivity of vegetation to antecedent climate conditions and the preponderance of lag relationships in fire history data suggest the possibility of considering lag relationships equally.

Once the suite of year-of-fire predictors had been exhausted, I continued to build forward models with the lag 1 climate predictors, but limited the minimum candidate model to a single variable and allowed the lag 1 predictors to preempt the year-of-fire predictors if the AIC of the candidate model was lower. I then evaluated the lag 2 climate predictors in the same way. I calculated the variance inflation factor (VIF) for each predictor in the candidate model to evaluate the influence of co-linearity. For predictors with VIF > 5, I iteratively discarded and re-entered collinear variables until a balance between acceptable VIF and minimized AIC was achieved. The final candidate model was accepted when all variables or interactions in the model were $t \leq 0.15$, $VIF < 5.5$, and no variables could be added or removed without increasing the AIC while maintaining the first two criteria.

Results

Primary Fire Data and Pre-treatment

Summary statistics for WFAB in each ecoprovince in 1980-2000 and ecoprovinces abbreviations used throughout the text are summarized in Table 2.1. There are orders of magnitude differences between mean WFAB in the Pac.Low (least) and the

IM.SemDes (greatest). When adjusted by ecoprovince area in the analysis, the CalC.Wood ecoprovince has the highest mean annual ecoprovince fraction area burned. For the period 1980-2000, the gridded WFAB ecoprovinces have variable seasonality. Fire seasons in ecoprovinces characterized primarily by higher elevation mountain vegetation types and those farthest north tended to peak later in the year compared to lower elevation, more southern ecoprovinces (Table 2.1).

A nonlinear relationship exists between the mean and variance for the gridded, large fire ecoprovince, and state observed WFAB time series (Figure 2.2). Each can be characterized as log-normal, but the relationship between the variance and mean for all three areal aggregations of fire data (lat/long grid square, state, or ecoprovince) indicates a gamma distribution where the log of the variance is approximately proportional to the mean squared. Only the uncorrected state-level dataset has an unsatisfactory resemblance to the gamma relationship.

Reconstructing Ecoprovince Area Burned

I produced reasonable reconstructions of ecoprovince area burned for 16 of the 19 ecoprovinces for the 11 Western states (Table 2.2). The CalC.Steppe, SW.PlatPl , and Pac.Low ecoprovinces had the smallest analysis area and smallest mean annual area burned of the ecoprovinces in the West. The variability in annual WFAB for these provinces was not significantly related to the state WFAB time series; I did not pursue these further. The model fit for CalC.Chap and Casc.Mix ecoprovinces, though significant, was poor compared to the rest of the ecoprovinces (Table 2.2). I limited prediction for CalC.Chap to 1931-2004 because model residuals indicated very poor fit prior to 1931. Proportion variance explained for the log-log models varied from 0.36 to 0.96, and the proportion null deviance explained for the gamma models ranged from 0.34 to 0.80.

Overall, gamma models were superior to logarithmic models in seven reconstructions: AM.SemDes, AZNM.Mts, CalC.Chap, Chi.SemDes, CP.SemDes, NVUT.Mts, and SRM.SOWC. Gamma models produced large errors for the year 2002 in four southwestern ecoprovince models with Colorado and Arizona as predictors, both states that had relatively low annual WFAB values during the training period. These models were still superior in an RMSE sense, so I constrained the 2002 values to the maximum predicted WFAB for the ecoprovince during the rest of the 1916-2003 period to avoid the influence of the extreme outlier year on climate/fire relationships. The P.R.E.S.S. RMSE values (Table 2.2) underscore the importance of correct predictions of large values for the strength of the regression relationships, but many of the values approximated mean WFAB and reflected reasonably good fit given the short time period of the training data and the high variability in the observed values. Overall, the reconstructions capture the observed total, adjusted state-level WFAB for the West (Figure 2.3), underpredicting on average by $B_0 = -6.1 \times 10^4$ hectares ($r^2 = 0.93$, $F = 1052$ on 1 and 87 d.f., $p = 0.000$).

Climate Data and Pre-treatment

The first PCA time series of the aggregated ecoprovince climate division time series was in all cases positively correlated with each constituent time series. In some of the larger ecoprovinces the magnitude of correlations between each constituent climate division and the leading PC time series varies more than in smaller ecoprovinces, indicating that the heterogeneity of the climate divisions probably resulted in lower proportions of total variance explained. The range of variance explained was 0.48 to 0.96 for the first PC time series, values were typically highest for temperature variables and lowest for precipitation variables (data not shown), and the season of maximum or minimum variance explained varied by ecoprovince. The second PC time series usually represented a weak contrast between two constituent groups of climate divisions.

Climate - Fire Relationships

1977-2003 Correlations

There are several general patterns of seasonal correlation between climate variables and ecoprovince WFAB (Table 2.3). For the period 1977-2003, all significant ($n = 27$, $r_{sig} = 0.3218$, $p = 0.05$) year-of-fire seasonal temperature variables are positive. Growing season temperature was the most frequently important, with significant

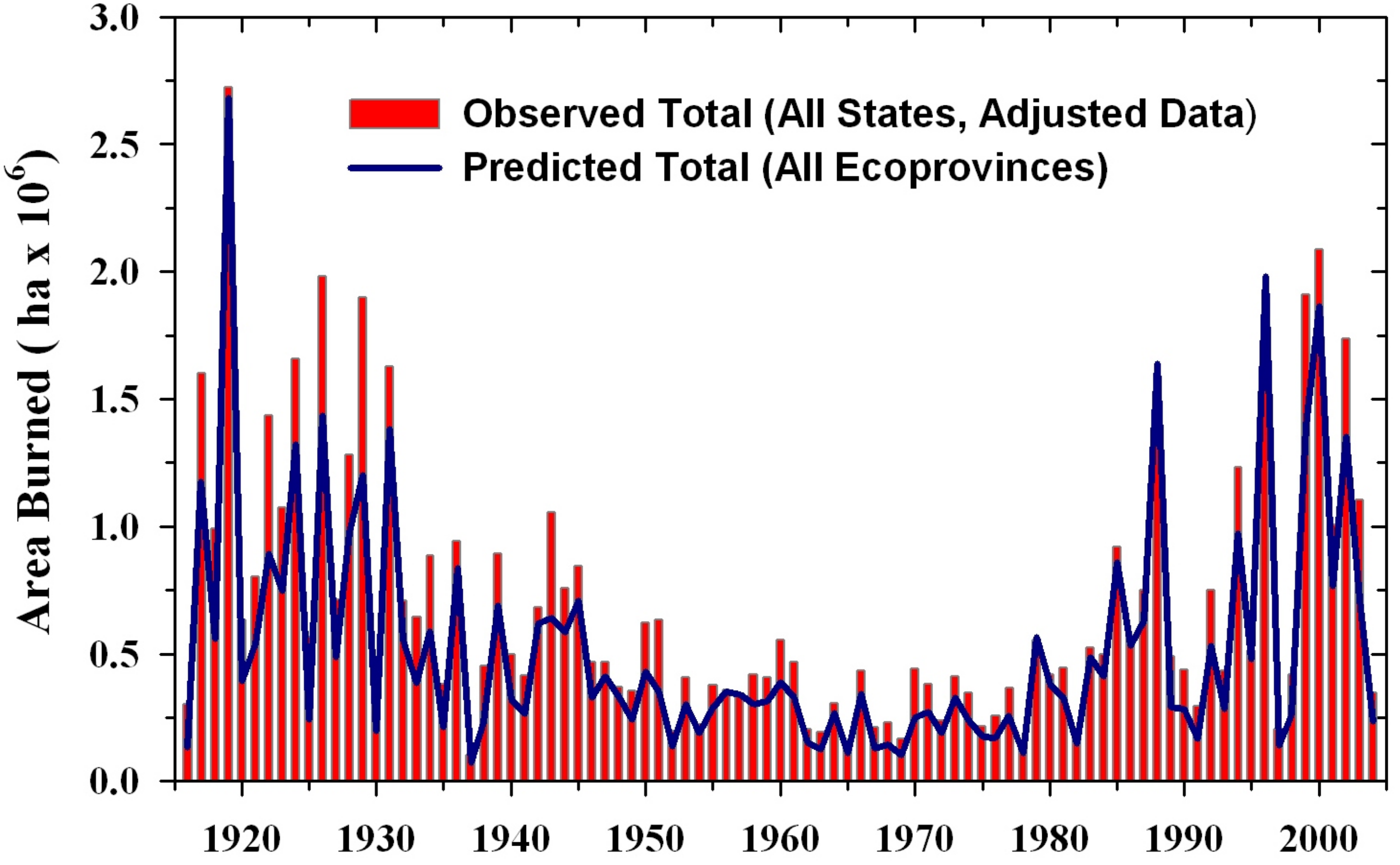

FIGURE 2.3. Observed and Reconstructed Area Burned Comparison. 1916-2004 time series of observed total WFAB for 11 Western states (bars, adjusted for area-reporting bias) and reconstructed total WFAB for 16 ecoprovinces (line).

TABLE 2.3A. 1977-2003 Fire-Climate Correlations. Pearson correlations between pre-whitened year-of-fire (YO), lag 1 (L1) and lag 2 (L2) ecoprovince seasonal climate variables and $\log_{10}$ ecoprovince WFAB for 1977-2003. Significant correlations ($p<0.05$, $n = 27$, $|r| > 0.32$) are indicated by a numerical correlation coefficient; all other correlations are indicated by the sign of the relationship.

		Temperature					Precipitation					PDSI				
Ecoprovince		Ann*.	Wnt.	Spr.	Gs.	Sum.	Ann.	Wnt.	Spr.	Gs.	Sum.	Ann.	Wnt.	Spr.	Gs.	Sum.
Am.DesDes	YO	-	-	-	+	+	-	-	-	-0.36	-0.40	-	+	-	-	-0.37
	L1	-	-	+	+	+	0.37	0.52	+	-0.36	-0.35	0.43	0.41	0.45	0.40	+
	L2	+	+	+	+	+	+	+	+	-	-	+	+	+	+	+
AZNM.Mts	YO	0.34	+	+	0.34	+	-	-	-	-	-	-0.35	-	-	-0.37	-0.41
	L1	-	-	+	-	-	0.34	0.51	+	-	-	0.38	0.44	0.39	+	+
	L2	+	-	+	0.38	0.40	-	-	+	-	-0.32	+	+	+	+	+
Cal.DryStp	YO	+	+	+	+	+	-0.47	-0.48	-0.49	-0.33	-0.42	-	-	-	-	-
	L1	-	+	-	-	+	+	+	+	+	+	+	+	+	+	+
	L2	-	-	+	+	-	-	-	-	-	-	-	-	-	-	-
CalC.Chap	YO	+	+	+	+	+	-	-	-0.41	-	-0.38	-0.35	-0.39	-0.34	-	-
	L1	-	-	+	-	-	-	-	-	-	+	-	+	-	-	-
	L2	-0.38	-0.34	-0.45	-	-	+	+	+	+	-	+	+	0.34	0.40	0.40
CalC.Wood	YO	+	-	-	+	+	-	-	-0.36	-	-0.40	-	-	-	-	-
	L1	+	+	-	-	-	+	+	+	+	+	+	+	+	+	+
	L2	-	-0.34	-	-	-	-	-	+	+	+	+	-	-	-	-
Casc.Mix	YO	+	+	+	0.40	+	-	-	-0.44	-0.52	-	-	-	-0.34	-0.38	-0.38
	L1	-	-	-	-	-	+	+	+	+	-	+	+	+	+	+
	L2	0.42	0.32	0.38	0.36	+	-	+	-	-	-	-	+	-	-	-
Chi.SemDes	YO	0.40	+	0.34	+	+	-0.52	-0.36	-	-	-	-0.56	-0.36	-0.38	-0.46	-0.43
	L1	-	-	+	-	+	+	0.44	+	-	-	0.35	0.43	0.46	+	+
	L2	+	+	+	+	+	-	-	+	-	-0.32	-	-	+	+	-
CP.SemDes	YO	+	+	+	+	+	-	-	-	-0.42	-0.39	-	-	-	-0.33	-0.42
	L1	+	+	+	+	+	+	0.35	+	-0.44	-0.46	+	+	+	+	+
	L2	+	+	+	0.40	+	-	-	-	-	-	-	-	-	-	-

*Ann. = Oct.-Sep., Wnt = ONDJFM, Spr=MJJ, GS = MJJAS, Sum = JAS

TABLE 2.3B. 1977-2003 Fire-Climate Correlations Continued. Pearson correlations between pre-whitened year-of-fire (YO), lag 1 (L1) and lag 2 (L2) ecoprovince seasonal climate variables and $\log_{10}$ ecoprovince WFAB for 1977-2003. Significant correlations ($p<0.05$, $n = 27$, $|r| > 0.32$) are indicated by a numerical correlation coefficient; all other correlations are indicated by the sign of the relationship.

		Temperature					Precipitation					PDSI				
Ecoprovince		Ann*.	Wnt.	Spr.	Gs.	Sum.	Ann.	Wnt.	Spr.	Gs.	Sum.	Ann.	Wnt.	Spr.	Gs.	Sum.
GPP.Steppe	YO	0.48	0.35	+	0.53	0.53	-0.66	-0.46	-0.40	-0.72	-0.77	-0.48	-	-	-0.60	-0.68
	L1	+	+	-	-	+	+	+	-	+	+	+	-	+	+	+
	L2	+	+	+	+	+	-	-	-	+	+	-	-	-	-	-
IM.DesDes	YO	+	+	+	+	+	-	+	-	-	-	-	+	+	-	-
	L1	-	+	-	-	-	0.37	0.49	+	+	-	0.39	+	0.43	0.39	0.36
	L2	0.37	+	0.35	+	+	+	+	-	+	+	+	+	+	+	+
IM.SemiDes	YO	+	+	+	+	+	-	-	-	-0.46	-0.43	-	-	-	-	-0.35
	L1	-0.41	-	-	-	-	+	+	0.35	+	+	+	+	0.36	0.34	0.33
	L2	+	+	0.37	0.34	+	+	+	-	-	+	+	+	-	-	-
MRM.FSC	YO	0.46	+	+	0.55	0.37	-0.56	-	-0.35	-0.67	-0.61	-0.43	-	-0.38	-0.64	-0.70
	L1	-	-	-	-	-	+	+	+	-	-	+	-	+	+	+
	L2	0.38	+	0.49	0.51	+	-	-	-0.36	-	-	-	+	-0.34	-0.46	-0.44
NevUt.Mts	YO	+	+	-	+	-	-	-	-	-	-	-	+	-	-	-
	L1	-	+	-	-	+	0.45	+	0.39	0.48	+	0.41	+	0.39	0.49	0.45
	L2	+	+	+	+	+	+	+	-	+	+	+	+	+	+	+
NRM.FSC	YO	0.55	0.40	+	0.55	0.58	-0.61	-	-	-0.71	-0.75	-0.54	-	-0.46	-0.69	-0.76
	L1	-	-	-	-	+	+	0.34	+	+	-	+	+	+	+	+
	L2	+	+	+	0.45	+	-	-	-	-	-	-	-	-	-0.33	-
Sier.Mix	YO	+	+	+	0.41	+	-0.38	-0.35	-0.48	-0.45	-0.39	-0.43	-	-0.41	-0.46	-0.47
	L1	-	-	-	-	-	+	0.32	+	-	-	+	+	+	+	+
	L2	+	+	+	+	+	-	-	-0.35	-	-	-	-	-	-	-
SRM.SOWC	YO	+	+	+	0.50	0.40	-0.54	-0.35	-0.46	-0.49	-0.33	-0.50	-0.43	-0.39	-0.50	-0.52
	L1	+	+	+	-	-	-	+	-	-	-	-	-	-	-	-
	L2	0.44	0.43	0.53	+	+	-	-	-	-	+	-	+	-	-	-

*Ann. = Oct.-Sep., Wnt = ONDJFM, Spr=MJJ, GS = MJJAS, Sum = JAS

responses primarily confined to mountainous ecoprovinces and the GPP.Steppe ecoprovince. Lag 1 seasonal temperatures were rarely significant. Lag 2 seasonal temperature vary in significance and sign with ecoprovince, but most significant relationships were positive; only the CalC.Chap and CalC. Wood ecoprovinces had negative lag 2 temperature correlations.

I observed only negative significant relationships between area burned and year-of-fire precipitation or PDSI. In the SRM.SOWC, Sier.Mix, GPP.Steppe, and Cal.DryStp, precipitation was correlated with annual WFAB for all seasons, while the WFAB for SRM.SOWC and the Chi.SemDes were correlated with PDSI for all seasons. AZNM.Mts, IM.DesDes, and the NVUT.Mts had no significant year-of-fire correlations with precipitation, and Cal.DryStp, CalC.Wood , IM.DesDes, and the NVUT.Mts had no significant year-of-fire PDSI correlations. Lag 1 precipitation correlations differ among ecoprovinces, but the significant relationships are nearly all positive. The AM.SemDes, AZNM.Mts, Chi.SemDest, CP.SemDes, IM.DesDes, NRM.SCFM, and Sier.Mix all have significant, positive correlations with lag 1 winter precipitation. Furthermore, *all* ecoprovinces except CalC.Chap exhibited positive correlation coefficients (significant or not) with lag 1 winter precipitation. Significant lag 1 PDSI correlations were all positive, and nearly all non-significant correlation coefficients for lag 1 PDSI were also positive. Lag 2 precipitation was generally not important in most ecoprovinces. Lag 2 PDSI was correlated in spring, growing season and summer for CalC.Chap (positive) and MRM.SCFM (negative), but was otherwise not important.

Significant coprovince climate-fire correlations exhibit three qualitative patterns. First, several mountainous ecoprovinces exhibit strong, approximately equal correlations between WFAB and year-of-fire temperature (positive) and precipitation-PDSI variables (negative) with few lag 1 or 2 precipitation relationships. The only significant positive lag 1 relationship is for winter. This pattern is evident in Casc.Mix, NRM.SCFM, MRM.SCFM, SRM.SOWC, and Sier.Mix. Second, several drier ecoprovinces have more and stronger positive lag 1 precipitation/PDSI correlations, especially winter, than year-of-fire climate variables. This pattern is evident in the AM.SemDes, AZNM.Mts, IM.SemDes, and Chi.SemDes. Third, IM.DesDes and NVUT.Mts have no significant year-of-fire climate relationships, but several moderately strong lag 1 precipitation and PDSI correlations. The CP.SemDes ecoprovince has weaker characteristics of the second and third groups, with no significant year-of-fire temperature relationships and generally weak year-of-fire precipitation and PDSI, but it is also missing the stronger lag 1 precipitation/PDSI relationship. The three California (CalC.Chap, CalC.Wood, Cal.DryStp) ecoprovinces do not fit neatly into any of these categories, but all three have significant, negative associations with both spring and summer (but not growing season) precipitation. GPP.Steppe is characterized by strong year-of-fire relationships similar to the mountain ecoprovinces but with no significant lag 1 or lag 2 correlations.

1916-2003 Correlations

Correlations were generally weaker for the 1916-2003 period, but some patterns emerge (Table 2.4). All significant ($n = 88$, $r_{sig} = 0.169$, $p = 0.05$) temperature (precipitation and PDSI) relationships the year-of-fire were again positive (negative). There were higher numbers of significant temperature correlations for 1916-2003 than 1977-2003, especially in spring. Significant lag 1 relationships were rare for temperature, always positive for precipitation, and common and always positive for PDSI. Growing season temperature was significant for five more ecoprovinces than for 1977-2003, while lag 1 winter precipitation and PDSI were still significant for several ecoprovinces.

The qualitative patterns observed for the period 1977-2003 also occurred in the extended 1916-2003 period. The mountainous group (Casc.Mix, NRM.SCFM, MRM.SCFM, SRM.SOWC, and Sier.Mix) still consisted of the same ecoprovinces, but all significant temperature correlations were positive and all significant precipitation and PDSI correlations were negative; winter precipitation no longer figured significantly in any of these ecoprovinces. The remaining ecoprovinces are characterized by significant positive correlations with lag 1 precipitation and/or PDSI. However, there are two different responses within this generalization. The first group is similar to the mountainous ecoprovinces but with a few significant positive lag 1 or 2 precipitation or PDSI correlations (e.g., CP.SemDes). The second group consists of ecoprovinces with

TABLE 2.4A. 1916-2003 Fire-Climate Correlations. Pearson correlations between pre-whitened year-of-fire (YO), lag 1 (L1) and lag 2 (L2) ecoprovince seasonal climate variables and $\log_{10}$ ecoprovince WFAB for 1916-2003. Significant correlations ($p<0.05$, $n = 87$, $|r| > 0.1$) are indicated by a numerical correlation coefficient; all other correlations are indicated by the sign of the relationship.

		Temperature					Precipitation					PDSI				
Ecoprovince		Ann*.	Wnt.	Spr.	Gs.	Sum.	Ann.	Wnt.	Spr.	Gs.	Sum.	Ann.	Wnt.	Spr.	Gs.	Sum.
Am.DesDes	YO	+	+	+	0.18	0.21	-0.23	-	-0.25	-0.25	-0.25	-0.23	-	-	-0.29	-0.37
	L1	+	+	0.17	0.17	+	0.27	0.35	+	-	-	0.25	0.26	0.24	0.20	+
	L2	0.18	+	0.17	0.18	+	+	0.18	0.21	-	-	+	+	+	+	+
AZNM.Mts	YO	0.24	+	0.27	0.29	0.24	-	+	-	-	-	-	-	-	-	-
	L1	+	+	+	-	-	+	0.25	+	-	-	0.19	0.26	0.19	+	+
	L2	-	-	+	+	0.23	0.19	0.19	0.34	+	-	0.20	0.18	0.21	0.20	0.18
Cal.DryStp	YO	+	+	0.19	+	+	-0.33	-0.31	-0.22	-	-0.26	-0.18	-	-	-	-
	L1	-	+	-	-	-	0.18	+	0.27	+	-	0.22	+	0.24	0.25	0.25
	L2	+	+	+	-	-0.18	-	-	-	+	-0.17	+	-	+	+	+
CalC.Chap	YO	+	-	+	+	-	-0.23	-0.20	-0.30	-	-	-0.22	-	-0.22	-	-
	L1	-	-	-	-	-	+	+	0.18	-	+	0.17	+	0.20	0.22	0.23
	L2	-	-	-	-0.20	-0.24	+	+	+	+	-	+	+	0.18	0.23	0.23
CalC.Wood	YO	-	-	+	-	-0.23	-0.24	-0.24	-0.18	-	-0.24	-	-	-	-	-
	L1	-	+	-	-0.22	-0.22	0.21	0.17	0.27	+	+	0.30	0.22	0.32	0.33	0.33
	L2	-	-	-	-0.19	-0.34	-	-	+	-	-	+	+	+	+	+
Casc.Mix	YO	+	-	0.18	0.31	0.20	-0.27	-	-0.20	-0.37	-0.23	-0.37	-0.23	-0.33	-0.41	-0.42
	L1	-	-	+	-	-	-	-	+	-	-	-	-	+	-	-
	L2	+	+	0.19	+	+	-0.18	-	-0.19	-	-	-0.17	-	-	-	-
Chi.SemDes	YO	0.45	0.35	0.26	0.39	0.31	-0.38	-0.19	-0.25	-0.27	-0.27	-0.40	-0.25	-0.28	-0.39	-0.39
	L1	-	-	-	-	+	0.20	0.31	+	+	+	0.24	0.32	0.30	+	+
	L2	+	+	+	+	+	0.19	0.20	0.33	0.20	+	0.22	0.21	0.26	0.26	0.22
CP.SemDes	YO	0.28	0.30	+	0.26	0.22	-0.24	-	-0.22	-0.36	-0.30	-0.24	-	-0.19	-0.31	-0.35
	L1	+	+	+	+	+	0.18	0.25	+	-	-	+	0.17	+	+	+
	L2	0.21	0.19	0.20	0.23	+	+	+	+	-	-	+	+	+	+	+

*Ann. = Oct.-Sep., Wnt = ONDJFM, Spr=MJJ, GS = MJJAS, Sum = JAS

[2] Soil Survey Staff, USDA NRCS

TABLE 2.4B. 1916-2003 Fire-Climate Correlations Continued. Pearson correlations between pre-whitened year-of-fire (YO), lag 1 (L1) and lag 2 (L2) ecoprovince seasonal climate variables and $\log_{10}$ ecoprovince WFAB for 1916-2003. Significant correlations ($p<0.05$, $n = 87$, $|r| > 0.1$) are indicated by a numerical correlation coefficient; all other correlations are indicated by the sign of the relationship.

		Temperature					Precipitation					PDSI				
Ecoprovince		Ann*.	Wnt.	Spr.	Gs.	Sum.	Ann.	Wnt.	Spr.	Gs.	Sum.	Ann.	Wnt.	Spr.	Gs.	Sum.
GPP.Steppe	YO	0.33	0.18	0.21	0.41	0.37	-0.52	-0.23	-0.30	-0.58	-0.48	-0.42	-	-0.28	-0.53	-0.58
	L1	+	+	-	-	+	+	0.30	-	-	+	+	0.18	+	+	+
	L2	-	-	-	-	-	+	+	+	+	+	+	+	+	+	+
IM.DesDes	YO	0.34	0.25	0.31	0.18	+	-	+	-	-0.19	-0.18	-	+	-	-0.20	-0.21
	L1	0.22	0.26	+	-	-	0.25	+	0.19	0.26	+	+	+	+	0.17	0.18
	L2	+	+	+	+	+	+	0.22	+	+	-	+	0.19	+	+	+
IM.SemiDes	YO	0.35	0.22	0.41	0.31	0.19	-0.31	-	-	-0.28	-0.20	-0.33	-	-0.30	-0.37	-0.38
	L1	+	+	+	-	-	0.22	+	0.27	0.29	0.20	+	+	+	+	+
	L2	+	-	+	+	+	-	+	+	+	+	+	+	+	-	-
MRM.FSC	YO	0.40	0.20	0.35	0.46	0.38	-0.55	-0.30	-0.23	-0.55	-0.37	-0.44	-	-0.38	-0.59	-0.62
	L1	+	+	+	-	+	+	+	+	+	+	-	-	-	+	+
	L2	+	+	0.24	0.22	0.18	-	-	-	-	+	-0.17	-	-0.18	-0.21	-0.21
NevUt.Mts	YO	+	0.18	+	+	+	-	+	+	-	-	-	+	+	-	-
	L1	-	+	-	-0.17	-	0.41	0.30	0.36	0.41	0.21	0.32	0.21	0.30	0.38	0.36
	L2	+	0.17	0.18	+	+	0.18	0.19	+	+	+	+	0.17	+	+	+
NRM.FSC	YO	0.42	0.25	0.30	0.46	0.44	-0.52	-0.26	-0.24	-0.51	-0.45	-0.47	-0.24	-0.42	-0.59	-0.61
	L1	+	+	+	+	+	+	+	+	-	-	+	+	+	+	+
	L2	+	-	+	0.19	+	-	-	-	+	+	-	-	-	-	-
Sier.Mix	YO	0.26	+	0.29	0.31	+	-0.35	-0.29	-0.34	-0.34	-0.32	-0.38	-0.27	-0.34	-0.40	-0.42
	L1	+	+	+	-	-	+	+	+	-	-	+	+	+	+	+
	L2	+	+	0.21	+	-	-	-	-	+	-	-	-	-	-	-
SRM.SOWC	YO	0.25	+	0.26	0.45	0.39	-0.35	-0.23	-0.23	-0.29	-	-0.33	-	-0.27	-0.39	-0.40
	L1	+	0.17	0.20	+	-	+	+	+	+	+	-	-	-	-	-
	L2	+	+	+	+	+	-	+	+	-	+	-	+	+	-	-

*Ann. = Oct.-Sep., Wnt = ONDJFM, Spr=MJJ, GS = MJJAS, Sum = JAS

weak year-of-fire relationships and stronger positive correlations with lag 1 precipitation and PDSI.

Diagnostic Regression Models

The AIC procedure for building diagnostic linear models of WFAB as a function of seasonal climate variables produced significant models for each of the 16 ecoprovinces that yielded a significant reconstruction. In many cases, the AIC procedure discriminated against one candidate predictor in favor of another when both predictors would have resulted in significant models. There are thus several diagnostic regression models that would be statistically acceptable for a given ecoprovince. The models and diagnostic terms presented are those meeting three criteria: minimum AIC, acceptable VIF for each term, and maximum variance explained. In most cases, the first term in the model is the single best predictor in both a correlation sense (see Table 2.3 and 2.4) and a minimum AIC sense. When it is not, correlations are usually similar for several candidate predictors. When interpreting the full models, subsequent variables reflect the sensitivity of the model residuals to an additional predictor given that the first predictor is already in the model. The sign of terms entered last into the regression model are therefore sometimes indicative of contingent relationships.

Between $R^2 = 0.33$ and $R^2 = 0.87$ (mean $R^2 = 0.64$) of the variability in reconstructed WFAB could be explained by three to six climate predictors, and in a few cases, their interactions (Figure 2.4). Precipitation terms (34) were more common than either temperature (20) or PDSI (16). The first term in 11 of 16 models (and the second term in seven models) for the 1977-2003 period was a negative relationship with precipitation or PDSI during some part of the primary fire season (spring, summer, or growing season) the year-of-fire (Table 2.5). Similarly, negative lag 1 or lag 2 predictors were significant for eight models, while positive lag 1 or lag 2 predictors for the same variables were important in seven models. Annual PDSI the year-of-fire was a better negative predictor for Chi.SemDes andAZNM.Mts. The NVUT.Mts had no significant year-of-fire predictors; the best predictor was *positive* annual precipitation the year prior to fire. Finally, IM.DesDes had a positive relationship with winter precipitation in the

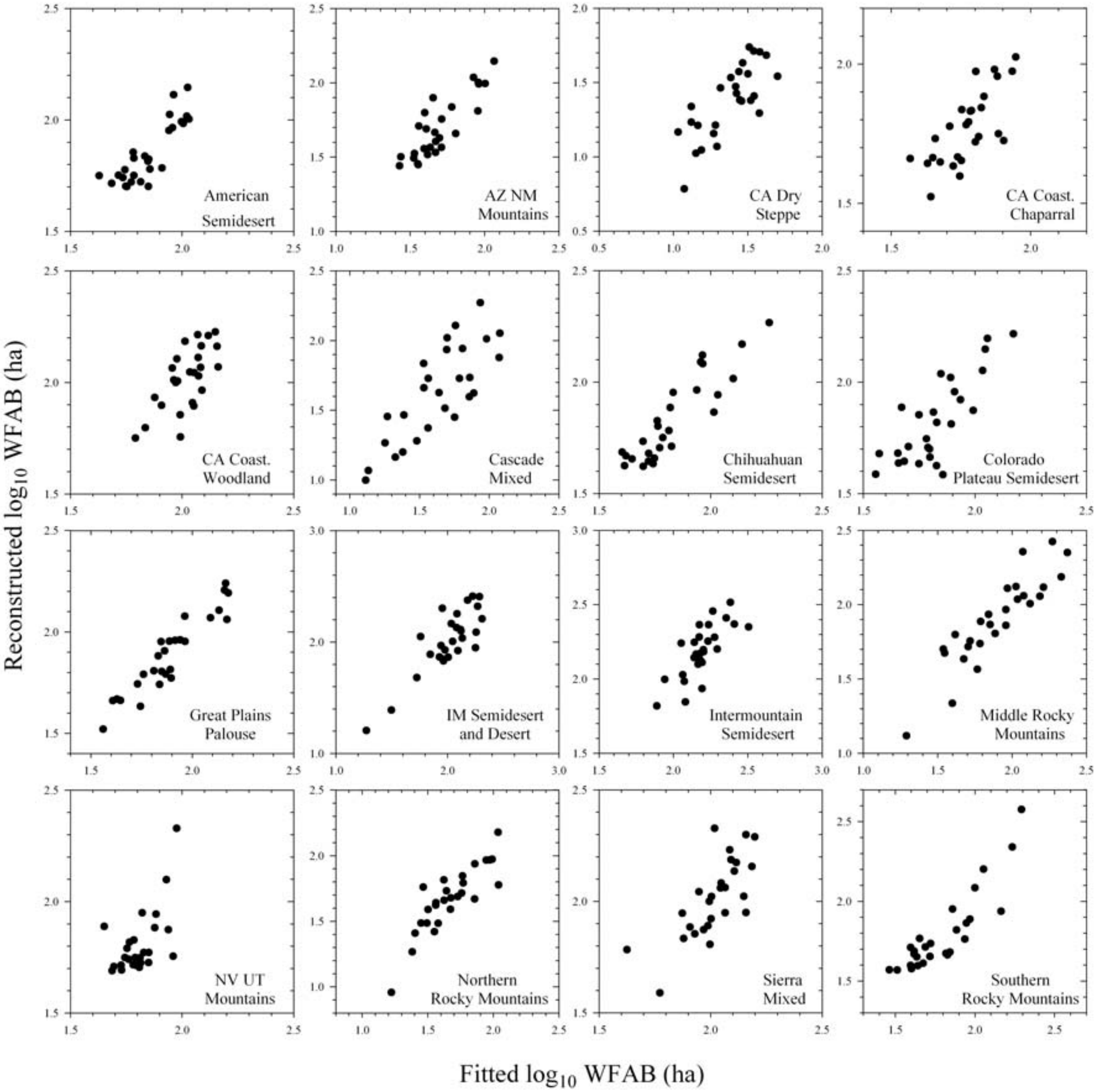

FIGURE 2.4. Reconstructed vs. Climate Predicted WFAB 1977-2003. Reconstructed ecoprovince WFAB versus fitted values from diagnostic climate-fire prediction models for 1977-2003. Note that scales change with ecoprovince.

TABLE 2.5. Climate-Fire Diagnostic Regression Models for 1977-2003.

Ecoprovince	1977-2003 Model*	R^2
AM.SemDes	- GS.P + - Spr.P + - Spr.T + - L1.GS.P +L1.Wnt.PDSI**	0.72
AZNM.Mts	- ANN.PDSI + - Sum.P + L1.WNT.P + L1.SPR.T +L2.Sum.T	0.74
CalC.Chap	-Wnt.PDSI + -Sum.P + Wnt.PDSI :Sum.P +-L2.Spr.T	0.54
CalC.Wood	- Sum.P + L1.Wnt.T + - L1.Spr.T + L1.Sum.P	0.47
Cal.DryStp	-Sum.P + -Spr.P + Spr.PDSI + -Wnt.P	0.59
Casc.Mix	- GS.P + L1.Wnt.P + - L1.Wnt.T + L2.Wnt.P +- L2.Sum.P	0.65
Chi.SemDes	- Ann.PDSI + Wnt.P + L1.Spr.PDSI + Ann.PDSI :Wnt.P	0.80
CP.SemDes	-Sum.P + -Sum.PDSI + -L1.GS.P + L1.Ann.P + L2.GS.T	0.63
GPP.Steppe	-Sum.P + -Spr.P + -Wnt.P + L1.Wnt.T +-L1.Spr.P + L1.Sum.PDSI	0.87
IM.SemDes	- GS.P + L1.Spr.PDSI + L2.Wnt.PDSI + L2.Spr.T	0.56
IM.DesDes	Wnt.P + Wnt.T + L2.Spr.T +L2.Wnt.PDSI + L2.Wnt.T + Wnt.P :Wnt.T	0.71
MRM.SCFM	-Sum.PDSI + Wnt.P + L2.Spr.T + L2.Spr.PDSI +-L2.Sum.P +- L2.Ann.T	0.81
NVUT.Mts	L1.Ann.P + L2.Spr.T + L2.GS.P	0.33
NRM.SCFM	-Sum.PDSI + Wnt.T + -L1.Sum.P +-L1.GS.T	0.74
Sier.Mix	-Sum.PDSI + L1.Wnt.P +- L1.GS.P + L1.Wnt.P :L1.GS.P	0.53
SRM.SOWC	-Spr.P + -Sum.P + Wnt.T + -Spr.T +L2.Spr.PDSI + Spr.P :Sum.P	0.77

* All models are statistically significant; all $p < 0.02$.

** Notation: + followed by – refers to the additive regression effect of a negative predictor; the absence of a – symbol indicates the predictor is positve.

winter immediately preceding fire while the CalC.Chap had a negative relationship with winter PDSI for the same winter.

The 1916-2003 models did not perform as well as the 1977-2003 models (Figure 2.5, Table 2.6). Between 0.25 and 0.57 (mean = 0.39) of the variance could be accounted for by between three and nine predictors and, in some cases, their interactions. Temperature and precipitation had similar numbers of significant model terms (37 and 38 respectively), while PDSI had fewer significant terms (21). The first term in 15 of 16 models was year-of-fire climate: seven models had a negative precipitation term, three models had negative summer PDSI, and five models had positive temperature. The first term in NVUT.Mts was positive lag 1 growing season PPT.

Winter predictors were significant in 14 of the 16 1977-2003 models (Table 2.5). Eight ecoprovinces (AM.SemDes, AZNM.Mts, Casc.Mix, Chi.SemDes, IM.SemDes, IM.DesDes, MRM.SCFM, Sier.Mix) had one or more significant positive terms for prior (year-of, lag 1, or lag 2) winter precipitation or PDSI. Winter temperature was a significant positive predictor in NRM.SCFM, SRM.SOWC, and IM.DesDes. Winter climate variables were also prominent in the 1916-2003 models (Table 2.6). CP.SemDes, GPP.Steppe, and IM.SemDes Chi.SemDes, IM.DesDes, and NRM.SCFM all had significant, positive predictors for year-of-fire winter P or PPT. AM.SemDes, AZNM.Mts, CalC.Wood, CP.SemDes, GPP.Steppe, IM.SemDes, NVUT.Mts, NRM.SCFM had significant positive lag 1 winter precipitation or PDSI predictors. Only CalC.Wood and MRM.SCFM had negative winter precipitation terms, both in the winter immediately preceding the fire season.

Spring predictors were significant in 12 1977-2003 models. Negative associations with year-of-fire spring precipitation were the first or second term in AM.SemDes, GPP.Steppe, and SRM.SOWC. The same relationship occurs in Cal.DryStp, but Cal.DryStp also has a positive relationship with spring PDSI. This apparent inconsistency (negative precipitation and positive PDSI associations in the same season) may indicate either a contingency or non-stationary mechanism for WFAB. Seven models had positive lag 1 or lag 2 spring temperature predictors, and five models had positive lag 1 or lag 2 spring precipitation or PDSI predictors. For 1916-2003, year-of-fire, lag 1 or lag 2 spring

TABLE 2.6. Climate-Fire Diagnostic Regression Models for 1916-2003.

Ecoprovince	1916-2003 Model	R^2
AM.SemDes	-Sum.PDSI + L1.Wnt.P + L1.Spr.T + L1.Spr.T :L1.Wnt.P	0.33
AZNM.Mts	GS.T + SPR.T + L1.WNT.P + L2.Sum.T + L2.SPR.P + GS.T :SPR.T	0.34
CalC.Chap	-Spr.P + Sum.PDSI + Spr.T + L1.GS.PDSI +-L1.GS.P + -L2.Sum.T + L2.Sum.PDSI + L2.Spr.T + Sum.PDSI :Spr.T +L1.GS.P :L1.GS.PDSI	0.46
CalC.Wood	-Wnt.P + Spr.PDSI + -Sum.T + L1.Spr.P +L1.Wnt.PDSI + L1.Spr.P :L1.Wnt.PDSI	0.30
Cal.DryStp	-Ann.P + Spr.PDSI + Spr.T + -Sum.P +L1.Spr.P + L1.Ann.T + L2.Spr.PDSI + -L2.Ann.P + L2.Wnt.T + L1.Ann.T:L1.Spr.P	0.44
Casc.Mix	-Sum.PDSI +- L1.GS.P + L2.Spr.T	0.25
Chi.SemDes	Ann.T +- Ann.P + Wnt.P + L1.Spr.PDSI +- L1.Sum.PDSI + L2.Spr.PDSI + L2.Ann.T + Ann.T :Ann.P + Ann.P :Wnt.P	0.53
CP.SemDes	- GS.P + Wnt.T + L1.Wnt.P + L1.Wnt.T +GS.P :Wnt.T + L1.Wnt.P :L1.Wnt.T	0.34
GPP.Steppe	- GS.P + Ann.T + L1.Wnt.T + L1.Wnt.PDSI + L2.Wnt.PDSI + L1.Wnt.PDSI :L2.Wnt.PDSI	0.51
IM.SemDes	Spr.T + - Ann.P + Spr.P + Wnt.P + L1.Spr.P +L1.Wnt.P + L1.Wnt.T + L2.Wnt.PDSI	0.42
IM.DesDes	Ann.T + -Ann.P + Wnt.PDSI + L1.Ann.T +L1.GS.PDSI + L1.Spr.T + L2.Wnt.P + Ann.P :Wnt.PDSI	0.38
MRM.SCFM	-GS.P + -Wnt.P + Wnt.T + GS.T + L1.Ann.T +L2.Spr.T + L2.Spr.P	0.56
NVUT.Mts	L1.GS.P + L1.Wnt.P + L2.Spr.T + L2.GS.P +- GS.P + Spr.P + L1.GS.P :L1.Wnt.P	0.46
NRM.SCFM	-Ann.P + Ann.T +- GS.P + Wnt.PDSI + L1.Wnt.P +L1.Sum.T + L2.Spr.T + L2.Sum.P + L2.Sum.T	0.57
Sier.Mix	-Sum.PDSI + L1.Spr.PDSI + L1.Spr.T + -L1.GS.P +L2.Spr.T + -L2.Sum.P + -L2.GS.T	0.39
SRM.SOWC	GS.T + - Sum.PDSI + + L1.Spr.T + GS.T :Sum.PDSI	0.33

** Notation: + followed by – refers to the additive regression effect of a negative predictor; the absence of a – symbol indicates the predictor is positve.

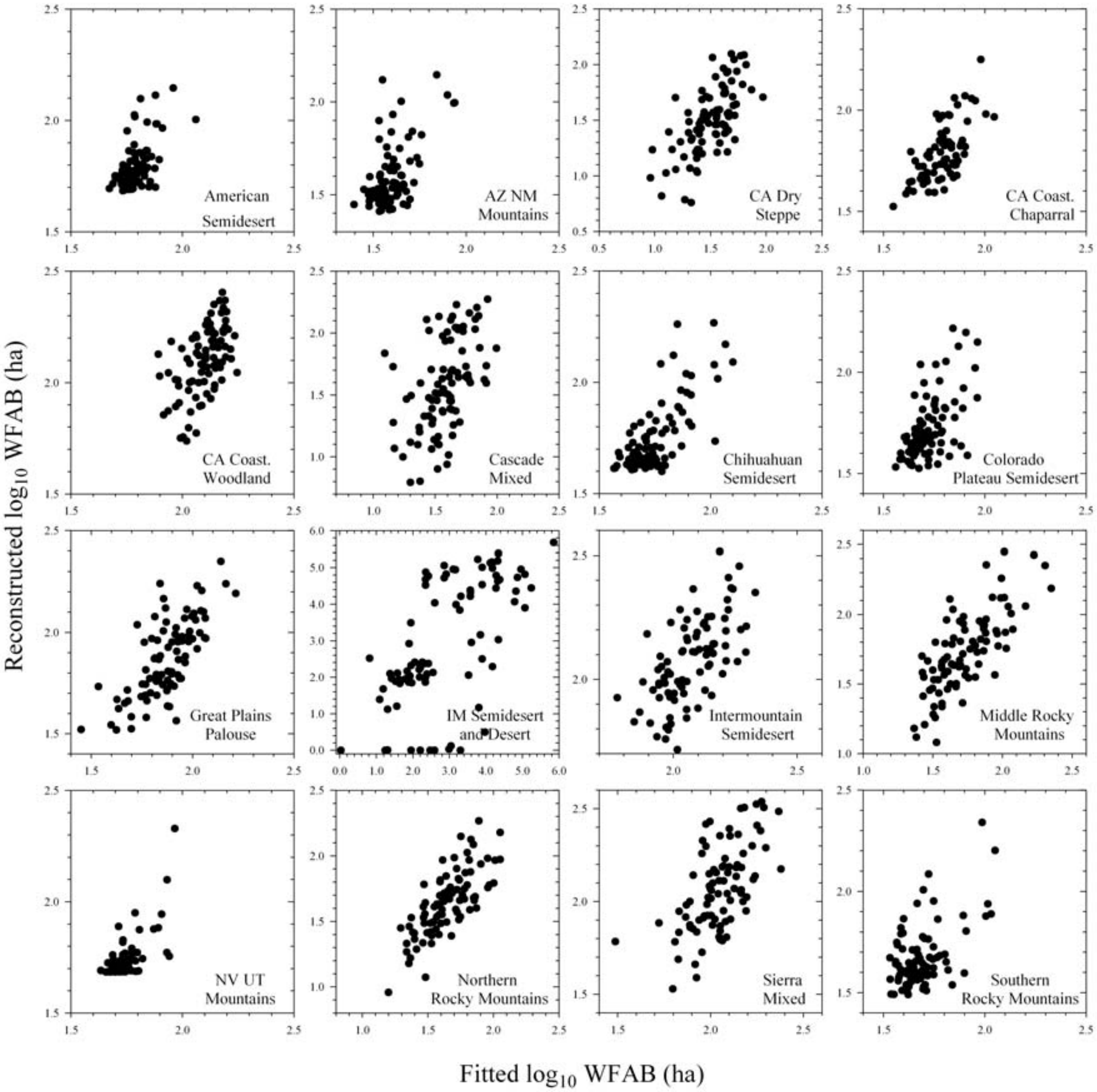

FIGURE 2.5. Reconstructed vs. Climate Predicted WFAB 1916-2003. Reconstructed ecoprovince WFAB versus fitted values from diagnostic climate-fire prediction models for 1916-2003. Note that scales change with ecoprovince.

temperature was a positive predictor in twelve models, while year-of-fire, lag 1, or lag 2 spring precipitation or PDSI was a positive in eight models. Only CalC.Chap had a negative spring precipitation term.

Discussion

Fire Data and Reconstructions

This is the first published description of a consistent power law describing the mean and variance of area burned. Malamud et al. (2005) demonstrated that frequency-area power laws described the distribution of area burned very well and have promise for describing fire regimes across scales and solving inherent difficulties in emulating disturbance processes (McKenzie et al. 1996). The gamma relationship described by the mean/variance structure of the WFAB totals (Figure 2.2) is independent of the size of the grain (from 1° x 1° grid cells to large states and ecoprovinces) considered. Modeling the areal component of fire regimes is therefore a tractable problem. The gamma distribution illustrates that potential increases in mean annual ecoprovince area burned are likely to be accompanied by very large increases in the interannual variability in area burned, and the fact that the general relationship is conserved is a powerful tool. For example, such a relationship allows a realistic specification, over any time frame or spatial scale, of the parameters for fire area burned in dynamic vegetation models. It also may help assess the impacts of climate change on ecosystem vegetation; if models can reliably forecast changes in the mean area burned, it is possible to also specify the variability about that mean and better constrain the uncertainty in modeling ecosystem response to climate change.

Gamma regression models were superior in the southwestern ecoprovinces, whereas logarithmic models were superior in the cooler mountainous and transitional ecoprovinces. At least during the model training period, the assumption that the model errors are log-normally distributed is insufficient, and specifying the gamma link relationship provides better reconstructions. In practice, for ecoprovinces of the Southwest, the variance for a given mean WFAB is consistent, implying an underlying mechanism. One explanation is that these ecoprovinces are usually dry enough to burn in most fire seasons because the fire season is longer in the Southwest than the mountainous or northern ecoprovinces (Westerling et al. 2003), and interannual variability is high due in part to the alternately facilitating and limiting climate conditions associated with the El Niño-Southern Oscillation (Swetnam and Betancourt 1998). For example, the correlation coefficients and regression model parameters show that the largest fire years are facilitated by antecedent positive moisture anomalies. This mechanism likely produces large, spatially homogeneous areas of continuous fine fuels; a regional but temporary climate shift increases quantity or continuity of fuels via vegetation growth and leads to subsequent non-linear increases in WFAB. Alternatively, the relative rate of fire spread associated with different ecoprovince fuel types (e.g., Fosberg et al. 1993) may determine whether gamma or logarithmic models better describe WFAB.

Climate Relationships with Wildland Fire Area Burned

Dry, warm conditions in the seasons leading up to and including the fire season are associated with increased WFAB in most ecoprovinces, presumably because low precipitation and high evapotranspiration depletes fuel moisture in existing vegetation (Keetch and Byram 1968, Bessie and Johnson 1995) (Tables 2.3, 2.4, 2.5) and thus increases the probability of ignition and the potential area burned. The role of precipitation is more important than PDSI or temperature in many cases, although PDSI is a better predictor in some ecoprovinces, especially all three Rocky Mountain ecoprovinces. NVUT.Mts and IM.DesDes, which together comprise the Great Basin and its basin-and-range mountains, are exceptions and the positive role of antecedent precipitation is more important. These ecoprovinces have lagged relationships and appear to be fuel limited (e.g., Knapp 1995) because the only significant relationships with WFAB are associated with fuel production – warm, wet conditions in winter and spring lead to larger WFAB a year or more in the future.

The pattern of climate-area burned correlations and diagnostic regression models for the Rocky Mountains, Sierra Nevada, and Cascades indicates a common mechanism for climate-fuel-fire relationships in primarily forested ecoprovinces. Low precipitation, high temperature, and negative PDSI immediately preceding and during the year-of-fire are associated with increased WFAB, probably because persistent hot temperatures and low humidity are required to dry out fine fuels in these ecoprovinces even when winters are comparatively mild. For the period 1977-2003, correlations between area burned and seasonal climate suggest the Cascades and Northern Rockies are primarily sensitive to low precipitation during the fire season (summer and growing season), whereas WFAB in the Sierra Nevada, Southern Rockies, and Middle Rockies is sensitive to low precipitation during a longer window from the winter immediately preceding fire through the fire season. This is consistent with a length-of-fire season limitation on WFAB in northern mountainous ecoprovinces, although the relationships are significant for all seasons during the 1916-2003 period. The regression models for all ecoprovinces in this category implicate precipitation and PDSI more than temperature in large WFAB, and the interactions between year-of-fire temperature and precipitation were usually not significant.

For 1977-2003, negative correlations between year-of-fire winter precipitation and WFAB for the Sierra Nevada and Southern Rockies indicate a limiting influence of above-average snowpack on fires in these ecoprovinces. The other mountainous ecoprovinces share this relationship between 1916 and 2003. Most ecoprovinces exhibit a negative relationship with winter precipitation, but few are significant. These relationships all suggest that the drying of fuels is the primary mechanism for large WFAB in the higher elevation and northern mountainous ecoprovinces. These ecoprovinces thus appear to be climate and/or ignition limited.

In contrast, much of the southwestern U.S. appears to require a more complicated mechanism for large WFAB. AM.SemDes, AZNM.Mts, Chi.SemDes, CP.SemDes, and IM.SemDes are all best correlated with climate variables consistent with climatic facilitation of vegetation growth the winter prior to fire and secondarily with moderate climatically driven drying of fuels the year-of-fire. These ecoprovinces appear to be in the middle of the gradient between fire regimes that are exclusively fuel limited and those that are primarily climate limited, with elements of both apparent, especially in the 1916-2003 correlations and regression models. These results corroborate prior inferences about climate-fire relationships in the Southwest (Westerling et al. 2002, 2003, Crimmins and Comrie 2004).

The 1977-2003 climate-fire models for California coastal ecoprovinces confirmed some of the relationships Keeley (2004) described for the central and south California coast. Keeley found that area burned in the central Californian coast was negatively correlated with summer precipitation, which I observed in CalC.Wood and CalC.Chap. Winter PDSI and temperature were also important relationships in Keeley's analysis, and I observed comparable results. Lagged spring temperature was also common between the two studies.

The repeated importance of winter climate variables in the correlation and regression analyses reveal the capacity for antecedent climate to precondition large fire years in the American West, presumably via water stored in snow or soil. While I did not examine snowpack explicitly, the sensitivity of ecoprovince WFAB to winter precipitation and drought merits further investigation. If the observed late 20th century trend toward winters with warmer temperature, lower snowpack, and increased proportion of rain in low-to-mid elevation precipitation in the western U.S. (Mote et al. 2005) continues, increases in the area burned by fire are likely in lower elevations of mountainous ecoprovinces. In the Southwest, the role of winter conditions in future area burned depends on how much winter precipitation falls as snow and how long it persists. Warming spring and winter conditions will presumably continue to lengthen the fire season in these areas, and if this results in less favorable conditions for fine fuel production by eliminating the carryover of soil moisture, WFAB might decrease because vegetation production will decrease. If, on the other hand, the combination of warmer and wetter conditions leads to increased vegetation production, the earlier onset of dry fuels with a longer growing season could lead to increased WFAB.

A concise interpretation of climate-vegetation-fire mechanisms for each ecoprovince is challenging. Ecoprovinces of the western U.S. are heterogeneous in their vegetation composition, especially in mountainous areas, (e.g., SRM.SOWC, which stretches from open woodland to alpine meadows). The mixture of sensitivities observed in some ecoprovince regression models probably represents the mixture of vegetation types, but it is also possible that the change in protected area influenced the results despite my attempt to control for it. Moving correlations (not shown, Littell et al. in prep) indicate that non-stationary climate-fire relationships may exist, especially in ecoprovinces that are in the middle of the climate-to-fuel gradient of limitations such as the southwestern ecoprovinces.

Ecosystem Controls on Climate-Fire Relationships

The relationships described above suggest that a contrast between “fuel limited” and “climate limited” fire regimes in Western ecosystems does not hold up under close scrutiny at the scale of ecoprovinces. For example, the northern/mountain ecosystem pattern is characterized by positive temperature and negative precipitation correlations and diagnostic model terms that suggest drying of fuels is the proximate mechanism. However, secondary relationships more consistent with fuel production are also significant such as in NRM.FSC and Sier.Mix, which both have positive correlations with lagged winter precipitation. In the 1916-2003 diagnostic regression models, Casc.Mix, NRM.FSC, and MRM.FSC also have positive lagged winter precipitation terms. In a given year, several climatic mechanisms can together produce a year with large WFAB. Statistically speaking, the most common of these additive influences can produce diagnostic models that capture most of the variability in WFAB, but the residual variance (Figure 2.4 and 2.5) evident in most models implies a noisy relationship. It is possible, from an ecological perspective, for one climatic variable (e.g., a summer drought) to override *or* add to the impacts of an antecedent climatic variable (e.g., high winter snowpack) depending on vegetation type. Given this variability, it may be important to evaluate the future impacts of climate change on fire in the West for a variety of vegetation types and relative sensitivities to different combinations of climate. Most ecoprovinces have stronger characteristics of fuel or climate limitation, but the results support the idea that there is a range of vegetation types and seasonal climates that produce both fuel and climate limitation of fire.

The ecoprovince concept clarifies climate-fire relationships in terms of dominant vegetation type. My study confirms that effects of high temperature, low precipitation, and drought on fire hold most strongly in forested ecosystems where these factors, in the months leading up to and during the fire season, have strong effects on WFAB. However, the influence of above-average antecedent precipitation in ecosystems dominated by grass-shrubland is clear. Differences in ecoprovince vegetation and climate-fire relationships also imply that the area burned by fire does not mean the same thing ecologically in all places. Fire severity is probably a much better indicator of the ecological impacts of a fire, large or small, on an ecosystem. The relationship between climate and fire severity, measured across different vegetation types, might give better insight into the future impacts of climate than area burned alone.

Previous fire history evidence for the antecedent influence of precipitation on fire in dry forest ecosystems (Swetnam and Betancourt 1998) is consistent with the relationships I observed. The positive influence of high antecedent precipitation on fire is more widespread than fire histories from the southern and middle Rocky Mountains alone would imply, although it is difficult to interpret ecologically without knowing exactly how much of the relationship is attributable to fires occurring in lower elevation montane forests. Knapp (1995) found similar predictive capacity in antecedent climate variables for ecosystems in the Great Basin. Westerling et al. (2002) observed a more widespread wet-dry pattern that expanded on that observed by Swetnam and Betancourt (1998). I show that the antecedent relationship is driven by precipitation more than PDSI and temperature and is much more widespread, occurring even in ecoprovinces with a significant fraction of mountain and forested area.

The hypothesized mechanism of fuel limitation, fuel production, and fuel drying appears reasonable for grass, shrub, and open-forest ecosystems where surface fires are common. But why would antecedent winter precipitation be a positive (though small) influence on WFAB in forested ecosystems where transient fuels are not likely to be important drivers of fire (e.g., Bessie and Johnson 1995)? It is possible that the nature of understory fuels is poorly understood, both in their sensitivity to climate (drying and productivity) and their dynamics through time at regional scales. Alternatively, there may be a necessary distinction between the cause of fire starts and the factors that influence fire spread (Knapp 1995). While my analyses indicate that year-of-fire climate is the strongest influence on area burned in forested ecosystems, fire size may be limited secondarily by fuel continuity between or within forest stands (Rollins et al. 2002). Continuity may be less limiting for fire regimes in which crown fires are the dominant mechanism than, for example, in lower elevation forests characterized by surface fires, but my analysis does not have the detailed vegetation data required to address this. I did not analyze fire starts, but the relationship between WFAB and antecedent climate could reasonably be expected to be stronger than for more proximate causes associated with fire starts such as atmospheric conditions governing storms during the fire season (Schaefer 1957, Schroeder 1969, Gedalof et al. 2005).

Climate variables were sufficient to explain variations in WFAB in many ecoprovinces for the period 1977-2003. Especially successful predictions in the southwestern and western mountain ecoprovinces demonstrate the potential to use climate variables for predicting WFAB in most of the ecoprovinces in the West. Explained variance for the full 1916-2003 reconstructions may be lower than for 1977-2003 because the linear relationships are not stationary or the reconstructions do not adequately estimate WFAB earlier in the century. The latter explanation appears to be unfounded, because the reconstructions explained most of the variance observed for most ecoprovinces (Table 2.2), produced P.R.E.S.S. RMSE values generally consistent with mean WFAB (Table 2.2), and captured the total area burned (Figure 2.3). The former explanation, while not treated explicitly here, is possible given the influence of decadal climate variability on fuel moisture and production, the influence of shifts in fire policy and human ecosystem management on land use, or the role of different climate-vegetation interactions within an ecoprovinces over time. The fact that I was able to account for most of the WFAB with a few climate variables and the fact that the patterns of climate-fire associations make sense given ecoprovince vegetation structure shows that climate impacts to fire in the western U.S. are diverse and must be considered in the context of ecosystem vegetation and its response to climate. The strong relationships I observed in the mountainous ecoprovinces also suggest that fire disturbance is perhaps more likely to be a more dominant driver of ecosystem change than climate-mediated changes in community structure. Although on average less than a few percent of the area of ecoprovinces burn in a given year (Table 2.1), the ecological effects of these fires are locally important, and over time, might contribute to relatively rapid ecosystem changes. Those ecosystems in which WFAB is sensitive to temperature (especially the facilitating role of fire-season temperatures in depleting soil moisture through evapotranspiration) are especially vulnerable in the short term. The uncertainty associated with future patterns of precipitation (both spatial and seasonal) represents a large source of uncertainty for ecoprovinces that are largely sensitive to precipitation and drought (McKenzie et al. 2004).

Implications for Ecosystem Management

The climate-fire relationships presented here are a useful advance in identifying ecosystem-specific mechanisms relating climate to WFAB. Ecoprovinces proved a useful compromise between ecologically imprecise state-level aggregations of fire data and highly localized gridded fire data, and the differences in climate-fire relationships among the ecoprovinces underscore the necessity of considering ecological context (vegetation, fuels, and seasonal climate) to identify specific climate drivers of fire area burned. Future research should relate WFAB to the seasonality of proximate climate mechanisms such as water balance deficit, soil moisture, and foliar moisture. Similarly, multi-scale predictive models that link hemispheric climate variability to sub-regional climate and vegetation production and drying could significantly improve prediction of WFAB. The impacts of fire suppression, changes in land use, and public land management could then be assessed in the context of known climate-fire relationships derived from such models. Fire-based ecosystem management strategies might also be refined. Other applications include fire area burned forecasting (e.g., Westerling et al. 2002) and the capacity to develop future climate-fire models based on a much larger range of climate conditions than the standard late-20th century datasets. The ecological impacts of climate change can potentially lead to larger and more frequent fires, and to cascading effects on vegetation and carbon balance (e.g., Kasischke et al. 1995) and other ecosystem services.

Climate controls on the area burned by wildfire in the western U.S. are strong, even through the dominant period of fire suppression and exclusion in the last two-thirds of the 20th century. Roughly 39% (1916-2003) to 64% (1977-2003) of the fire area burned can be related directly to climate. The unexplained variability could be due to a number of factors, including fire suppression, land use, or climate variables I did not consider. Statistically, variance could also be explained by tailoring the scale of climate and fire relationships to more specific ecological divisions, although there is a law of diminishing returns until the area and location of all large fires in the 20th century is known. The variance that is explained by climate, however, implies that fuel treatments, for example, might be tailored to specific ecosystems and climate-fire relationships. Recognizing that most ecoprovinces have significant ecological variability, climate-limited ecoprovinces may be less influenced by fuel treatment than fuel-limited ecoprovinces (at least for area burned, if not fire severity). This argument also implies that ecosystem managers' responses to climate change might be more or less limited depending on the nature of fire-climate limitation. In fuel-limited ecosystems, fuel-treatments can probably mitigate fire vulnerability and increase resilience more readily than in climate-limited ecosystems where adaptation to climate change is a more realistic approach.

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CHAPTER 3
DOUGLAS-FIR GROWTH IN MOUNTAIN ECOSYSTEMS: WATER LIMITS TREE GROWTH FROM STAND TO REGION

Summary

The long-term impacts of climate on tree growth are understood primarily at highly local scales through detailed ecophysiological studies or at broad scales through dendroclimatic reconstruction derived from the most climatically-sensitive trees in a population. The former approach is generally limited to local scales, short time periods, or both. The latter approach is generally limited in its extrapolation to the rest of a species' range. To understand the climatic limitations on tree growth across a species' range, sampling methods must consider the full gradient of climatic conditions as well as the factors influencing growth-climate relationships at multiple scales. In this study, I used a multi-scale sampling strategy that considers continentality, physiography, and topography as non-climatic factors that could influence the relationship between tree-growth and climate. I developed a network of Douglas-fir (*Pseudotsuga menziesii*) tree-ring chronologies from the western Olympic Peninsula in Washington to the eastern Rocky Mountain Front in Montana. Growth-climate correlations across the sampled gradients consider two different scales of climate variables as potential controlling factors on tree growth. Annual radial growth in 60-65% of the plots across the entire region is significantly correlated with variables describing precipitation, drought or water balance during the late summer prior to growth and the early summer the year of growth. Few plots are significantly positively correlated with cool-season temperature or negatively correlated with snowpack. Water availability is therefore more commonly limiting to Douglas-fir growth than factors influencing the length of the growing season.

The first principal component derived from the sampled chronologies is significantly correlated with independent tree-ring reconstructions of Palmer Drought Severity Index. However, the PDSI reconstruction has a stronger expression of droughts and wet periods suggesting that the gradient sampling method sacrificed some dendroclimatic sensitivity. The sampled Douglas-fir population's sensitivity to summer water balance deficit (potential evapotranspiration minus actual evapotranspiration) indicates that increases in

April to September temperature without increases in summer precipitation or soil moisture reserves are likely to cause decreases in growth over much of the sampled area, especially east of the Cascade crest. In contrast, Douglas-fir at some higher elevation sites where seasonal photosynthesis is currently limited by growing-season length or low growing-season temperature may exhibit increases in growth. From a management perspective, the potential for increases in susceptibility to combined impacts of drought, insects, and/or fire over larger areas is probably more important than a decline in Douglas-fir growth rates. However, life-history processes such as establishment, growth, and morality are precursors to changes in biogeography, and measurements of climate impacts to those processes can provide early indications of severe climate change impacts on ecosystems.

Introduction

Tree species' sensitivity to climate at continental scales is usually described in terms of biogeographic distribution; the factors limiting species ranges are often at least partially climatic (e.g., Thompson et al. 2000). Range limits for long-lived trees represent the integration of limitations on establishment, growth, and reproduction at time scales of several decades or longer. Effects of climate, therefore, influence life-history processes such as growth (Peterson and Peterson 2001) and seedling establishment (Daniels and Veblen 2004) well before noticeable biogeographic changes occur. Extreme events, such as multi-year droughts or large fires, can produce broad-scale, temporally coherent pulses of mortality that lead to rapid ecological changes (Allen and Breshears 1998). However, climate can also lead to gradual shifts in population or community processes such as differential species growth, turnover, or establishment play a role in biogeographical changes by altering community composition over large areas. Changes in growth and establishment (Stephenson and van Mantgem 2005) may presage measurable mortality in established trees. Understanding climate-mediated population processes, especially their underlying mechanisms and geographic distribution, is a key step to better prediction of climate-change impacts to forest ecosystems. For example, to model the future response of forest vegetation, quantitative relationships derived from long-term climate data and observed population processes at multiple scales can be efficiently extrapolated across mountain terrain where such data are generally lacking. In this paper, I describe the application of hierarchical sampling, dendroecological methods, and gradient analysis to improve understanding of the climate mechanisms limiting growth of Douglas-fir in montane forests of the northwestern United States (U.S.)

Growth-climate relationships derived from dendrochronological data represent one metric of temporal variation in climate-mediated ecosystem processes (Graumlich et al. 1989, Graumlich and Brubaker 1995). Variance in tree rings is typically controlled by the factors most influencing growth (Fritts 1976), and tree-ring evidence from a wide variety of biophysical settings supports the idea that tree growth is limited by water in some ecosystems and by energy (growing season length, degree days, or mean temperature) in other ecosystems (Waring and Running 1998). In arid ecosystems (usually montane to lower treeline), the interannual variability in tree rings is primarily related to factors affecting water supply, especially precipitation (Douglass 1919, Fritts 1974) or water balance deficit (Pederson et al. 2006), while in ecosystems where precipitation is more abundant or energy is more limiting (usually subalpine or high latitude), factors affecting the length of the growing season (e.g., growing season temperature or snowpack) explain most of the variability in tree growth (Graumlich and Brubaker 1986, Peterson and Peterson 1994, Peterson and Peterson 2001, Peterson et al. 2002, Nakawatase and Peterson 2006).

Abiotic gradients in ecologically limiting factors, such as climate, occur at multiple scales. Ecological amplitudes of species are expected to be unimodal with respect to a single biotic or climatic gradient (Whittaker 1956), but can be shown to have non-normal distributions in practice when multivariate climate relationships are considered (McKenzie et al. 2003). For example, growth rates of mountain hemlock (*Tsuga mertensiana* (Bong.) Carr.) exhibit complex relationships in response to summer temperature (positive) and winter snowpack (negative) (Graumlich and Brubaker 1986, Peterson and Peterson 2001).

What is the distribution of tree-growth relative to climate across wide ranges of biophysical conditions for a species with broad ecological amplitude? The first step in answering this question empirically is to address growth-climate relationships for stands and scales traditionally not sampled in dendroclimatic studies (Littell and Peterson 2005) in order to understand growth-climate relationships for the rest of the population. To do this, it is necessary to consider the factors affecting the local climate to which such stands are subjected. For example, local topography can mediate the climate of a forest stand and moderate or exacerbate the influences of regional climate (Bunn et al. 2005, Holman and Peterson 2006). At larger scales, physiographic and topographic variability in the mountainous western U.S. lead to two extremes within forest ecosystems: those that are characteristically water limited in places where annual precipitation is much less than potential evapotranspiration and those that are energy limited where potential evapotranspiration is much less than precipitation (Stephenson 1990). This contrast occurs because of the water and energy limits on photosynthesis. When environmental conditions are such that more water can be evaporated and transpired than falls as precipitation, plant photosynthesis is water limited. On the other hand, when more precipitation falls than can be evaporated or transpired, thermal or light energy tends to be more limiting. Finally, hemispheric patterns of ocean-atmosphere interactions affect regional and sub-regional climate variability on time scales of years to several decades (e.g., Wang and Schimel 2003, McCabe et al. 2004). These patterns exert strong effects on regional climate that have the potential to temporarily override conditions usually determined by local topography or physiography. Significant progress in understanding current and future climatic limitations on growth (and by proxy, other ecological processes such as productivity and ecosystem carbon balance) will be achieved if the mechanisms of such limitations are quantified across important climatic dimensions of a species' niche (i.e., a realized Hutchinsonian hypervolume (Hutchinson 1957) with some dimensions principally defined by climate).

To understand the climatic limitations on tree growth across a species' range, sampling methods must consider the full gradient of climatic conditions in that range as well as the factors (e.g., topography) influencing growth-climate relationships at multiple scales. (Littell and Peterson 2005). Networks of precipitation-sensitive (Watson and

Luckman 2001, 2002) or temperature-sensitive trees (e.g., Wilson and Luckman 2003, Pederson et al. 2004) have been developed for the purposes of climate reconstruction, but networks to examine variability in climate sensitivity across the biophysical niche of a species have not been established. Such a network would be an important step towards estimating the effects of climate change on growth and would be more informative than one based on only a small fraction of regional tree populations with known sensitivity (i.e., those most useful for dendroclimatic reconstruction) (Littell and Peterson 2005).

Prior research on growth-climate relationships in northwest Douglas-fir has focused on evaluating the role of climate in tree growth (Brubaker 1980, Case and Peterson 2005) and productivity (Hessl and Peterson 2004, Nigh et al. 2004) or on reconstructing climate from tree-ring sequences (e.g., Biondi 1999, Watson and Luckman 2002, Pederson et al. 2006). Brubaker (1980) described a dominant pattern of positive correlation between spring-summer precipitation and Douglas-fir growth across most of Washington, northeastern Oregon and northern Idaho, with a secondary contrast between the negative (west of the Cascades) and positive (east of the Cascades) correlations with winter precipitation and summer temperature. Short-term growth variability was predominantly related to growing season precipitation in several lower-elevation Cascades sites (Brubaker et al. 1992). Little et al. (1995) related low-elevation Douglas-fir growth to climate in the Siskiyou Mountains of Oregon and found moderate influences of temperature (negative) and precipitation (positive) on growth. In British Columbia and Alberta, Watson and Luckman (2002) demonstrated regionally coherent patterns of significant climate correlations with Douglas-fir growth. Precipitation was positively correlated with growth in some chronologies in all months between April of the year prior to growth and August the year of growth, with the greatest sensitivity to prior July/August and current May/June precipitation. Temperature relationships with growth were negative during the growing season and weakly positive in winter, with the largest number of chronologies responding negatively to prior July and current June temperature. Pederson et al. (2006) found similar relationships for Douglas-fir in Glacier National Park in the northern U.S. Rockies and concluded that mean summer water deficit and Palmer Drought Severity Index (PDSI) best described patterns of growth-climate correlations during the 20th century.

Recent studies have diverged from the emphasis on populations useful for climatic reconstructions and have examined growth-climate relationships across a range of environmental conditions (Case and Peterson 2005, Littell and Peterson 2005). Growth-climate relationships of several subalpine conifer species varied substantially according to climate and location (Villalba et al. 1994). Similarly, efforts to describe the growth-climate relationships in diverse forest environments in the Pacific Northwest have focused more specifically on the controls on tree-growth than on dendrochronological interpretation (Case and Peterson 2005, Holman and Peterson 2006, Nakawatase and Peterson 2006). Case and Peterson (2005) conducted an intensive dendroecological census of Douglas-fir in a North Cascade Range (Washington, U.S.) watershed and found both precipitation facilitation (lower elevation stands) and snowpack limitation (higher elevation stands) along a 1000-m elevation gradient. Two studies of growth-climate relationships in the Olympic Mountains of Washington showed that local conditions sometimes buffered growth in multi-species stands (Holman and Peterson 2006) from regional climate variability that clearly influenced growth at sub-regional scales in forest types limited by summer drought or snow (Nakawatase and Peterson 2006). Elevation, aspect, and slope are frequently successful predictors of vegetation responses (e.g., distribution, growth, etc.) to climate, but this success is a function of the strong autocorrelation of the topographic environment with physical conditions to which plants are actually sensitive (Lookingbill and Urban 2005). A key step in advancing understanding of the spatial and temporal processes that limit tree growth is to develop better plant-relevant climate predictors that help us understand how climate-growth relationships vary with topography (local) and physiography (sub-regional).

In this study, I use radial growth data from a network of Douglas-fir stands (coast Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii*]; Rocky Mountain Douglas-fir [*P. menziesii* var. *glauca* (Beissn.) Franco]) to develop growth-climate relationships along a gradient of maritime-to-continental climate in the northwestern U.S. The distribution of Douglas-fir covers a large range of climatic (Thompson et al. 2000) and ecological (Franklin and Dyrness 1988, Hermann and Lavender 1990) conditions. I use and extend dendroecological principles by establishing growth-climate relationships along abiotic gradients that encompass the range of environments inhabited by Douglas-fir in Washington (WA), Idaho (ID) and Montana (MT). My objective in this study is to describe the patterns of correlations between Douglas-fir growth and climate across a significant portion of its range in this region. My working hypothesis is that growth-climate relationships for Douglas-fir are structured along a gradient of water-balance deficit that integrates limiting and facilitating components of temperature and precipitation. Specifically, the climate variables most limiting to growth are spatially variable (e.g., Brubaker 1980, Case and Peterson 2005) but consistent with the local ecohydrological regime: at some threshold, water ceases to be the most limiting factor in the environment and energy begins to be more limiting.

Methods

Study Area

This study focuses on mountain ecosystems between the maritime western Olympic Peninsula in western Washington and the continental eastern slope of the Rocky Mountains in northwestern Montana. A longitudinal transect from 124° to 113.3° W between 47.5° and 49° N latitude passes through four targeted sampling areas: Olympic National Park (ONP), North Cascades National Park (NCNP), the Selkirk Mountains in the Idaho Panhandle National Forest (IPNF), and Glacier National Park (GNP) (Figure 3.1). The three national parks are part of the CLIMET transect (Fagre et al. 2003).

Mean climate varies from maritime ONP (warm, wet winters and cool, dry summers) to continental GNP (cold, dry winters and warm, dry summers) (Table 3.1). Mean climate for the sampled watersheds is summarized in Table 3.2; specific climate variables for each sample plot are in Appendix 1. Annual precipitation decreases from west to east along the transect (533 cm at highest plot elevations in ONP to 68 cm at lowest plot elevations in GNP). Mean January temperature varies by 14°C between warmer sites in the ONP (4°C) lowlands and colder sites in GNP (-10°C); mean July temperature ranges from ~10°C in GNP to ~19°C in NCNP and IPNF (Figure 3.2).

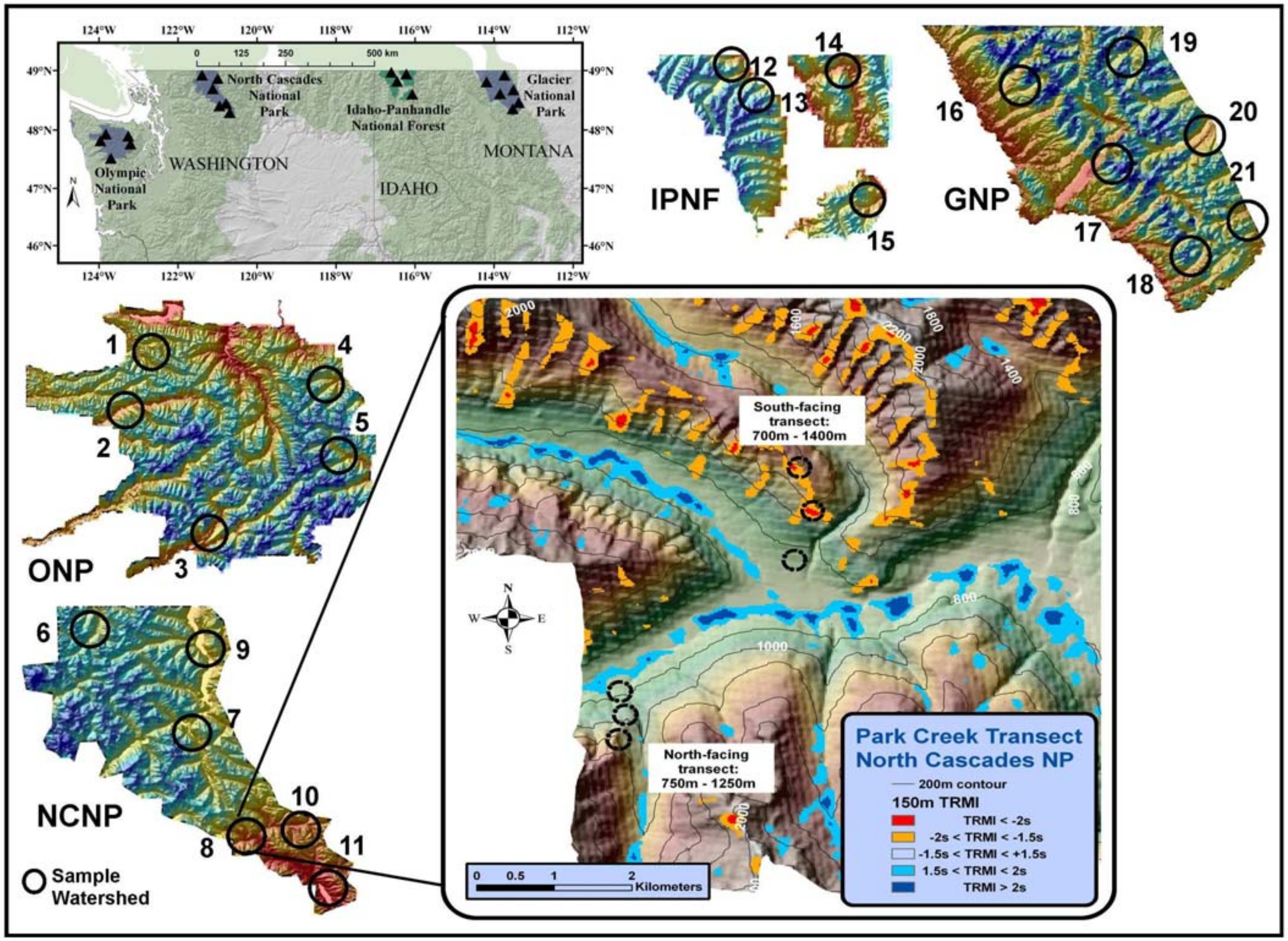

FIGURE 3.1. Hierarchical Sampling of the Study Area. Sample sites in four areas comprise the network of tree-ring sites describing the range of Douglas-fir in the northwestern U.S. Sample watershed numbers refer to site numbers in Table 3.2. Shading in the upper left inset indicates the range of Douglas-fir. Shading in sample areas indicates the JJA precipitation (red is -2σ, blue is +2σ for each sample area). Lower right inset shows TRMI and location of plots in one sampled watershed

TABLE 3.1. Hierarchical Sampling Strategy for Evaluating Douglas-fir Growth Responses to Climate

Hierarchy level	Location	Range of DAYMET targeted climate	
		Ann. precipitation (cm)	July temperature (C°)
Continentality: 1 transect	Latitude 47.5-49.0 North, Longitude 124.0-113.3 West.	Maritime - continental	Maritime - continental
Physiography: Four mountain ranges, each with west/east rainshadow	Olympic Mountains: Olympic National Park (ONP)	244 - 533	11.6 – 16.1
	Cascade Mountains: North Cascades National Park (NCNP)	92 - 219	12.4 – 19.8
	Selkirk Mountains: Idaho Panhandle National Forest (IPNF)	71 -128	14.0 – 18.6
	Northern Rocky Mountains: Glacier National Park (GNP)	68 - 190	9.2 – 17.5
Watershed topography: Aspect and elevation Two aspects x three elevations	North and south aspects Lowest, mid, highest local elevation	Approx. same Low Mid High	Less north More south High Mid Low
Stand: trees within plot 10-15 trees per plot, one core per tree	None: Fundamental sampling unit		

TABLE 3.2. Transect Characteristics. Mean climate (1915-2003)*, substrate, soil, and forest type for sample watersheds.

Map #	Transect	Latitude	Longitude	Annual temp (C°)	Annual precip (cm)	Annual deficit (cm)	Parent material[1]	Predominant soil[2]
1	Sol Duc ONP	47.9	123.8	3.3	349	1.3	OE metasandstone	Entisols (xerorthents)
2	Hoh River ONP	47.8	124.0	6.8	352	2.2	ME metasandstone	Entisols (xerorthents)
3	Quinault ONP	47.5	123.7	6.2	411	1.5	EP metasandstone	Entisols (xerorthents)
4	Gray Wolf ONP	47.9	123.3	2.7	199	4.9	EP metasand./volc.	Entisols (xerorthents)
5	Dosewallips ONP	47.7	123.2	1.3	215	2.5	OE metasandstone	Entisols (xerorthents)
6	Chilliwack NCNP	48.9	121.4	1.6	245	0.8	O granite/int. rhy.	Inceptisols (haplaquepts)
7	Thunder Creek NCNP	48.7	121.1	3.5	219	7.3	TK granitic gneiss	Inceptisols (haplaquepts)
8	Park Creek NCNP	48.4	120.9	1.3	170	10.0	TK granitic gneiss	Inceptisols (xerochrepts)
9	Desolation Peak NCNP	48.9	121.0	2.7	240	8.3	PM calc-pyroclastic	Inceptisols (haplaquepts)
10	Bridge Creek NCNP	48.5	120.8	2.6	143	13.8	TK granitic gneiss	Inceptisols (xerumbrepts)
11	Stehekin NCNP	48.3	120.7	2.0	115	15.6	TK granitic gneiss	Inceptisols (xerumbrepts)
12	Boundary Mt. IPNF	49.0	116.6	2.4	121	5.6	Y/K metam. granite	Mollisols (cryoborolls)
13	Trout Creek IPNF	48.8	116.5	4.1	72	15.3	Y/K metam. granite	Mollisols (cryoborolls)
14	Round Prairie IPNF	49.0	116.2	3.5	85	11.7	Y metam. granite	Mollisols (cryoborolls)
15	Leonia Knob IPNF	48.6	116.1	3.5	98	10.3	Y metam. granite	Mollisols (cryoborolls)
16	Bowman Lake GNP	48.8	114.2	0.8	124	5.2	p argillite / T sedim.	Mollisols (haploxerolls)
17	Lake MacDonald GNP	48.6	113.9	2.8	101	7.6	p argillite / T sedim	Mollisols (haploxerolls)
18	Soldier Mt. GNP	48.3	113.5	1.5	118	5.0	p argillite / T sedim.	Mollisols (haploxerolls)
19	Belly River GNP	48.8	113.7	-0.7	170	2.7	p argillite / p limest.	Mollisols (cryothents)
20	Saint Mary GNP	48.7	113.5	-0.6	160	2.8	p limestone	Mollisols (cryothents)
21	Two Medicine GNP	48.5	113.4	-0.6	124	3.9	Q glacial / p argillite	Mollisols (argiborolls)

* VIC climate is used here to describe the mean climate for each transect.

[1] Substrate units : Q = Quaternary, O = Oligocene, M = Miocene, E = Eocene, T = Tertiary, K = Cretaceous, P = Paleocene, Y = middle Proterozoic, p = Precambrian. Virtually all transects have Quaternary glacial/alluvial deposits in valleys, and low elevation plots are situated on these.

[2] Soil Survey Staff, USDA NRCS

Dominant parent materials are marine sandstone with valley-bottom Quaternary glacial deposits in ONP; metamorphosed gneiss, orthogneiss, and granodiorite (with other intrusions and Quaternary deposits) in NCNP; metamorphosed granite in IPNF; and metamorphosed sedimentary rock in GNP. Soils are generally rocky, skeletal, with a various taxonomic classifications (Table 3.2).

The composition of forest types with canopy Douglas-fir vary with elevation, aspect and location along the sample transect. Pure or nearly pure stands of Douglas-fir occur in all four areas, but are most common in eastern ONP and NCNP. In western ONP, lowland forests are dominated by Sitka spruce (*Picea sitchensis* (Bong.) Carr.), western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), and western redcedar (*Thuja plicata* Donn ex D. Don). At higher elevations, Douglas-fir grows with Pacific silver fir (*Abies amabilis* Dougl. ex Forbes), western hemlock, mountain hemlock and subalpine fir (*Abies lasiocarpa* var. *lasiocarpa* (Hook.) Nutt.). In eastern ONP and northwestern NCNP, Douglas-fir and western hemlock are often the dominant species at low elevations, with important components of western redcedar, grand fir (*Abies grandis* (Dougl. ex D. Don) Lindl.), or, in drier sites, lodgepole pine (*Pinus contorta* Dougl. ex Loud. var. *latifolia* Engelm.). In southeastern NCNP, Douglas-fir, ponderosa pine (*Pinus ponderosa* Dougl. ex Laws), and lodgepole pine are common low elevation species. High elevations in eastern ONP and NCNP are similar to those in western ONP, including western hemlock, mountain hemlock and Pacific silver fir; in more continental areas, lodgepole pine, subalpine fir, and Engelmann spruce (*Picea engelmannii* Parry ex Engelm.) are dominant or codominant on dry high-elevation sites. In IPNF and western GNP, western larch (*Larix occidentalis* Nutt.), western hemlock, Douglas-fir, and ponderosa pine, with occasional western redcedar, are common at low elevations, High elevations in IPNF include western white pine (*Pinus monticola* Dougl. ex D. Don), subalpine fir, western hemlock, and western larch. High elevations in GNP include lodgepole pine, subalpine fir, Engelmann spruce, and occasionally whitebark pine (*Pinus albicaulis* Engelm.).

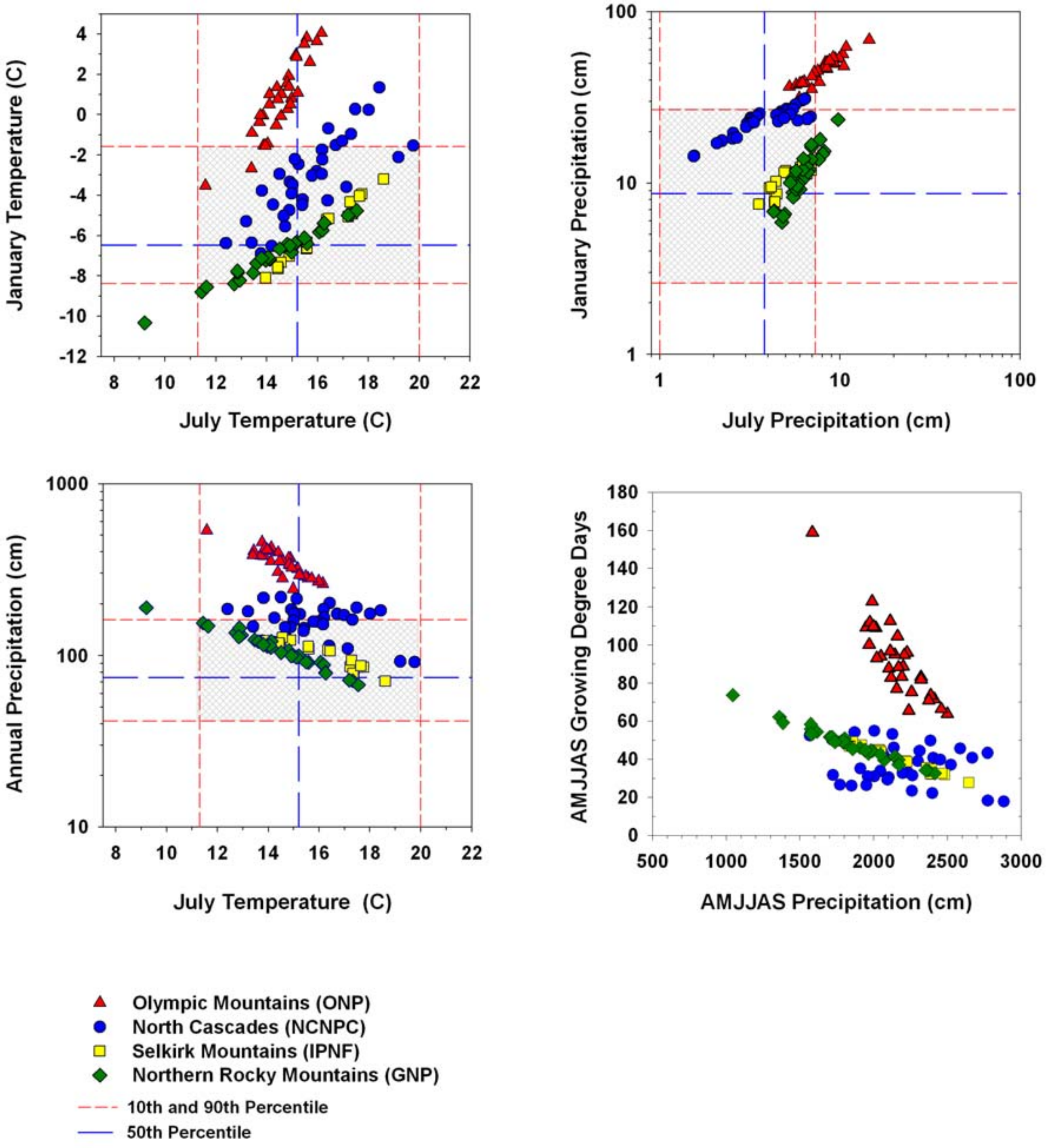

FIGURE 3.2. Climate Sampling Space for Douglas-fir. The sample sites are along a transect from the maritime western Olympic Peninsula, Washington to the continental eastern slope of the Rocky Mountains, Montana. Shaded boxes indicate the two-dimensional climate niche for Douglas-fir for the North American continent. Values of plot locator points were determined from DAYMET maps of the indicated climate variables for the period 1980–1997. Sampled plots are depicted in two dimensional climate space for. Dash/dot (10th and 90th percentile limits) and bold dashed lines (50th percentile median) indicate continent-wide climatic limits for Douglas-fir described in Thompson et al. (2000).

Site Selection and Sampling

I used a combination of geospatial analysis and sampling theory to identify sampling locations in each of the four targeted areas, (Figure 3.1). My sampling design was informed by four nested factors that bracket variability in growth as a function of climate (Table 3.1). First, the location of a stand along the maritime-to-continental gradient influences the amount and seasonality of temperature and precipitation. The CLIMET project transect (Fagre et al. 2003), from the maritime Olympic Peninsula in Washington to the continental eastern slope of the central Rocky Mountains in Montana, provided a prototype for this gradient. Second, the mountainous terrain in western North America influences climate, especially precipitation, via orographic and rain shadow effects (e.g., Loik et al. 2004). I focused on a few watersheds on each side of the Olympics, Cascades, Selkirks, and northern U.S. Rockies to bracket this physiographic variability (Figure 3.1, Table 3.2). Third, within a watershed, aspect influences local climate by modulating the daily and seasonal distribution of light and temperature and, as a consequence, moisture through evapotranspiration. I sampled generally north-facing and south-facing slopes within each watershed to provide maximum contrast in topographic influence on climate. Finally, elevation within an aspect determines the seasonal distribution of degree-days, precipitation, and snowpack duration (e.g., Running et al. 1987). I bracketed local Douglas-fir elevation ranges from valley floors to its local maximum elevation to sample the largest range of biophysical conditions possible.

I used geostatistical analysis of the watershed topography (slope, aspect, and elevation from USGS 10-m digital elevation models) to identify plot locations and regional 1980-1997 climate normals (DAYMET, 1-km resolution, Thornton et al. 1997) to evaluate watershed, rainshadow, and physiographic distributions of precipitation and a soil moisture proxy (topographic relative moisture index, TRMI, Parker 1982). Low values of TRMI indicate high runoff, sunlight, and day length (steeper slopes, convex terrain, south facing); high values of TRMI indicate low runoff and ambient energy (shallower slopes, concave terrain, north facing). TRMI provides a useful means of comparing local (~100-m x 100-m) topographically influenced water availability. DAYMET climate normals (1980-1997) allowed us to select target watersheds (Figure

3.1) with different mean precipitation. The sampling strategy outlined in Table 3.1 produced gradients of DAYMET climate parameters that bracket a substantial fraction of the range of Douglas-fir in the western U.S. (Figure 3.2).

Tree-ring Data

In 2003 and 2004, I located each plot with a global positioning system (GPS) unit and sampled a single increment core from 10-15 canopy dominant Douglas-fir in each plot (variable density plots). Each plot was defined *a priori* as relatively homogeneous in aspect, slope, and TRMI. Minimum sample size was determined by comparing published estimates of the mean number of trees required to achieve an appropriate signal quality in Douglas-fir dendroclimatic reconstructions (Mäkinen and Vanninen 1999, Watson and Luckman 2002). In practice, some plots had higher sample numbers than others because I was able to crossdate both cores extracted in the field to compensate for broken or otherwise incomplete samples. To minimize the influence of disturbance on growth-climate relationships, I avoided plots with obvious signs of recent disturbance by fire, insects, or windthrow; in some cases this criterion required that I locate substitute plots in comparable landscape facets.

Using standard dendrochronological techniques (Stokes and Smiley 1968, Fritts 1976, Pilcher 1990), I prepared all samples and measured tree-ring widths to the nearest 0.002 mm. All samples were visually crossdated and then checked for missing rings or other crossdating errors with the program COFECHA (Holmes 1999). I produced standardized residual tree-ring chronologies for each elevation and both aspects within each watershed for six plot chronologies per watershed.

A double detrending (standardization) method was employed (Fritts 1976) to remove biological growth trends and minimize the influence of unidentified stand disturbances or inter-tree competition. The first detrending was intended to remove the age-related growth trend using a negative exponential curve or linear trend line of negative or zero slope (Cook and Holmes 1999). In 10 younger (<100 yr) plots, the linear alternative often resulted in predicted values <0, and in these cases I employed Hugershoff growth curves (Briffa et al. 2001) in an attempt to simultaneously include the earliest portion of the tree's growth and still retain a reasonable detrending fit to the rest of the time series. The second detrending was intended to remove any residual stochastic (with respect to climate) age trends induced by stand dynamics, and I used a cubic smoothing spline (CSS) that preserved 50% of the variance at 128 yr frequency. I opted to stabilize the variance using a hybrid method that accounts for changing sample size and other sources of heteroscedasticity, such as a strong relationship between the variance and the mean ring width over the span of a tree's life. I used both the rbar method (Briffa 1995) and a CSS equal to 67% chronology length because sample size changed appreciably through time in many plots. Finally, the residual chronology was developed using autoregressive modeling tailored to the autoregressive order of each tree to account for the autocorrelation that can be imparted by climatological, ecophysiological and morphological influences on tree growth. The biweight robust mean of all series (Cook and Holmes 1999) was calculated to reduce error attributable to non-synchronous disturbances in the final mean chronology (Cook 1985). This procedure produces a time series with uncorrelated temporal error for each plot that can be statistically compared to climatic time series without artificially inflating correlation measures of linear association.

For each chronology, I calculated mean sensitivity (MS, Fritts 1976), first-order autocorrelation, expressed population signal (EPS, Wigley et al. 1984), and number of trees required to exceed an EPS value of 0.85. All these parameters describe the nature of the variability in the chronologies. MS describes the year-to-year variation in ring widths, and is one indicator of the degree to which interannual perturbations (e.g., climate) influence tree growth. The first order autocorrelation represents, on average, how well growth in one year is correlated with the next. The EPS statistic is an estimate of how much of the total variance in a chronology is expressed as the chronology signal. The number of trees required to exceed a threshold value of EPS is an estimate of how quickly the variance associated with the common chronology signal is saturated (e.g., at which point more samples do not improve the estimate of the common signal).

Climate Data

Long records of mountain climate are not available or suffer from inconsistent observation, especially for middle and high elevation plots. To achieve good comparison with tree-ring data, I sought long, consistent records of observed climate variables that met two basic criteria. First, I required records that preserved both interannual variability and mean climatic conditions in sample plots. I obtained monthly state climate-division total precipitation (PPT), average temperature (T), and PDSI data for 1895-2002 from the National Climatic Data Center (NCDC, online, Karl et al. 1986). Climate divisions containing sample plots include Washington divisions 1, 4, 5, and 6, Idaho division 1, and Montana divisions 1 and 3. I also used the program AET (Gavin and Hu 2006) to develop estimates of water-balance deficit from the divisional precipitation and temperature records. For this calculation, I assumed a field capacity of 100 mm, which is generally appropriate for poorly consolidated mountain soils (Stephenson 1988) and is corroborated by gridded field capacity data (Webb et al. 2000). I also assumed a non-linear declining availability function for plant-available water in the rooting zone (Willmott 1985).

Although the divisional climatic data satisfied the observed interannual variability criterion, the mean plot climate, especially for mean temperature and winter precipitation, varies with elevation across climate divisions. I therefore obtained more specific 0.125° x 0.125° gridded climate data from the input (developed from NCDC data) and output datasets for the Variable Infiltration Capacity hydrological model (VIC, Hamlet and Lettenmaier 2005, Hamlet et al. 2005, Hamlet et al. 2006). VIC uses interpolations of weather station precipitation and temperature data, as well as estimates of soil and vegetation properties, to estimate daily and monthly climate variables in places where minimal climate data exist. It is parameterized specifically to estimate hydrological variables such as evapotranspiration, snow water equivalent (SWE), and soil moisture. VIC driving data and modeled output variables therefore have the potential to provide estimates of climate at scales more appropriate to the sampled watersheds than can be achieved with divisional climate. Variables included were 1915-2002 monthly mean temperature, maximum temperature and minimum temperature; monthly total precipitation and evapotranspiration; and first-of-the-month soil moisture and SWE. All VIC variables except SWE were calculated for the mean elevation in the VIC cell; SWE was specific to four elevation bands within each VIC cell.

Analysis

In an effort to understand the full spectrum of climate-growth associations and how they vary with the scale of climate data, I used Pearson product-moment correlations to compare each plot chronology to the full monthly and seasonal climate time series from the climate division (1895-2002) and VIC cell (1915-2002) containing the plot. The sheer number of growth-climate correlations guarantees some spurious significant relationships. Rather than imparting an overly-restrictive correction (e.g., Bonferroni) that could mask patterns of low but significant correlations, I assumed that consistent patterns (across adjacent months and between sites) in the sign and magnitude of significant growth-climate correlations ($\rho = 0.01$) indicated a pattern worth investigating further. Seasonal aggregations of monthly climate variables are sometimes better than monthly approximations of the actual ecophysiological mechanisms leading to annual growth-climate correlations (e.g., Fritts 1976, Watson 2002). When several months exhibited similar correlations for a climate variable, I pooled the monthly values and tested the correlation between the composite seasonal variable and the tree-ring chronologies. For divisional climate, I chose to retain the same seasonal groupings for all variables: (ANN, Jan-Dec), water year (H2OANN, Sep-Oct), spring (AMJ, Apr-Jun), growing season (MJJAS, May-Sep), summer (JJA, Jun-Aug) and July/August (JA) for total PPT, average T, average PDSI, and total deficit. Due to the larger number of VIC climate variables, I used only specific groups of months with similarly high numbers of growth-climate correlations to develop seasonal climate variables.

To understand the important, common attributes of the sampled chronologies, I conducted a principal components analysis (PCA, e.g., Priesendorfer 1988) on the residual chronology covariance matrix. PCA, when applied to a matrix of time series covariances, solves for uncorrelated linear combinations of time series that explain the maximum amount of variance in the multidimensional space described by all the constituent time series. The first principal component (PC) effectively estimates the signal common to all the plot chronologies by explaining the largest possible fraction of the total variance; subsequent components describe residual variance, subject to the constraint that they be perfectly uncorrelated with the first and subsequent PCs. To assess the influence of a declining number of constituent chronologies and to determine the robustness of the PCA variance explained through time, I conducted six different PCA analyses on arbitrary centennial time periods: 1917-2002 (all 124 sampled chronologies), 1900-2002 (117 chronologies), 1800-2002 (71 chronologies), and 1700-2002 (22 chronologies) as well as the 1800-1900 and 1700-1900 portions of the latter two periods.

Given the repeated importance of summer water-balance deficit, precipitation and temperature in prior results as well as my own analyses, I compared the first PC of the study network to instrumental (1900-2002) and reconstructed (1800-2002) PDSI gridpoint time series (Cook et al. 2004) for the study region. I conducted two separate PCAs on the instrumental and reconstructed covariance matrices of gridpoints 25, 32, 43, 55, 68, and 83 to develop regional PDSI time series.

It is unlikely that a pure drought signal would be the driving factor in growth in all plots in this study. I therefore sought to understand the role of mean site water supply in mediating the relationship between tree growth and climate. Following Milne et al. (2002), I constructed an estimate of water surplus (precipitation minus evapotranspiration divided by precipitation) in the environment for each of the VIC cells used in the study and arrayed the correlation coefficients for two of the most important variables from the seasonal climate analysis above along the resulting gradient.

Results

I sampled trees in 21 watersheds (Figure 3.1, Table 3.2, Appendices 1 and 2), for a total of 124 chronologies (1388 trees, mean plot chronology = 11.2 trees). When arrayed in climate spaces described by Thompson et al. (2000), the sample plots describe a significant fraction of the climatic range of Douglas-fir (Figure 3.2). My transects failed to capture the coldest January/warmest July and driest January/driest July quadrants of the range of Douglas-fir, which lie in the most continental (e.g., interior British

Columbia, Alberta, and Wyoming) and arid (e.g., southwestern U.S.) portions of the species range.

Mean sensitivity was on average higher in GNP and IPNF than in NCNP and ONP, and the number of trees required to achieve an expressed population signal (EPS) of 0.85 was highest in ONP and lowest in IPNF (Table 3.3). Mean first-order autocorrelation was ~0.55 in all four areas. EPS in most plots exceeded 0.85, although in about 15% of the plots, the entire 1900-2003 common period was not present in enough trees to estimate the number of trees required to reach the 0.85 value. Relaxing the common period to 1925-2003 alleviated the problem in most of these. The average span of the chronologies was 260 (range = 91 to 689).

Growth-Climate Correlations

Divisional and VIC precipitation were similarly correlated with tree growth across the entire geographic range sampled. July (JUL), August (AUG), and September (SEP) in the year prior to measured growth and May, June (JUN), and JUL in the year of growth had the largest number of significant positive correlations with tree-ring time series (Figure 3.3). Divisional Lag 1 JUL, AUG, and SEP precipitation were significantly correlated with more chronologies in IPNF than GNP, NCNP, and especially ONP. VIC precipitation correlations were more consistent among sample areas across the months. VIC climate-growth correlations were much stronger than divisional climate-growth correlations for ONP.

Temperature variables were generally less frequently important than precipitation variables (Figure 3.4). JUL and AUG precipitation in the year prior to growth, as well as JUN and JUL precipitation the year of growth, were negatively correlated with Douglas-fir growth in more plots than temperature variables for the same periods. Lag 1 APR and NOV divisional temperature were positively correlated with annual growth at a number of plots in ONP and NCNP. A similar pattern is evident in the VIC relationships except that some plots in IPNF also exhibited a positive lag 1 NOV temperature relationship. VIC lag 1 OCT and NOV average minimum temperature was positively correlated with tree growth in a small number of plots, especially in ONP and IPNF (Figure 3.5) . Lag 1

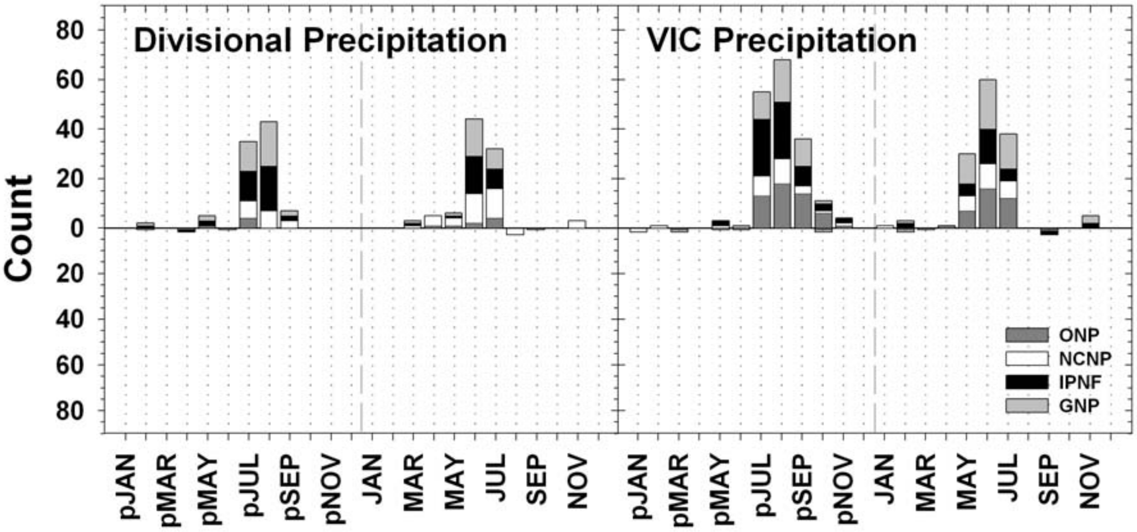

FIGURE 3.3. Monthly Divisional and VIC Precipitation Relationships with Growth. Number of significant ($p<0.01$) correlations between lag 1 / year-of-growth precipitation and tree-ring time series from all watersheds. In this and all subsequent correlation plots, counts have been weighted such that the different numbers of sample chronologies in ONP, NCNP, IPNF, and GNP have the potential to contribute equally to the total count and area in each bar. The maximum number of significant correlations is therefore 144, not 124, so that the area in the bars is directly comparable.

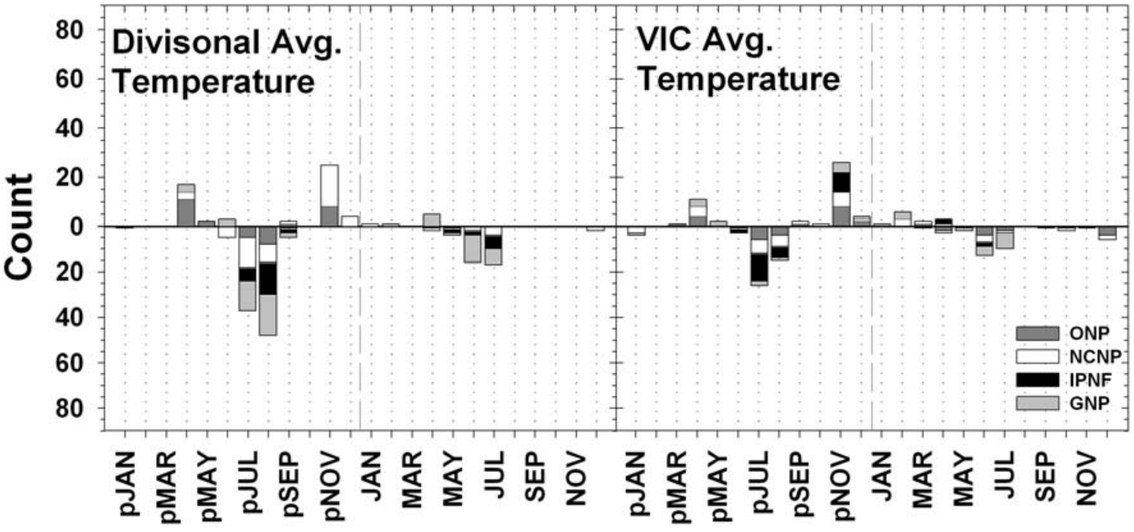

FIGURE 3.4. Monthly Divisional and VIC Average Temperature Relationships with Growth. Summary count of significant correlations between monthly temperature (divisional and VIC climate) and tree-ring chronologies.

TABLE 3.3. Selected Chronology Summary Statistics. Mean value ± standard deviation calculated over all sample chronologies within targeted sampling areas.

Area	Mean sensitivity	1st order AC	EPS	Trees to EPS 0.85
GNP	0.20 ± 0.04	0.52 ± 0.11	0.87 ± 0.06	6.8 ± 2.0
IPNF	0.21 ± 0.03	0.56 ± 0.08	0.89 ± 0.05	5.9 ± 1.6
NCNP	0.15 ± 0.03	0.55 ± 0.12	0.89 ± 0.03	7.1 ± 1.5
ONP	0.13 ± 0.01	0.54 ± 0.08	0.87 ± 0.04	8.3 ± 2.2

TABLE 3.4. PCA Results for Different Time Periods.

Period	Number of chronologies	Variance explained		
		PC1	PC2	PC3
1917-2002	124	0.34	0.13	0.06
1900-2002	113	0.37	0.11	0.09
1800-2002	71	0.35	0.12	0.08
1700-2002	22	0.38	0.11	0.10
1800-1900	71	0.37	0.11	0.07
1700-1900	22	0.37	0.11	0.09

NOV average maximum temperature was also positively correlated with tree growth in some plots. Lag1 JUL and AUG average maximum temperature (as well as average minimum JUL temperature in IPNF) was negatively correlated with growth, and year of growth JUN and JUL exhibited a similar pattern, but most correlations occurred in GNP (Figure 3.5).Generally, warmer late fall temperatures are associated with increased growth, but this relationship is not as common as the negative association with maximum temperature in the previous summer.

Divisional water-balance deficit (negative) and PDSI (positive) (Figure 3.6) were strongly correlated with the tree-ring time series. Significant relationships with water-balance deficit were primarily lag 1 JUL, AUG, and SEP and year of growth JUN and JUL. In all but lag 1 JUL, significant correlations were most numerous in IPNF. ONP had few year-of-growth correlations with water-balance deficit. Peak numbers of significant correlations occurred in lag 1 AUG, SEP, October (OCT) and MAY, JUN, JUL and AUG in the year of growth, but PDSI was significantly correlated with plot chronologies in most months, except in ONP.

Soil moisture in the year prior to growth was significant for most months in most plots, but relatively unimportant (except in OCT) during the year of growth (Figure 3.7). Tree-growth is frequently correlated with soil moisture between January (JAN) and APR in the year prior to growth, less frequently in MAY to JUL, and increasingly frequently from JUL to December (DEC). Evapotranspiration has a weaker year-prior pattern of correlations than soil moisture, and it also has a complex pattern of both positive and negative correlations from JUN to SEP in the year prior to growth (Figure 3.7). Snow water equivalent (not shown) had few significant monthly relationships, although ONP, NCNP, and GNP had a few positive correlations with JAN-MAY SWE.

Seasonal aggregations of divisional precipitation and temperature were more frequently correlated with tree-growth than monthly time series. Lag 1 July/August (JA) precipitation was positively correlated and with growth in most plots, and temperature for the same months exhibited negative correlations with tree-growth. JA precipitation/temperature variables were significant more frequently than extended summer variables derived from JAS or JJA data (Figure 3.8). GNP and IPNF plots were

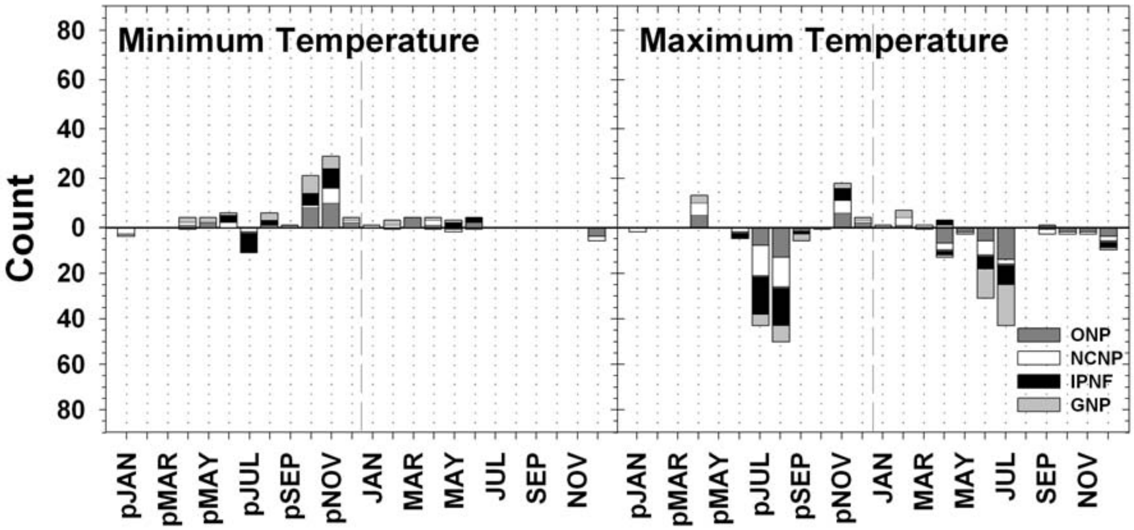

FIGURE 3.5. Monthly VIC Minimum and Maximum Temperature Relationships with Growth. Summary count of significant correlations between monthly VIC maximum/minimum temperature and tree-ring chronologies.

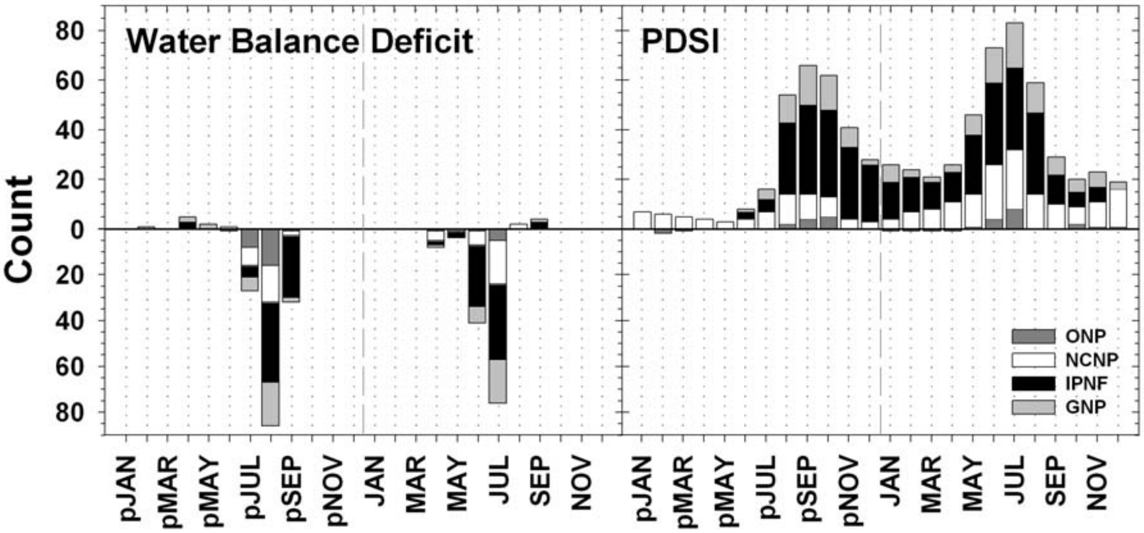

FIGURE 3.6. Monthly Divisional Water Balance Deficit and PDSI Relationships with Growth. Summary count of significant correlations between monthly divisional water-balance deficit / PDSI and tree-ring chronologies.

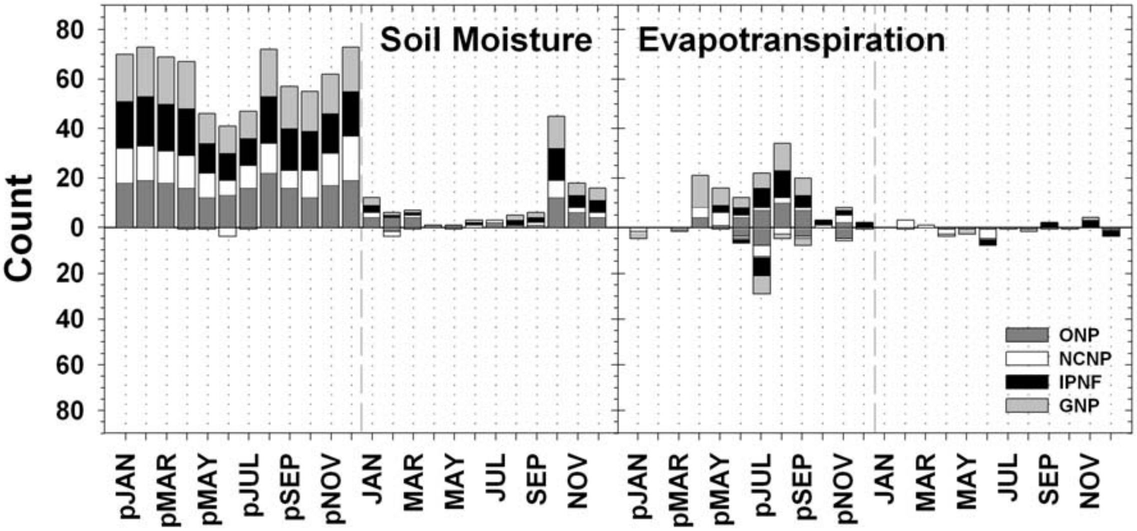

FIGURE 3.7. Monthly VIC Soil Moisture and Evapotranspiration Relationships with Growth. Summary count of significant correlations between monthly VIC soil moisture / evapotranspiration and tree-ring chronologies.

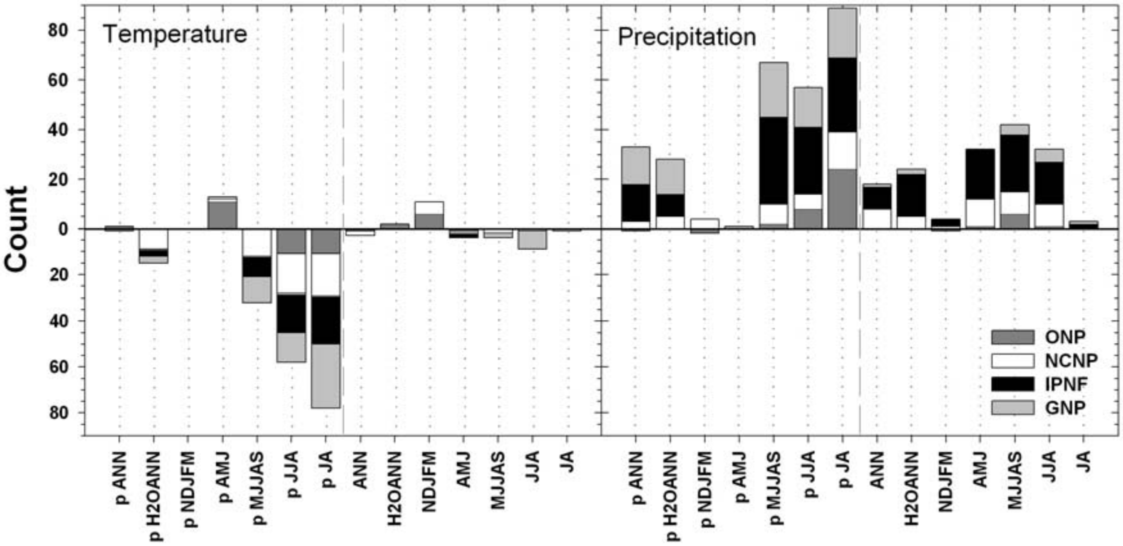

FIGURE 3.8. Seasonal Divisional Climate Relationships with Growth. Summary count of seasonal correlations between divisional temperature / precipitation and tree-ring chronologies.

most often correlated with precipitation in the year prior to growth, and IPNF and NCNP plots were most frequently related to precipitation the year of growth.

VIC seasonal climate variables were also more often significantly correlated with tree growth than were monthly variables. Seasonal soil moisture was important in IPNF, NCNP, and GNP and relatively unimportant in ONP (Figure 3.9). Lag 1 annual average soil moisture and lag 1 JA precipitation were positively correlated with growth in most plots, while lag 1 JJAS average maximum temperature was negatively correlated with growth in half the plots. AMJJ precipitation (positive) and AMJJ average maximum temperature (negative) in the year of growth were most often correlated with tree growth. In some plots, NOV-DEC SWE in the year prior to growth (winter prior to growth) was negatively correlated with tree growth, while JAN-JUN SWE the year of growth was occasionally positively correlated.

In summary, the most important relationships across the different parks in the transect are negative temperature (especially maximum temperature) and positive precipitation correlations in the late spring / early summer the year of growth and the mid-to-late summer the year prior to growth. These relationships are corroborated by more plant-relevant variables including water balance deficit, soil moisture, and PDSI. However, seasonal soil moisture and precipitation are important in a maximum of 65% of the plots (Figure 3.9).

Principal Components Analysis

PCA of the residual chronologies for the common period (1917-2002) explained 53% of the total variance in the data set in three principal components (Table 3.4). The first component (34%) is positively correlated with all residual chronologies (Figure 3.10, mean r = 0.55, range = 0.17 – 0.87). The weakest relationships occur in western ONP and NCNP, and the strongest occur in IPNF and western GNP (Figure 3.10). The second component (13%) represents a west-east contrast between ONP and NCNP on one hand (negative correlations) and IPNF and GNP (positive in correlations) on the other (Figure 3.10). The variance explained by the PC analysis is not sensitive to the time domain chosen for analysis (Table 3.4), and much of the common information is preserved during

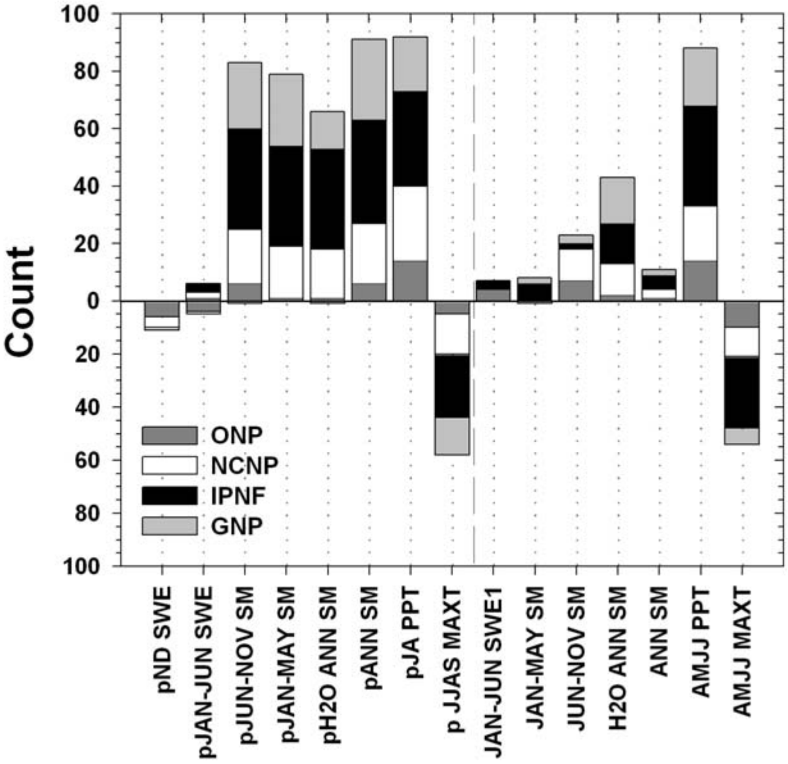

FIGURE 3.9. Seasonal VIC Climate Relationships and Growth. Summary count of seasonal correlations between selected VIC variables and tree-ring chronologies.

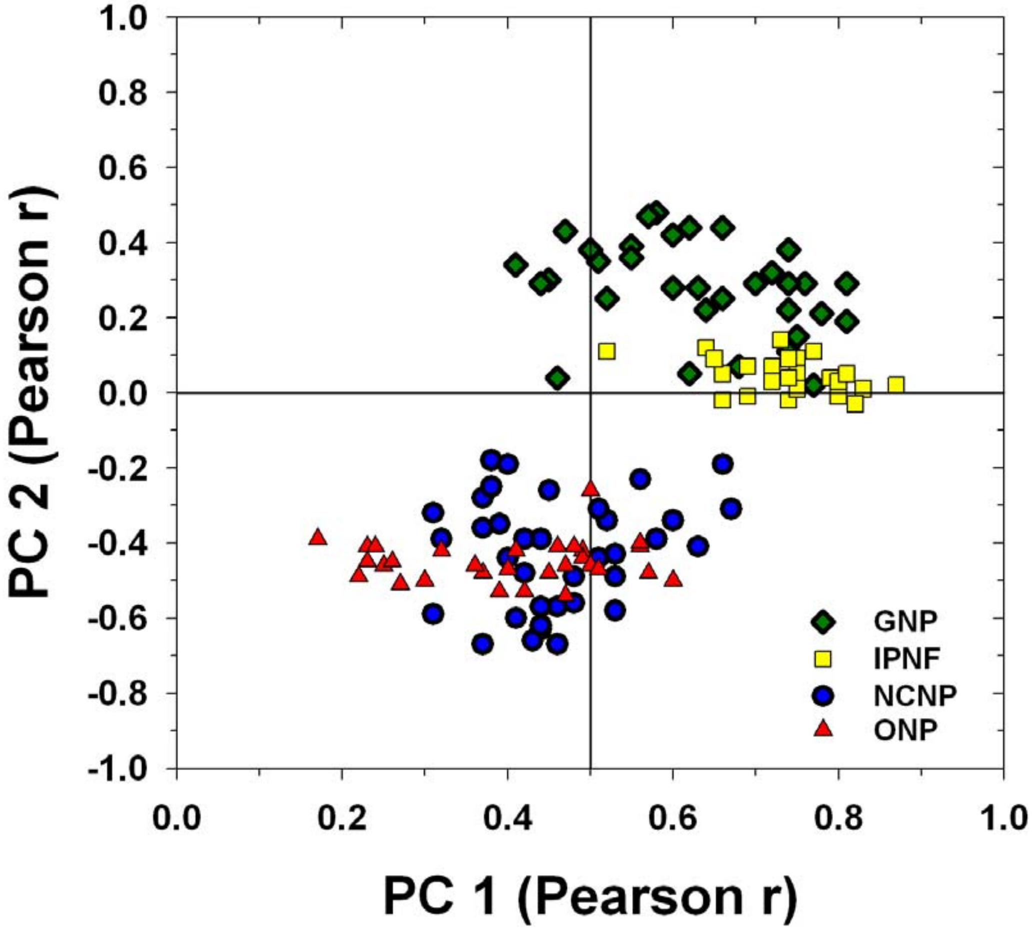

FIGURE 3.10. Principal Components Scores, PC1 and PC2. Pearson correlations between plot time series and the first two principal components of the 1917-2002 PCA.

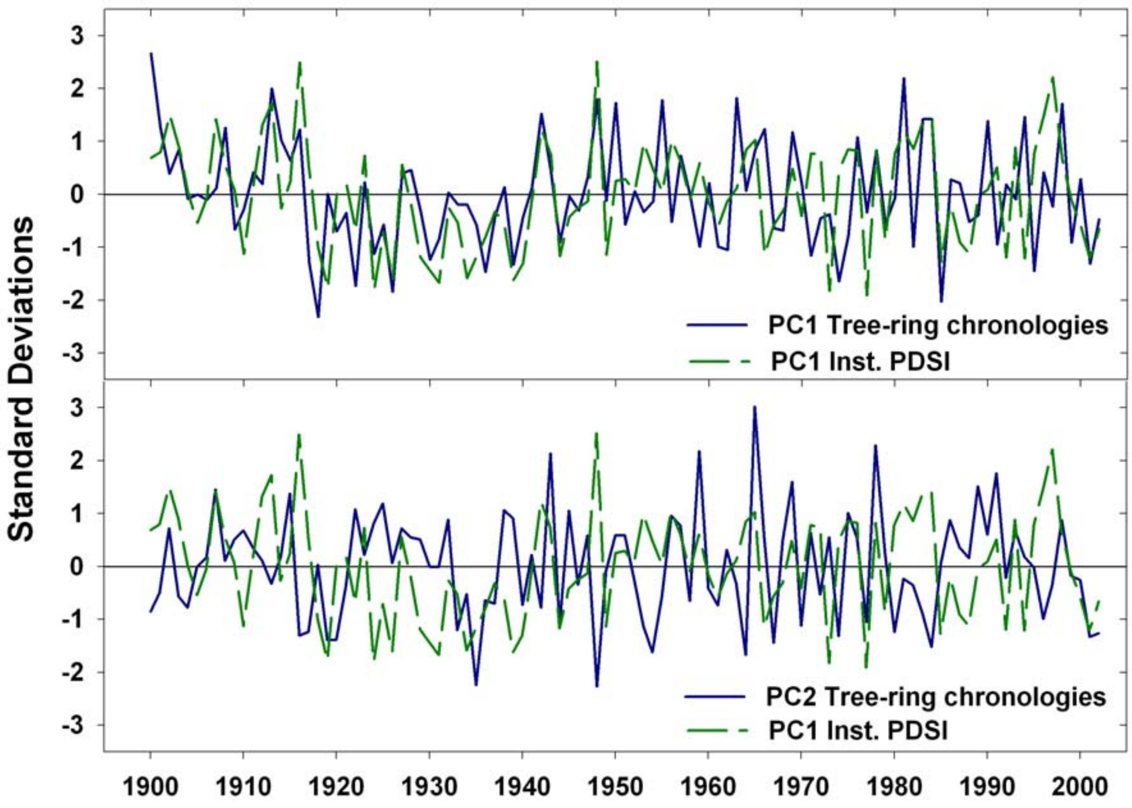

FIGURE 3.11. Principal Components Time Series and Instrumental PDSI. Principal components 1 (top) and 2 (bottom) for tree-ring chronologies for 1900 to 2002 compared to principal component 1 for six instrumental PDSI time series.

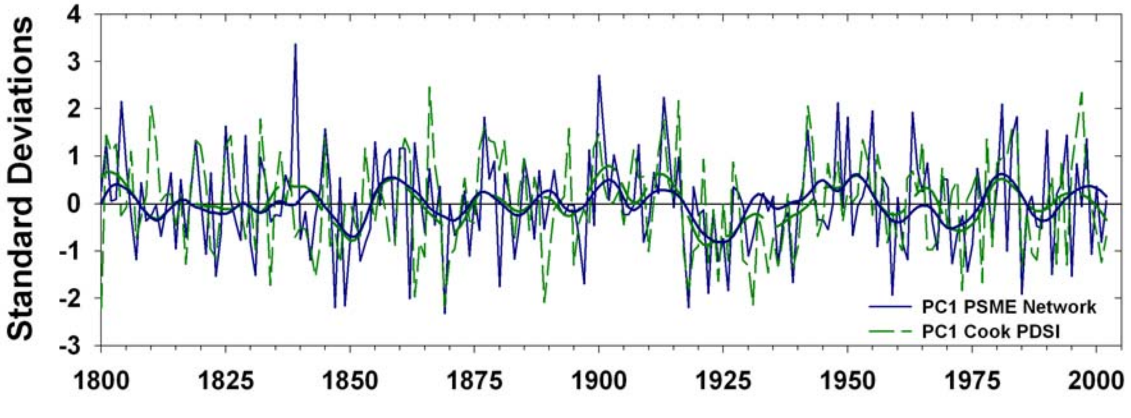

FIGURE 3.12. Smoothed PC Time Series and Reconstructed PDSI. PCA comparison of 1800-2002 common signal from this study and the common signal from six PDSI gridpoint reconstructions over the same region. Bold lines indicate 21-yr lowess-smoothed time series.

the 1800-2002 period. The 1700-2002 period consists primarily of chronologies in ONP and NCNP, so I eliminated it from further analysis because it is likely that the patterns are not comparable with the other periods given the obvious west-east split indicated by the second principal component in the other time periods. The third and fourth PC time series were not interpretable in terms of elevation, aspect, or park/forest. PCA results indicate that the common signal among all plot chronologies is strongly related to summer PDSI (Figures 3.11, 3.12), and that this relationship is conserved reasonably well through time (Table 3.4).

The correlation between lagged soil moisture and tree growth declines toward zero as surplus water increases, while the correlation between tree-growth and JUN-JUL precipitation in the year of growth increases linearly towards zero with the same increase (Figure 3.13).

Discussion

Hierarchical Sampling to Assess Tree Growth

Bracketing the likely determinants (topography, physiography) of mountain biophysical gradients (Figure 3.2) and using two different scales of climate variables allowed us to contrast the effects of localized biophysical and climatological variables on tree growth. While inferences in this study depend primarily on correlations, differences in the significance of (physically focused) divisional climate variables versus (biologically focused) VIC variables indicate the potential for studies over broad geographic areas to produce robust interpretations of climate-growth relationships. Despite these considerations, the primary response in the tree-ring data was a similar pattern of correlations with monthly and seasonal climatic variables across most sites, and there is little evidence of important, widespread topographic and physiographic differences in tree-ring response to climate. The main differences are in the mean sensitivity of the tree-ring series in different sample units (Table 3.3) and the decreasing importance of summer water balance and precipitation variables in the wettest plots (Figure 3.13). It is important to point out that this study focuses on the *variability* in tree growth through time; it is possible that the primary influence of topography for montane

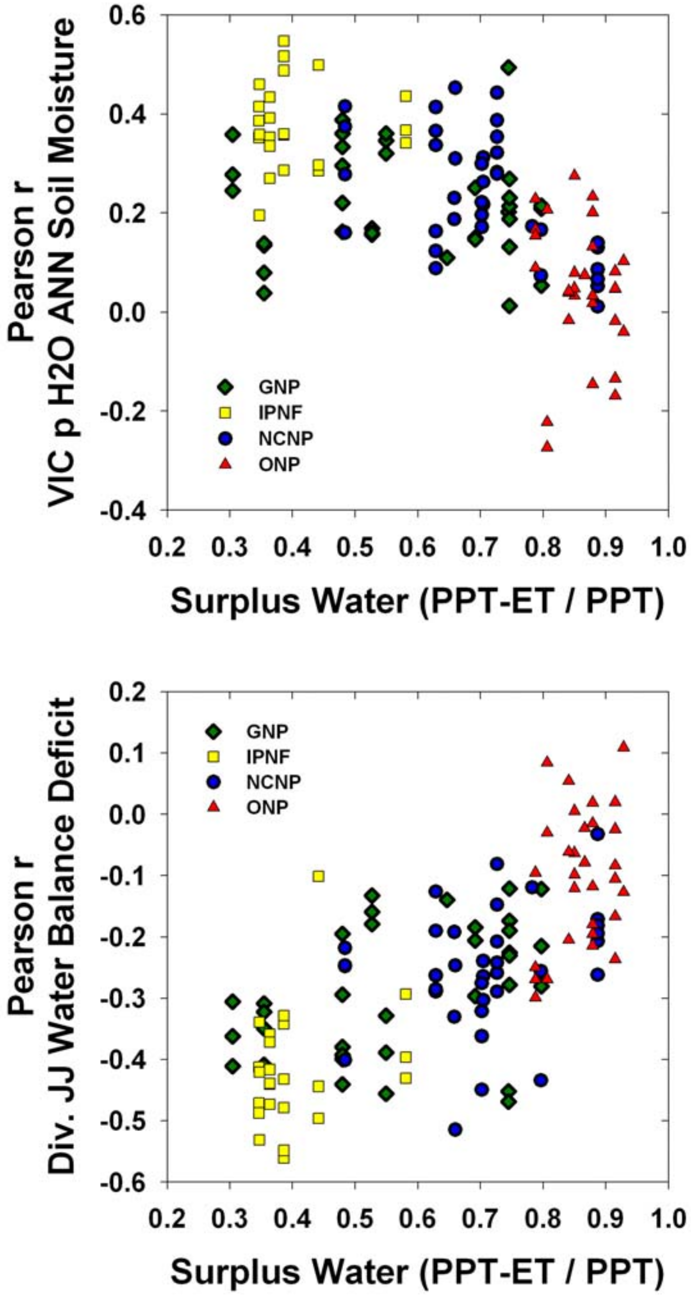

FIGURE 3.13. Surplus Water Gradients and Growth Sensitivity to Water Variables. Relationships between (1) mean annual surplus water at sample locations and (2) climate-growth coefficients. Correlations between lag 1 hydrological year (OCT-SEP) soil moisture and tree growth decline along a gradient of surplus water, while correlations between year of growth JJ water-balance deficit increase along the gradients.

Douglas-fir is in *mean* growth related to site constraints on productivity. My sampling methods could have demonstrated patterns of contrasting climate sensitivities (e.g., Case and Peterson 2005), but the most important limiting factor across the sample transect appears to be the common influence of regional climate.

Growth-Climate Relationships

By sampling along the full climatic range of Douglas-fir in Northwestern mountain ecosystems, I was able to evaluate growth-climate correlations in a wide variety of climatic settings. At most of the elevations sampled, groundwater and summer precipitation are the main sources of water for tree growth once snowpack has melted, and the repeated importance of hydroclimate variables such as precipitation, water balance deficit, and PDSI indicate that water supply is often the most limiting factor. This pattern is characteristic of water limitations on tree growth observed in montane and lower elevation locations (e.g., Schulman 1938, Fritts 1974).

In contrast, Douglas-fir growth in high elevation plots was sometimes more limited by factors that are usually associated with subalpine tree growth (e.g., Graumlich and Brubaker 1986, Peterson et al. 2002), where warmer growing seasons and shorter winters with less snowpack cause increased growth. The fact that average and minimum temperatures in April and November the year prior to growth are positively correlated with growth indicates that the plots in the coolest, wettest end of the transect (Figure 3.2, Table 3.2) are at least partially limited by the shorter growing seasons found at the highest elevations of Douglas-fir's range. I did not find a positive role of winter temperature as described in prior studies (Brubaker 1980, Brubaker et al. 1992), perhaps because the mountain ecosystem focus of my sampling design resulted in a greater proportion of high elevation sites. All mid-to-late summer temperature correlations were negative (Figures 3.4, 3.5), indicating high temperatures are limiting in summer.

Water-balance deficit and PDSI correlations (Figure 3.6) corroborate both the positive summer precipitation and negative summer temperature correlations. Once soil moisture is drawn down, precipitation represents the water available for plant growth and temperature represents an estimate of the atmosphere's ability to draw moisture out of plants. While other factors (such as soil or wind) play a role in site water balance, precipitation and temperature, integrated over a season, appear to be well correlated with Douglas-fir growth. This pattern effectively validates the idea that some of the same composite climate variables that best explain species distributions (Stephenson 1990) also explain temporal variation in tree growth, at least in a widely distributed species such as Douglas-fir. It is also corroborated by other local and sub-regional studies of Douglas-fir growth in relation to water balance (Spittlehouse 2003, Pederson 2006).

Differences between the year of growth and year prior pattern of soil moisture and evapotranspiration correlations (Figure 3.7) are more challenging to interpret. The abrupt change in the magnitude of the correlation between growth and soil moisture implies an irreversible ecophysiological process, such as bud set (e.g., in Coastal Douglas-fir, Lavender et al. 1968). Evapotranspiration (actual evapotranspiration [AET] in VIC) is also difficult to relate to growth because the combined negative and positive signals would need to be interpreted on a plot-by-plot basis. Actual evapotranspiration (AET) can represent either abundant water supply that meets environmental demand, or it may indicate that all available water is evaporated or transpired; the interpretation rests squarely on potential evapotranspiration (PET). It is likely that the mixed signal in July (Figure 3.6) the year prior to growth represents a divide between plots that are sensitive to increased water (positive correlations) and those that are sensitive to higher temperatures (negative correlations).

Seasonal integration of the factors limiting and facilitating tree growth increases confidence in the significant monthly relationships, and suggests the importance of ecophysiological mechanisms that operate across several months or seasons. Seasonal growth-climate correlations produced more significant relationships than monthly growth-climate correlations (Figures 3.7 and 3.8) for the most important relationships identified in the monthly analysis. Variables that are important at more than half the sample plots indicate that the most proximate climate control on growth is a combination of temperature-driven water demand and precipitation-driven water supply in the year prior to and year of growth.

At the limits of Douglas-fir distribution, characteristic relationships of the most important variables either intensify or erode completely. In ONP, for example, fewer plots are significantly correlated with climate variables related to water supply. This is likely because there is enough water in this maritime environment that water does not usually limit growth. Similarly, at some of the highest elevation plots in all sample areas, winter precipitation falling as snow is a limiting variable (Figure 3.8), because higher snowpacks are more likely to persist into early summer, thus decreasing the length of the growing season (Graumlich and Brubaker 1986, Peterson et al. 2002). Case and Peterson (2005) documented this relationship for Douglas-fir in NCNP, and the same pattern occasionally emerges in this study at high elevation sites where abundant snowpack accumulates or persists. However, the negative influence appears confined to early winter (Nov-Dec); snowfall after January appears to have a positive influence, presumably through its effect on growing-season water supply.

A Common Growth Signal

The relationships between PC1 from my network and PC1 of reconstructed PDSI is particularly surprising given that the trees sampled for this study come form a very wide range of ecological conditions. The relationship between this regional PDSI time series (Figure 3.11, 3.12) and the common signal in the 1900-2002 and 1800-2002 study network is significant (1900-2002 r = 0.46, 1800-2002 r = 0.37). The main difference between the study network PC1 and the reconstructed PDSI PC1 for the period 1800-2002 is the failure of the PC1 network to capture the full range of precipitation sensitivity captured by the PDSI network (Figure 3.12). For example, the wet period between 1900 and 1915, and the 1930s drought, are known periods of above and below average precipitation, respectively, but the network PC exhibits less variance during these periods than the Cook et al. PDSI reconstruction (Figure 3.12). However, the common signal implies that the climate regime most of the trees “sense” is driven by larger scale ocean-atmosphere variability that impacts the sampled areas similarly across decades. Another explanation is that the soil profiles in which the sampled trees are rooted are frequently well drained and skeletal, accentuating sensitivity in locations where climate alone would not likely produce high variability in radial growth given adequate soil water holding capacity.

The ubiquity of relationships indicating water limitation underscores the need to understand growth-climate relationships across broad ranges of biophysical conditions; the tree species assemblage alone would not have led us to believe growth in many stands was usually water limited. For example, in IPNF where a few plots in which Douglas-fir is sympatric with western hemlock and western redcedar, growth was still negatively correlated with water balance deficit. This unexpected pattern may indicate that a multivariate consideration of climate is necessary to understand the similarities and differences between climate controls on species distributions and controls on growth. If precipitation does not increase to compensate for temperature-driven increases in evapotranspirative demand, the sites that are most water limited can inform predictions of biological responses to climate change. The PCA results indicate that the factors most limiting to growth are conserved over a wide variety of ecological locations, and that the influence of local factors should be detectable as departures from the regional pattern of how climate influences growth (Figure 3.10).

Physiological Explanation of Growth-Climate Relationships

The growth-climate correlations described above should be directly related to water and energy limitations on physiological processes such as photosynthesis and respiration that affect net primary production (NPP). As water-balance deficit in Douglas-fir increases, foliar water potential declines, and if threshold water potential is exceeded, photosynthetic activity declines (Teskey et al. 1995). This threshold can be affected by species, age, growth conditions, and genotype, all of which vary across the sample transect. However, the common growth response to annual drought suggests that if these variables are important factors, they are influencing the unexplained residual, not the dominant, observed relationships (Figures 3.6, 3.10). Soil moisture status can influence photosynthetic response directly because reduced soil water around plant roots causes a hormonally-triggered reduction in stomatal conductance independently of whether a plant has sufficient water or not, causing lower transpiration, which in turn reduces photosynthesis (Teskey et al. 1995).

Water stress is generally associated with decreasing length of periods of net positive photosynthesis (McMurtrie et al. 1990). Reducing water stress in Rocky Mountain Douglas-fir shifts carbon allocation from belowground NPP (BNPP), especially fine roots, to aboveground (ANPP) in stem, twig, and foliage biomass within a year, leading to increased production efficiency (Gower et al. 1992). A similar mechanism relates increases in leaf area index (LAI) to increased stem volume increment in Douglas-fir (Schroeder et al. 1983), but Gower et al. (1992) note that it is particularly difficult to separate the influence of increased water availability from increased nutrient availability because the two are positively correlated. In years when growth continues into late summer due to adequate water supply, a warm autumn can increase annual net photosynthesis. Positive correlations between growth and autumn temperatures are also possibly the result of fewer nighttime frosts, which decrease maximum photosynthetic rate by damaging chloroplasts in the mesophyll (Hällgren et al. 1990). Similarly, warm spring temperatures can increase cambial expansion at the beginning of the growing season and increase the rate of repair to frost damage occurring in chloroplasts over the winter (Lundmark 1988). Net photosynthesis in Douglas-fir is also known to decrease rapidly with increasing vapor pressure deficit (Grieu et al. 1988), which may explain the direct negative effects of temperature on growth during the warmest months.

Several studies of subalpine forests in the northwestern U.S. imply that the mechanism for the few observed negative snowpack correlations is probably that annual growth rates are reduced by low soil temperatures and delayed cambial expansion in spring (Graumlich and Brubaker 1986, Peterson and Peterson 2001, Peterson et al. 2002), and these conclusions are corroborated by observations of soil temperature controls on photosynthesis at upper tree (Day et al. 1989). It is also possible that Douglas-fir generally has architecture that is less resistant to heavy snowfall than typical subalpine species such as subalpine fir and is therefore susceptible to snow damage, although this might manifest as a persistent response over many years.

Because many of the important growth-climate correlations are lagged as much as 18 months, storage or coupled source-sink relationships (e.g., both photosynthesis and respiration) may explain some of the variation in growth. Needle longevity or other long-term impacts to photosynthesis (Reich et al. 1992) might affect the growth signal in tree-ring series seasons or years following the direct climatic conditions resulting in changes in LAI have passed. It is also possible that lags could result from delays in opportunities to use stored resources for growth, much as in trees at treeline (Körner 2003). Gower et al. (1992) observed significantly longer leaf longevity for Rocky Mountain Douglas-fir in central New Mexico (7-9 yr, with a maximum of 20 yr) than for lowland WA Douglas-fir in the Northwest (4-5 yr, Turner 1975). The role of increased water availability observed in a multi-year manipulation of water (double ambient precipitation) in Douglas-fir (Gower et al. 1992) shows large shifts in carbon allocation, from BNPP to ANPP and from emphasis on large roots and fine roots (which have much reduced mortality) to small roots. These responses are fast enough to explain the lagged relationships often observed in tree-growth time series, and may indicate that the role of interannual climate variability in tree growth is a combination of source and sink feedbacks rather than a straightforward climate limitation on photosynthesis.

Climate Change and Implications for Ecosystem Management

Increased April to September temperature (expected to be +3.2°C by 2080; Mote et al. 2005) without increases in precipitation or soil moisture reserves is likely to cause decreased growth of Douglas-fir over much of the mountainous northwestern U.S., especially in eastern NCNP, IPNF, and western GNP. Evapotranspirative demand on plants increases sharply with small increases in temperature (McCabe and Wolock 2002), and summer precipitation in the study region is predicted to remain constant or decrease slightly (Mote et al. 2005). In contrast, Douglas-fir at some higher elevation sites where water is not limiting (ONP, western NCNP, northeastern GNP), and net photosynthesis is currently limited by growing season length or low growing season temperature, may exhibit increased growth. If climatically-driven source-sink tradeoffs are an important response in Douglas-fir, it is possible that increased temperature without concomitant increase in precipitation may result in increased growth variability (Hessl and Peterson 2004) at regional scales. The reason for this is that more stands will be (at least temporarily) closer to climatic thresholds at which the tradeoffs between ANPP and

BNPP become more pronounced. Decadal-scale climate variability may serve to mediate such variability via plant morphological controls on growth responses that are more stable (either prolonged high or low growth) over decades.

Interactions with other climate-mediated ecosystem processes such as fire and insect outbreaks may accentuate stress complexes in areas that previously had relatively long fire-return intervals and where trees were not routinely drought stressed. Planning for such changes can be improved by using a hierarchical sampling design along biophysical gradients to inform predictions about the effects of climate variation and change on ecological processes. Such sampling designs have the capability to bracket the range of climate-mediated responses at a variety of scales and, if appropriate climate data can be measured or modeled, specify the direct climatic mechanisms responsible for variation in the process of interest. Although the degree to which radial tree growth can be used as a proxy for other life-history components is unknown, reconciling the mechanisms by which climate mediates population processes could lead to inexpensive monitoring efforts that integrate regional climate and local biological response along quantifiable gradients.

Genetic variability could play an important role in observed growth differences along a transect encompassing so many populations. Elevation differences of 200 m between stands in the same watershed are sufficient to produce genetically-determined differences in growth in provenance trials (Rehfeldt 1983). However, the time scale associated with climatic variability recorded in tree rings is probably higher frequency than the time scale associated with selective pressures producing potential between-plot differences, so mean growth (or growth in extreme years) rather than mean sensitivity or variance would likely be more affected. I did not consider the potential for differential influences of coupled ocean-atmosphere variability on growth at these sites, although with reasonable estimates of the actual climate at most sites, such an analysis should be tractable.

The ability to adapt to climate change will be a critical management and policy issue in Western forests over the next several decades. Processes that are resilient to climate change probably do not merit expensive mitigation measures, and decreased

Douglas-fir growth rates in mountain protected areas would have fewer implications than an accompanying increase in susceptibility to drought, insects, and fire. Carbon dynamics may also change over very large areas, given the natural range of Douglas-fir in Western forests (Bachelet et al. 2001, Hessl and Peterson 2004). If the results from my transect approach are more widely applicable, most of the lower and mid elevation Douglas-fir east of the Cascade Crest will be less resistant to interannual variability in summer drought, and growth is likely to be more variable (Hessl and Peterson 2004). If winter temperatures increase enough to alter snowpack dynamics (e.g., Hamlet et al. 2005), the positive influence of snow on growth (Figure 3.9) will likely be lost as well. On the other hand, warmer winters with a greater percentage of precipitation falling as rain could lead to earlier onset of spring growth and compensate for the loss of summer growth. Only the coldest and wettest locations have the potential for carbon gain through relaxation of growth-limiting climate factors.

In actively managed forests where trees are planted, disturbances (timber harvest, fire, insect outbreaks) provide an opportunity for managers to speed mitigation of climate impacts by using provenances better adapted to the ecophysiological stressors associated with warmer climates. Nursery stock from seed sources outside the currently recommended seed zone may be better suited to future conditions, especially if there is not an increase in summer precipitation to offset evapotranspirative demand associated with increasing temperature. For a given location, Douglas-fir populations from a warmer and drier location (typically lower elevation or farther south) may produce seedlings that are more tolerant of drier soil conditions. Expected growth rate for a given climate, which may vary for different regional populations, must also be factored into ecological and silvicultural objectives. Data on forest growth and establishment – from the maximum observable range of the process of interest, and obtained across relevant biophysical gradients – will be needed to provide the scientific basis for adaptive decision making in a greenhouse climate.

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CHAPTER 4:
CLIMATE IMPACTS TO FOREST ECOSYSTEM PROCESSES IN THE WEST: SYNTHETIC VS. MULTI-SCALE RESEARCH

In Chapter 1, I made the case that three significant barriers need to be overcome for climate impacts science to realize its potential to provide scientific information to decision makers charged with ecosystem management. These barriers stem from the dynamic, non-equilibrium nature of the climate system and ecosystems, and they lead to large uncertainty in predictions of future ecosystem responses to climate change. Those barriers were: (1) the climate system is multi-scale; (2) ecosystem management deals with meso-scale processes, yet ecological studies tend to occur at very local scales or very broad scales; and (3) ecological processes have characteristics of complex systems, independent of scale alone, that render them difficult to measure, analyze, and predict. I proposed three strategies for dealing with those barriers.

First, the influence of climate on the process of interest must necessarily be measured at an appropriate scale. Second, by sampling and analyzing climate impacts along the full range of climate conditions influencing a process of interest, non-linear and threshold relationships can be discovered if they exist. Third, by sampling along gradients of limiting factors at multiple scales associated with controls on local climate, the hierarchical nature of climate impacts to ecosystem processes can be partitioned into appropriate scales of influence and, hence, prediction. In the paragraphs that follow, I describe the success and limitations I encountered in applying these strategies to a synthetic study of the climate impacts to the area burned by fire in the West and a multi-scale study of the climate impacts to Douglas-fir growth in the Northwest.

The area burned study (Chapter 2) is synthetic because I used existing data to develop methods and analyses to answer a question they were not designed to answer. I used a reconstruction and down-scaling method to produce an 87-year dataset of area burned for ecoprovinces in the western U.S. from (1) state-level data that was long-term but ecologically imprecise and (2) gridded data that was short-term but spatially explicit. This approach was intended to produce a meso-scale dataset that had more specific climate and ecosystem relationships than the state-level data and over longer period than the gridded data alone could address. To employ the first strategy (appropriate scale of climate analysis) for dealing with the barriers described above, I developed climate variables that described the same spatial scale as the fire area burned downscaling. To employ the second strategy (full range of conditions), I examined a range of ecosystems, from those dominated by grass and shrubland to those dominated by forests. This corresponds potentially to a range of factors limiting the area burned by fire, from fuel availability on one end to climate limitation on the other end. This study, therefore, did not employ the third strategy explicitly (it was not inherently hierarchical), but combined elements from the second and third strategies to describe relationships across a range of ecosystems, which are products of different climates.

This combination of strategies was successful in the sense that I was able to develop quantitative regression models from climate variables that could be used to predict the annual area burned by fire for most of the ecosystems in the West. This gets at uncertainty directly. However, the models are limited in their application to the scales of ecoprovinces; the lack of a true multi-scale approach limits their application. There are also qualitative patterns that emerge, consistent across ecoprovinces with similar vegetation types, that hint at very different responses to future climate change and suggest directions for new empirical research combining fire, vegetation, and climate. Another limitation of these models is that the *area* burned is less meaningful ecologically than, for example, the *severity* of the fires that occur. The synthetic approach was limited by the initial data, but by employing the three strategies described above, significant inroads into reducing uncertainty were realized.

In Chapter 3, I described a study of the multi-scale controls of climate on Douglas-fir growth in the northwestern U.S. In this study, the response data (tree-ring chronologies) did not exist, so I developed a sampling strategy that bracketed the biophysical gradients influencing how local climate derives from regional climate. However, the scale of response (a stand of trees on a homogeneous landscape facet) and the climate variables (divisional data and VIC data) were mismatched because the transects employed to sample the tree-ring data were 200-1200m in elevation, but the VIC data did not have elevation bands allowing the difference between temperature and precipitation between the lowest and highest plots in a transect to be accurately estimated. We employed my sampling methods along the full climatic range of Douglas-fir in the northwestern U.S., however, and therefore satisfied the second strategy. The third strategy, which deals with gradients of limiting factors, informed my sampling strategy from the start, and I expected to see a quantitative contrast between growth at high elevation and low elevation plots due to different limiting factors.

Combining the three strategies in the study of tree-growth revealed patterns of tree-growth that were remarkably well conserved across the high climatic variability of the sample transects. Most plots have significant correlations with variables indicating that summer and annual water limitation of growth variability is much more common in the region than energy limitation. However, until it is possible to develop more specific estimates of climate along elevation transects, comparison of the mean growth remains impossible. By employing the third strategy, I was able to observe thesholds of water supply at which correlations between water balance deficit and soil moisture become non-significant. This indicates that it is possible to map the vulnerability of a process across space and time by using these strategies in multi-scale, gradient-based research of ecological processes.

The hierarchical nature of the climate system, the multi-scale nature of ecological processes, and ecological complexity all contribute to uncertainty in climate impacts research. The goals of climate impacts research are to increase understanding and to understand the nature of predictability of climate-dependent processes; for ecosystems, these goals are well aligned with the goals of ecosystem management. I have shown that both synthesis of existing data and original multi-scale research can be accomplished through appropriate attention to the sources of uncertainty and barriers to understanding prediction. These strategies are the first step in developing widely applicable synthetic and multi-scale research that emphasizes predictive capacity, and, failing prediction, has the capacity to develop understanding of why prediction and uncertainty are elusive.

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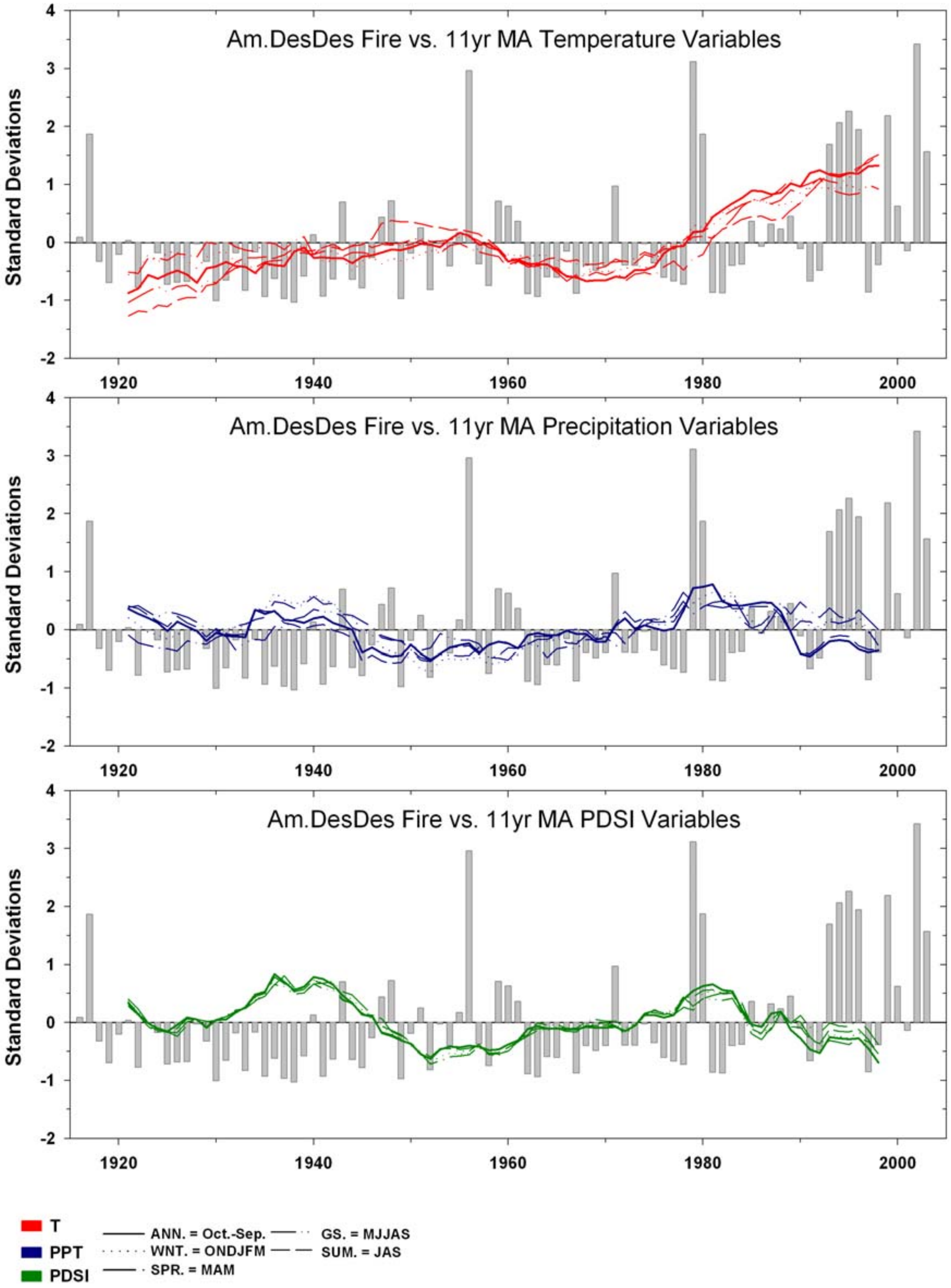
APPENDIX 1.

Moving Correlations and Smoothed Plots of Climate-Fire Time Series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Am.DesDes Fire vs. 11yr MA Precipitation Variables
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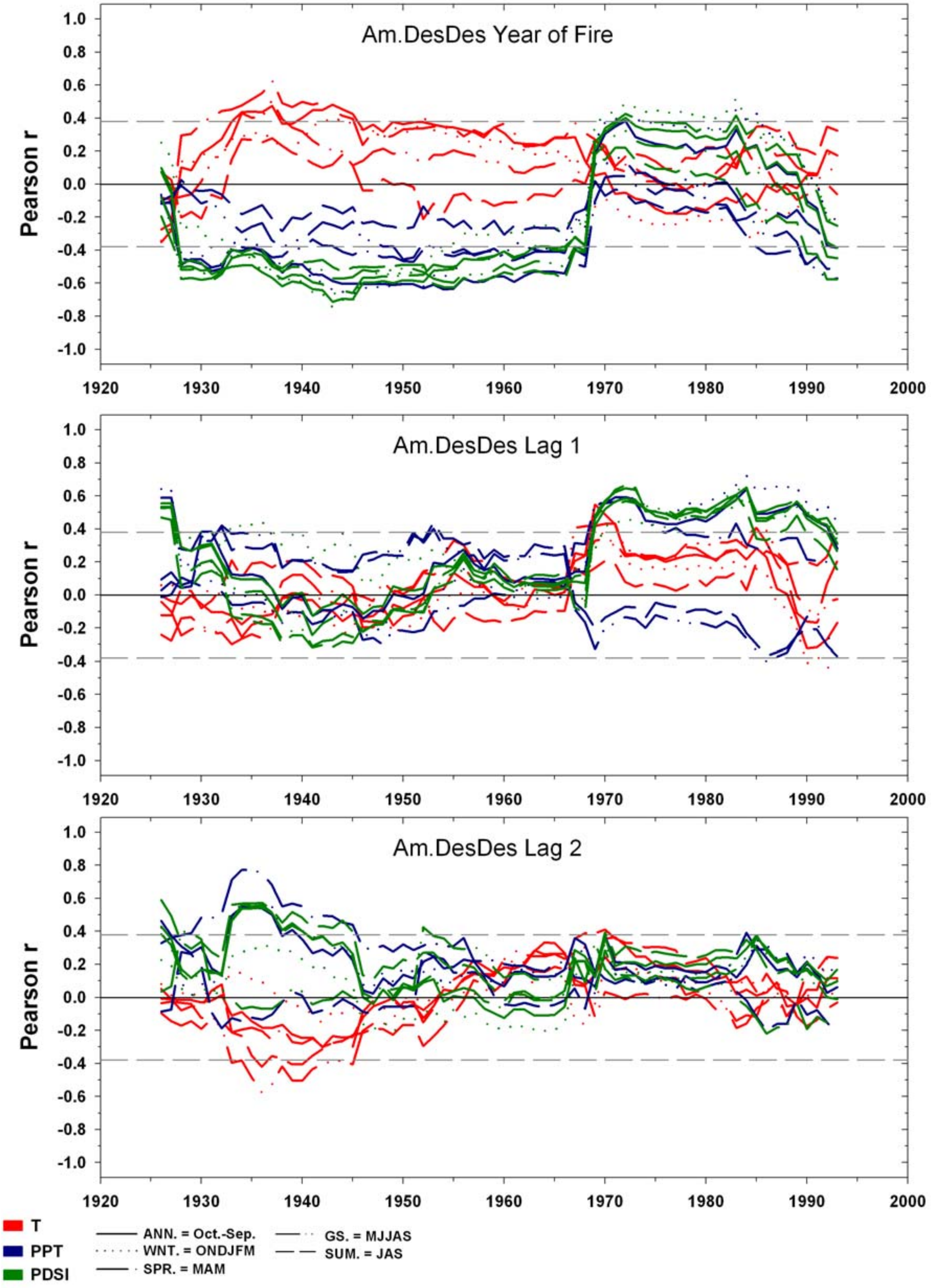
SPR. = MAM
GS. = MJJAS
SUM. = JAS


Am.DesDes Year of Fire
Am.DesDes Lag 1
Am.DesDes Lag 2
Pearson r
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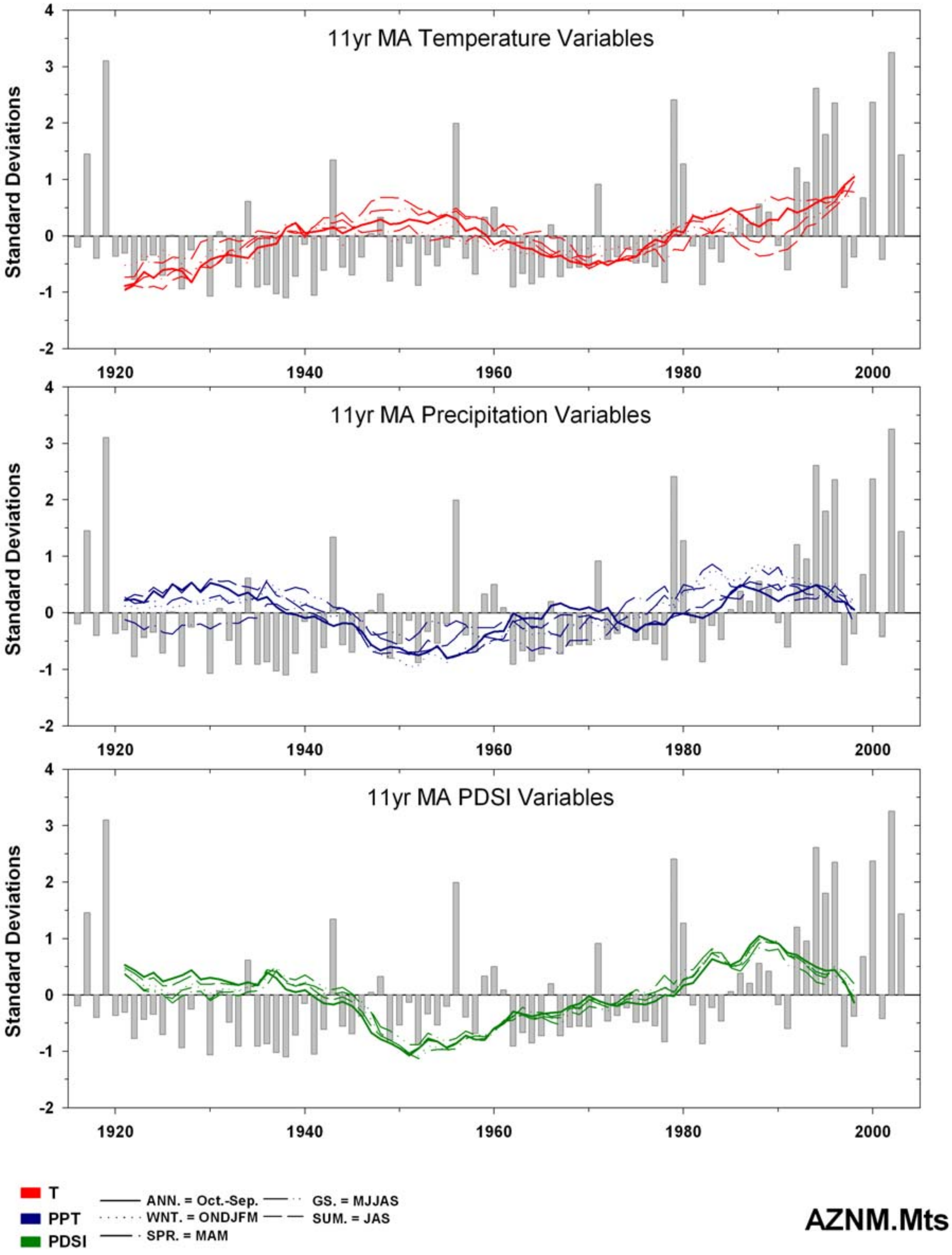
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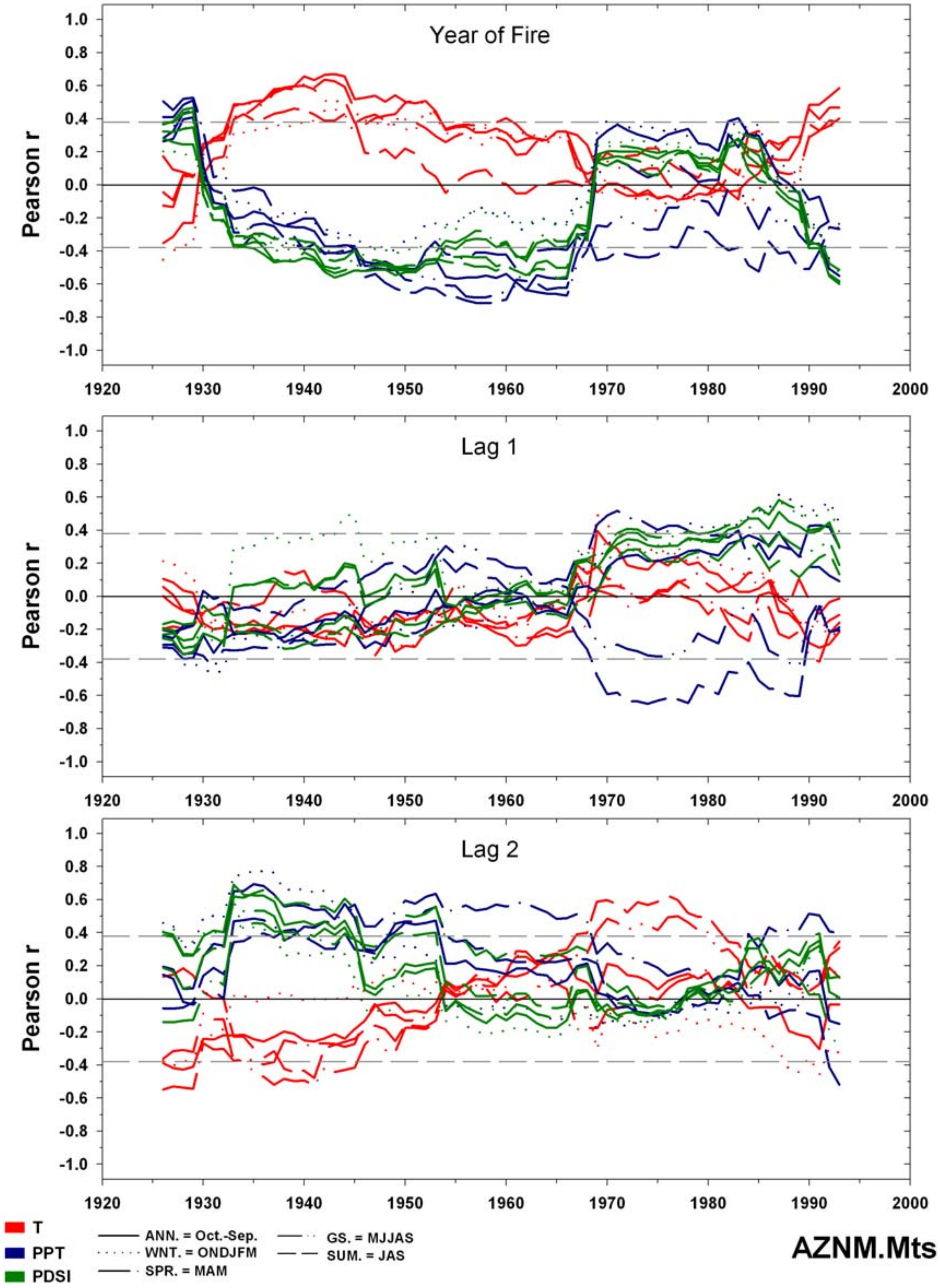
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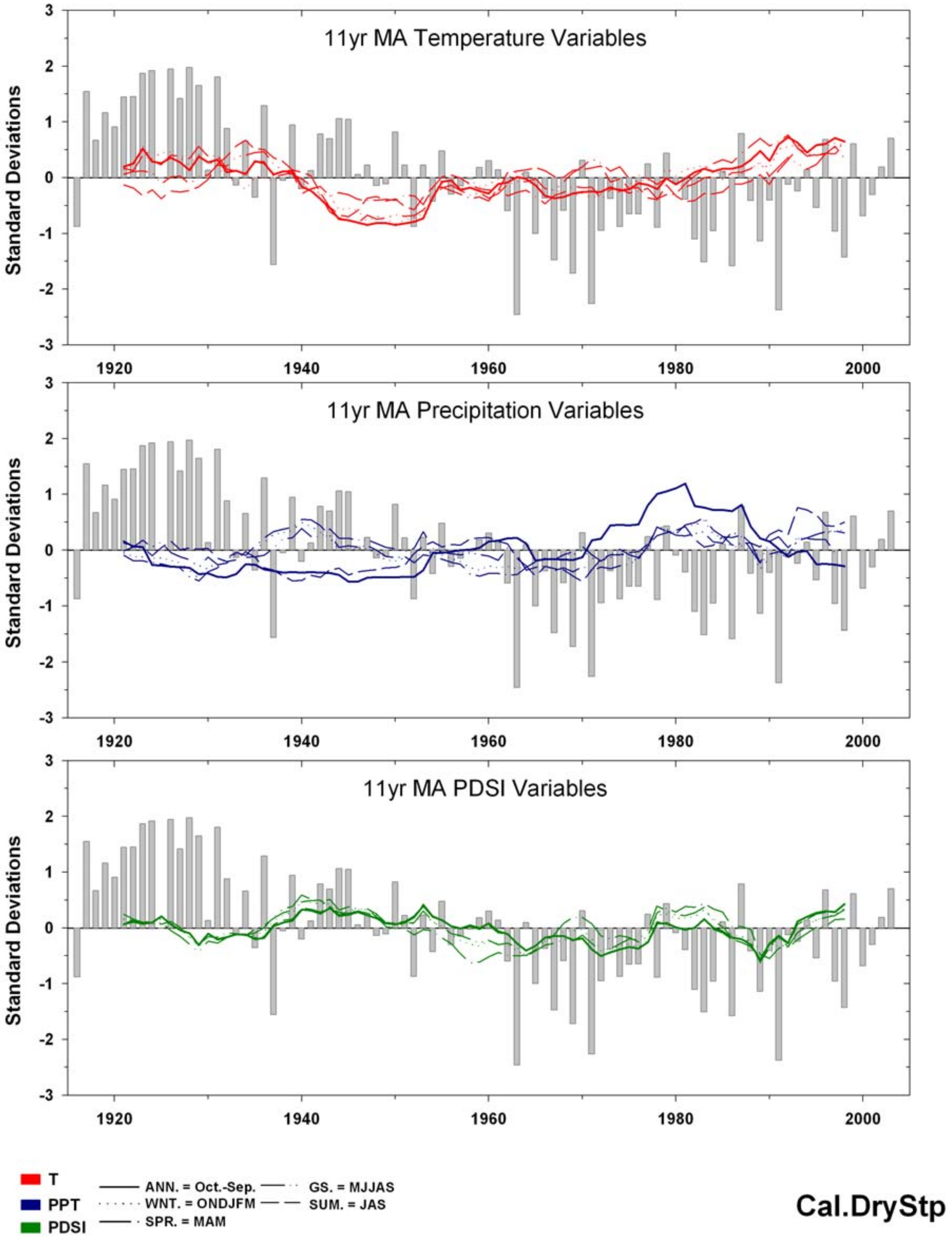
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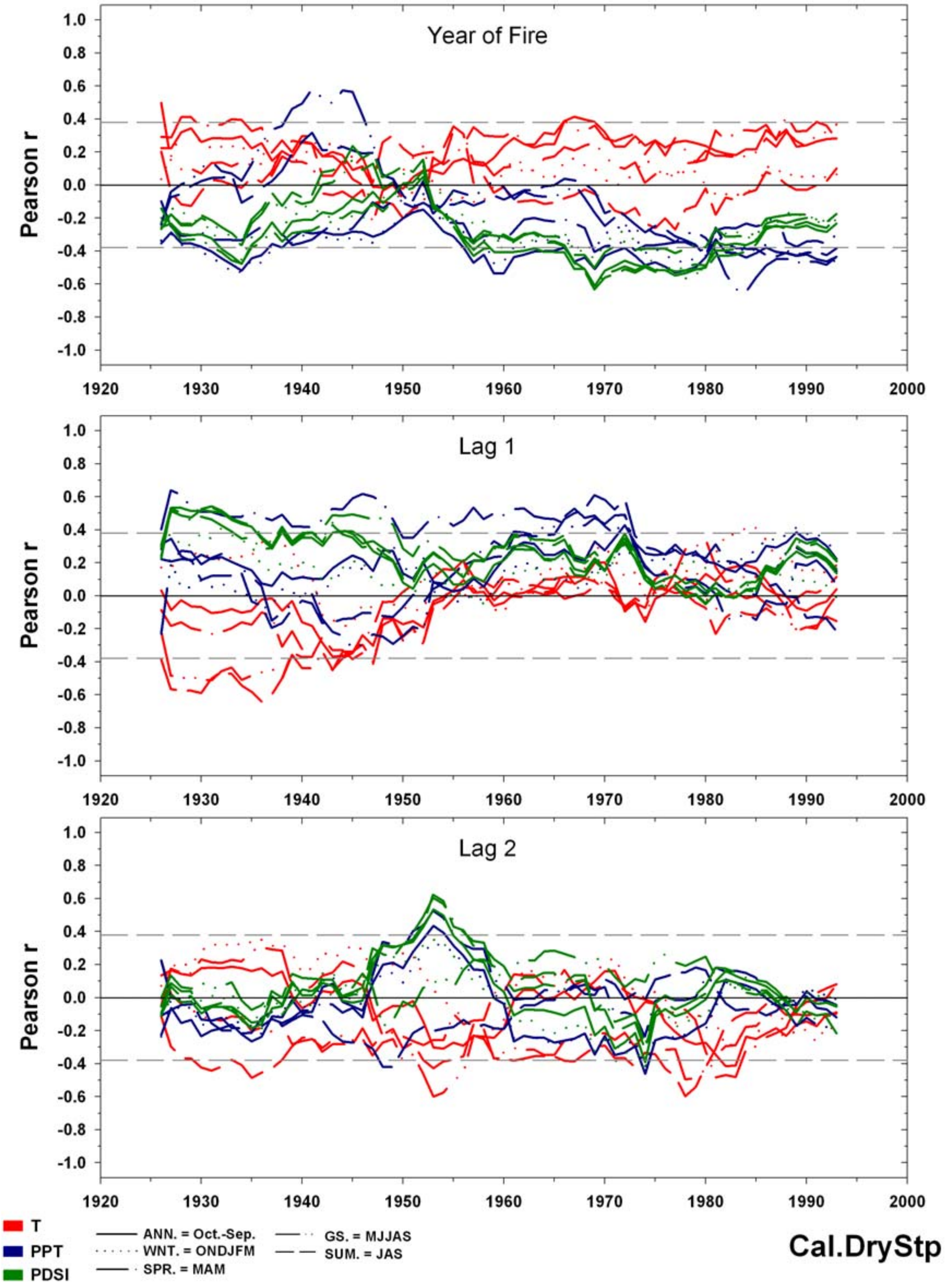
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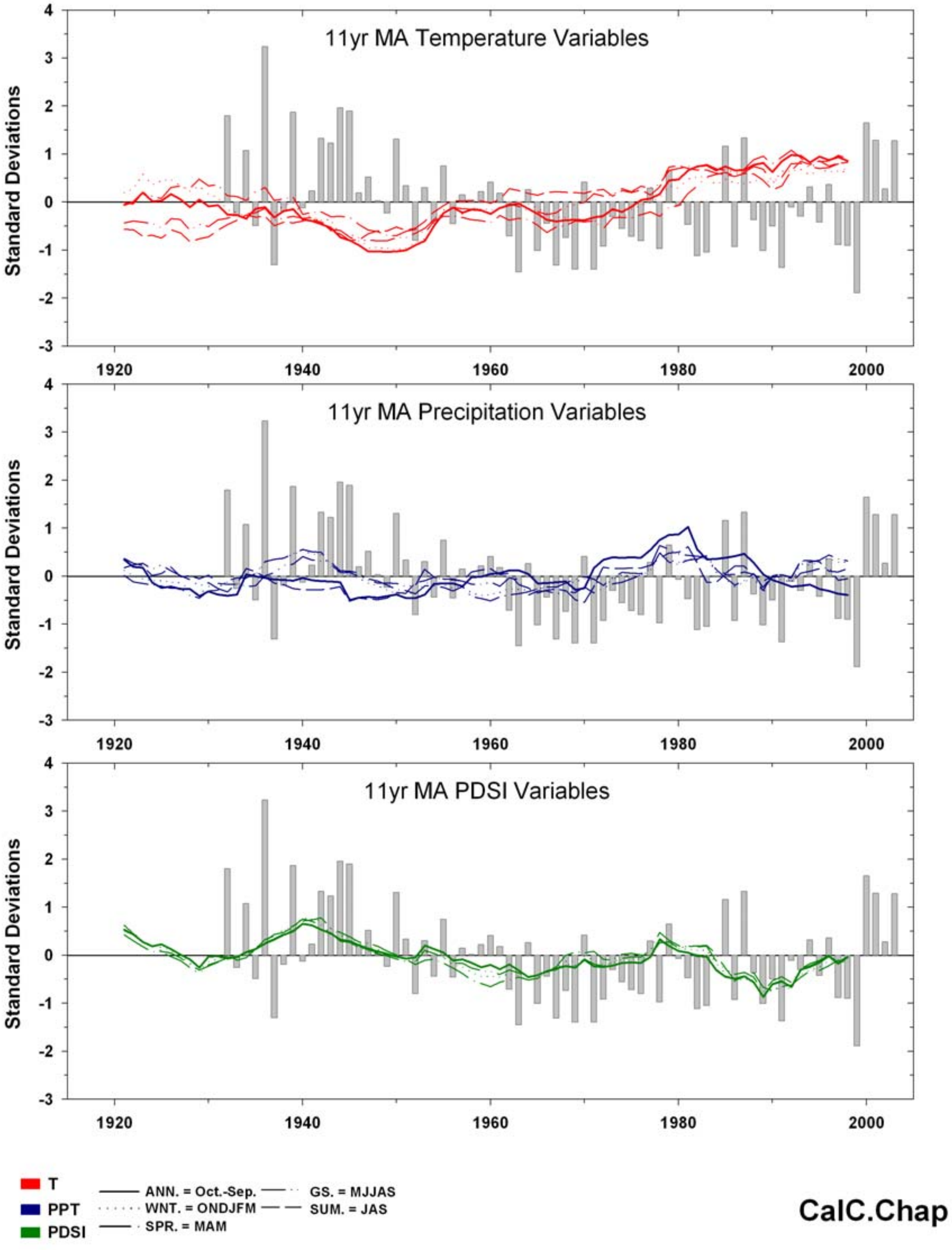
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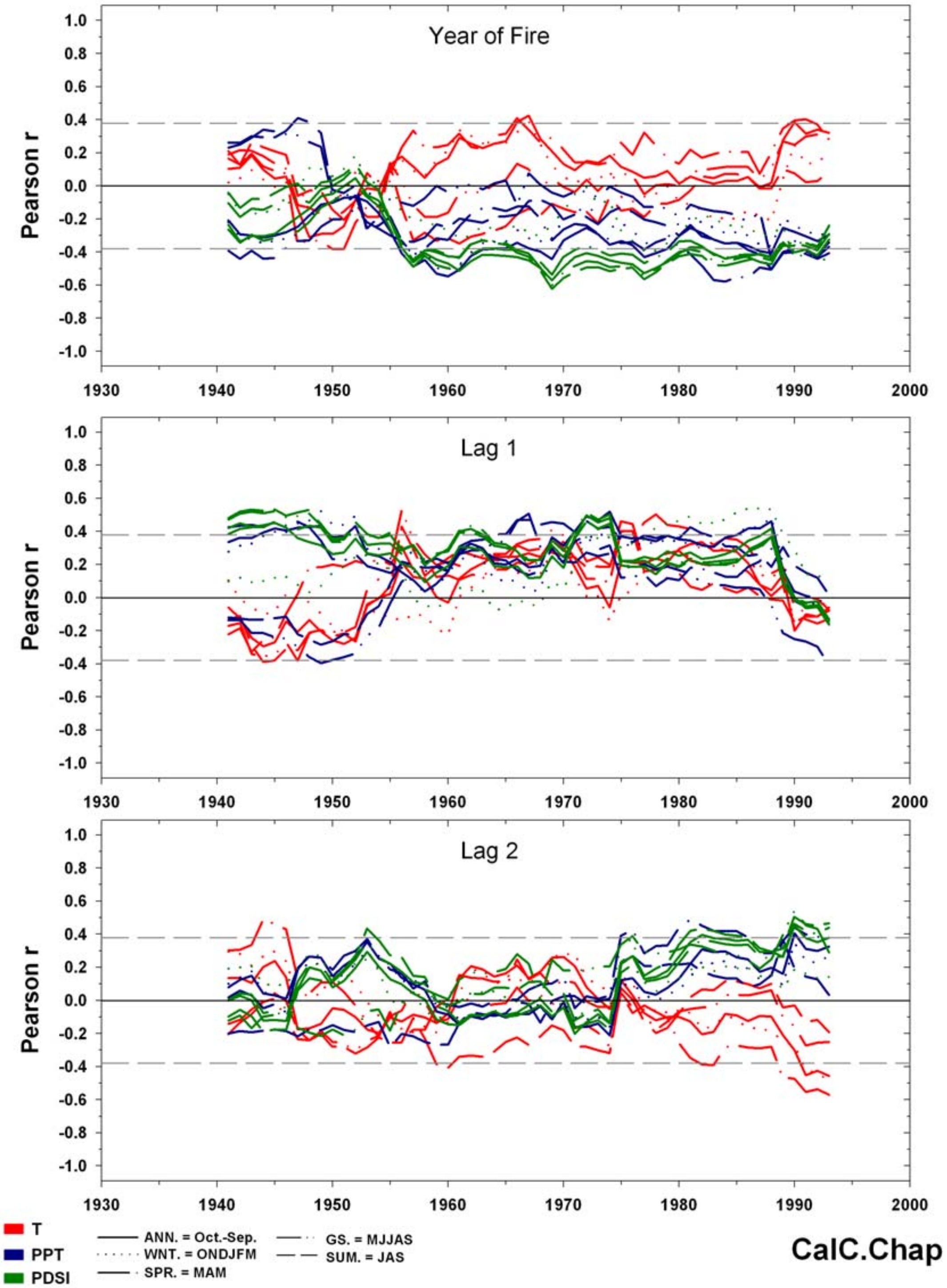
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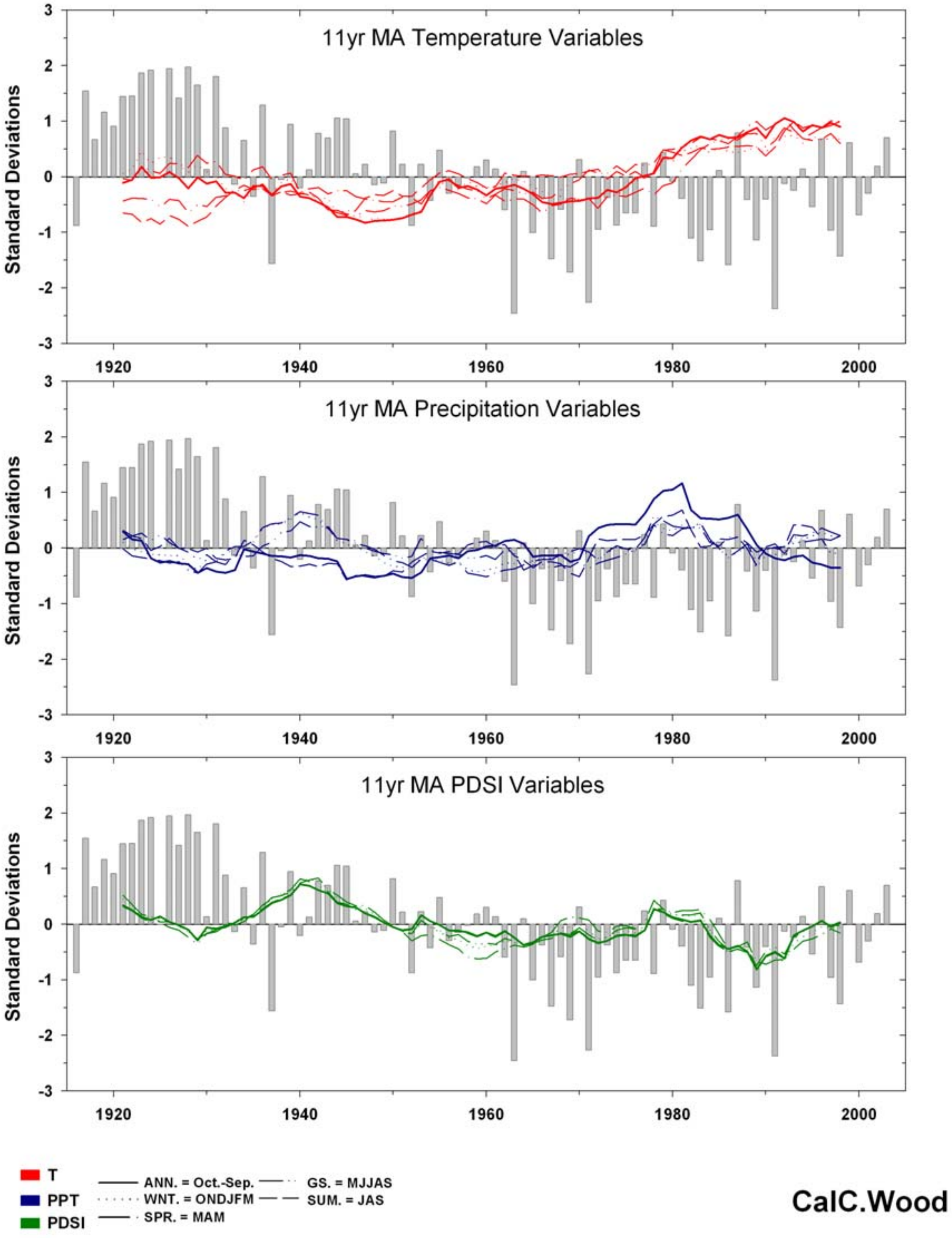
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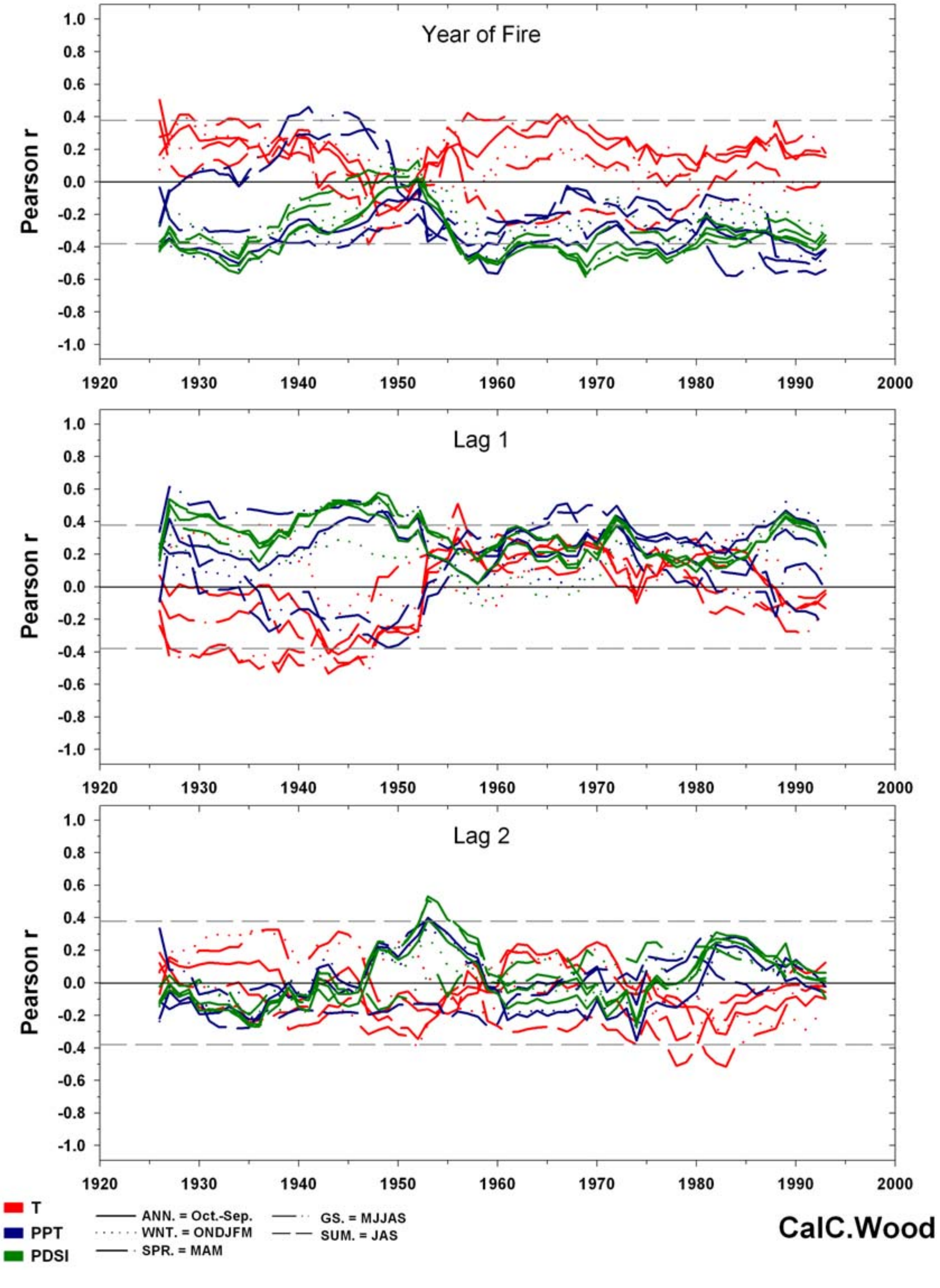
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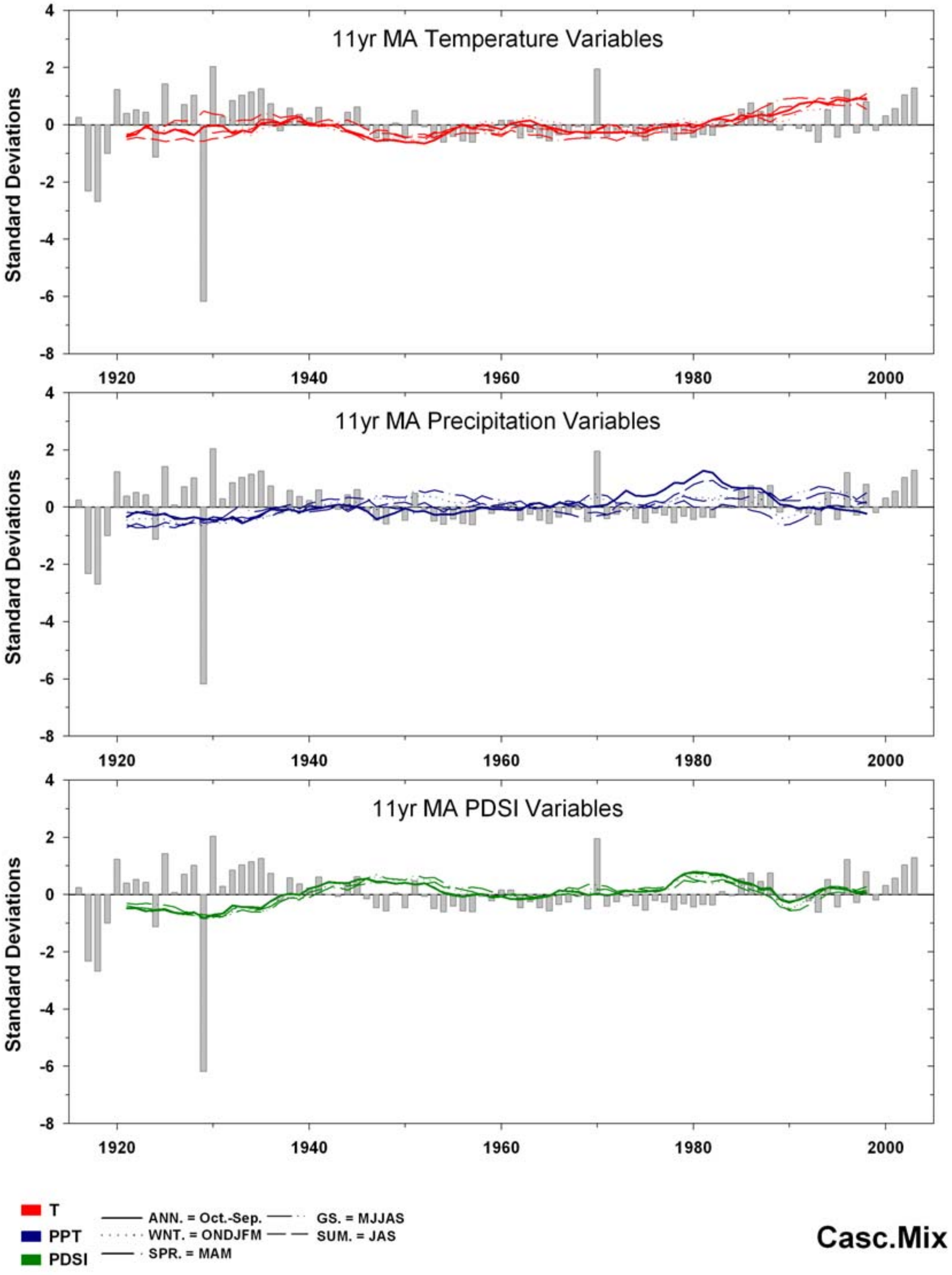
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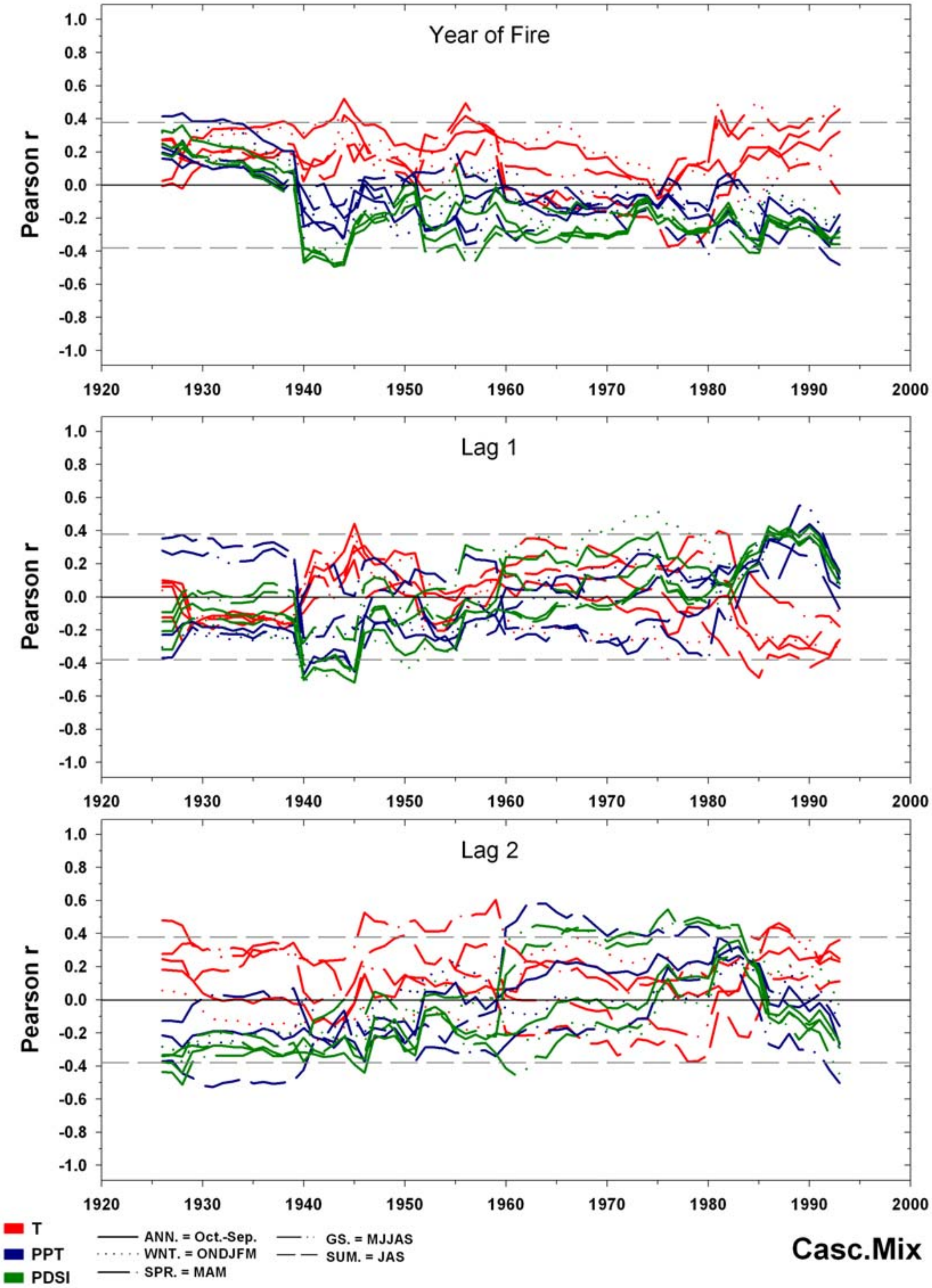
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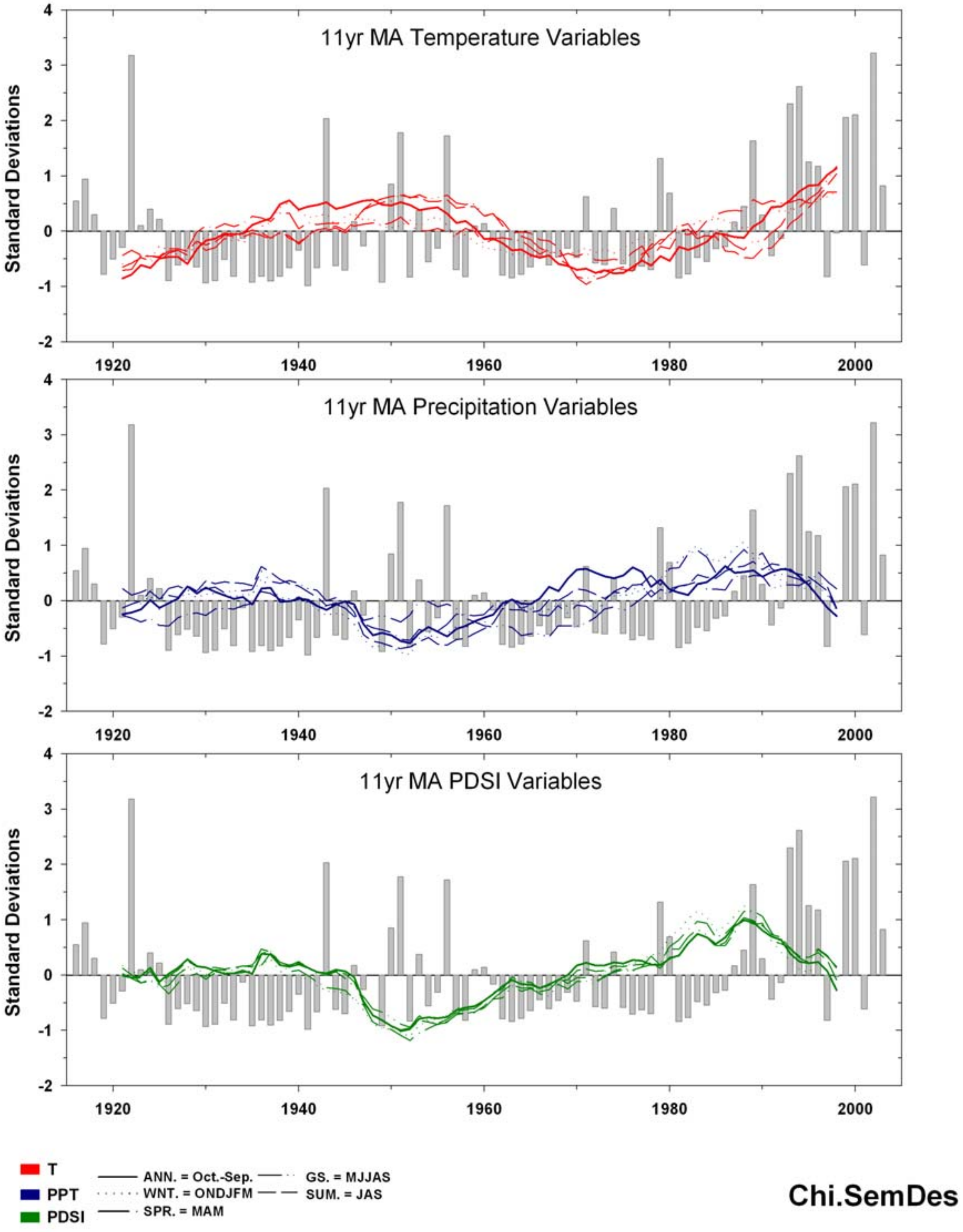
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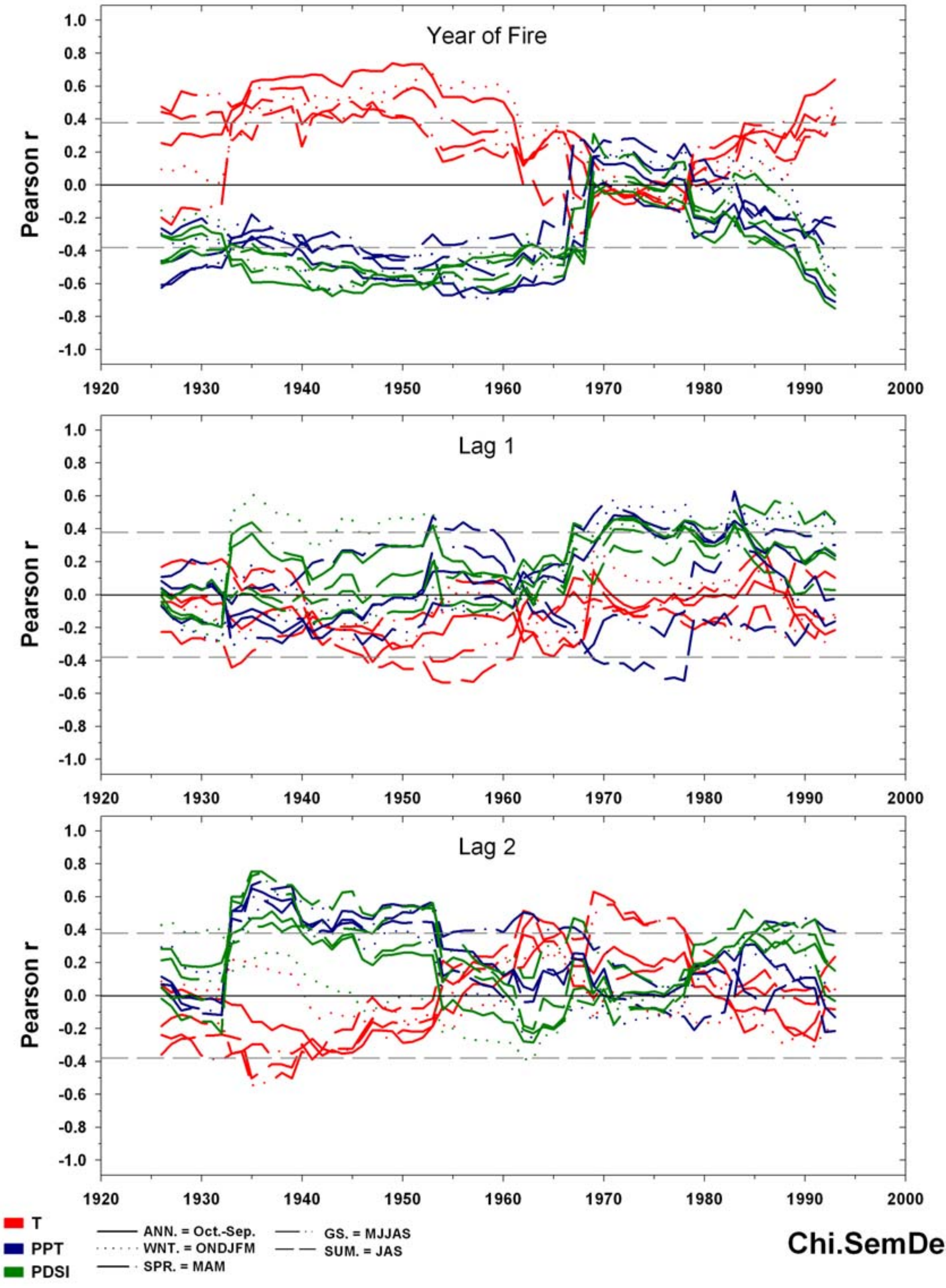
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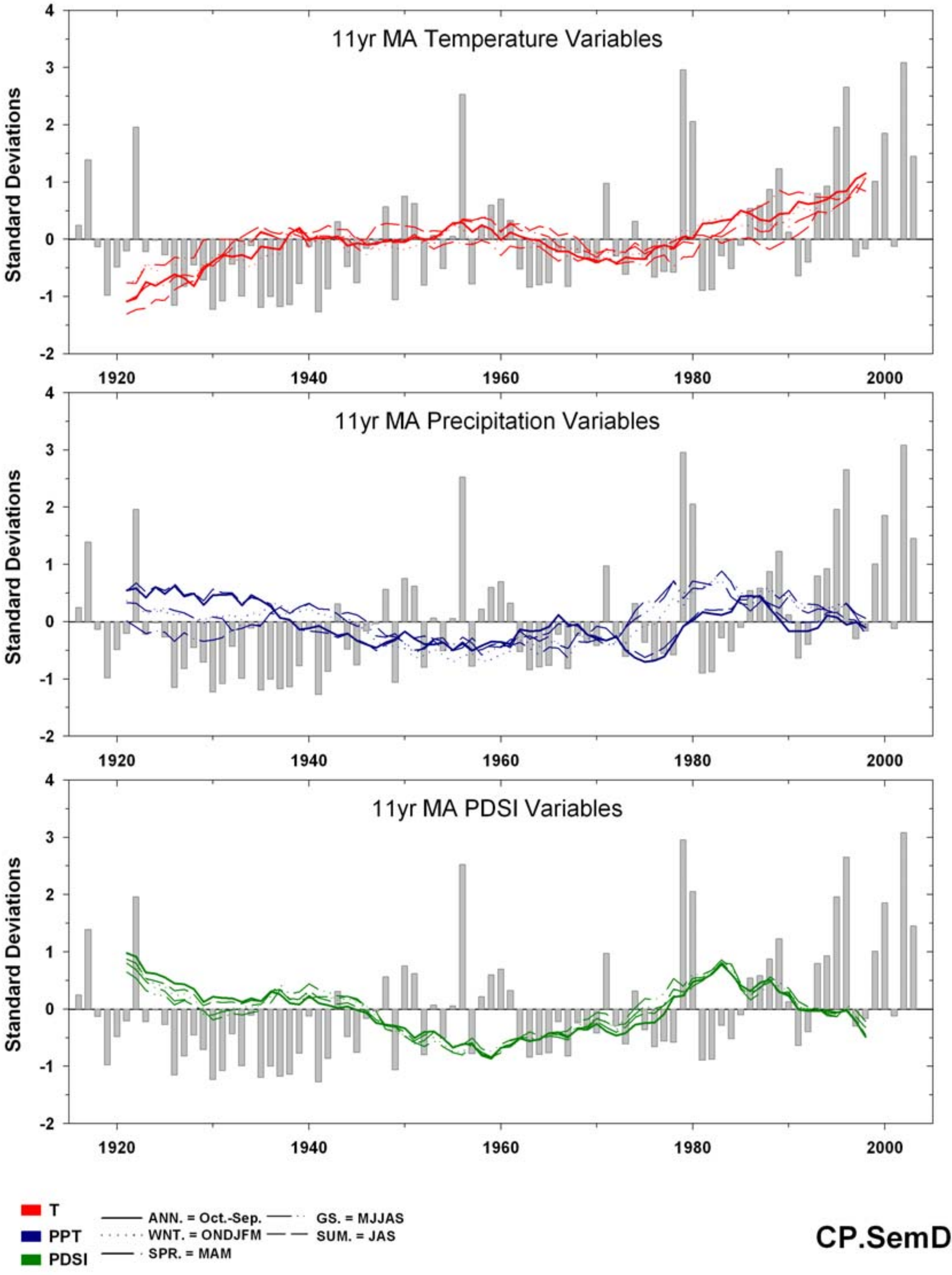
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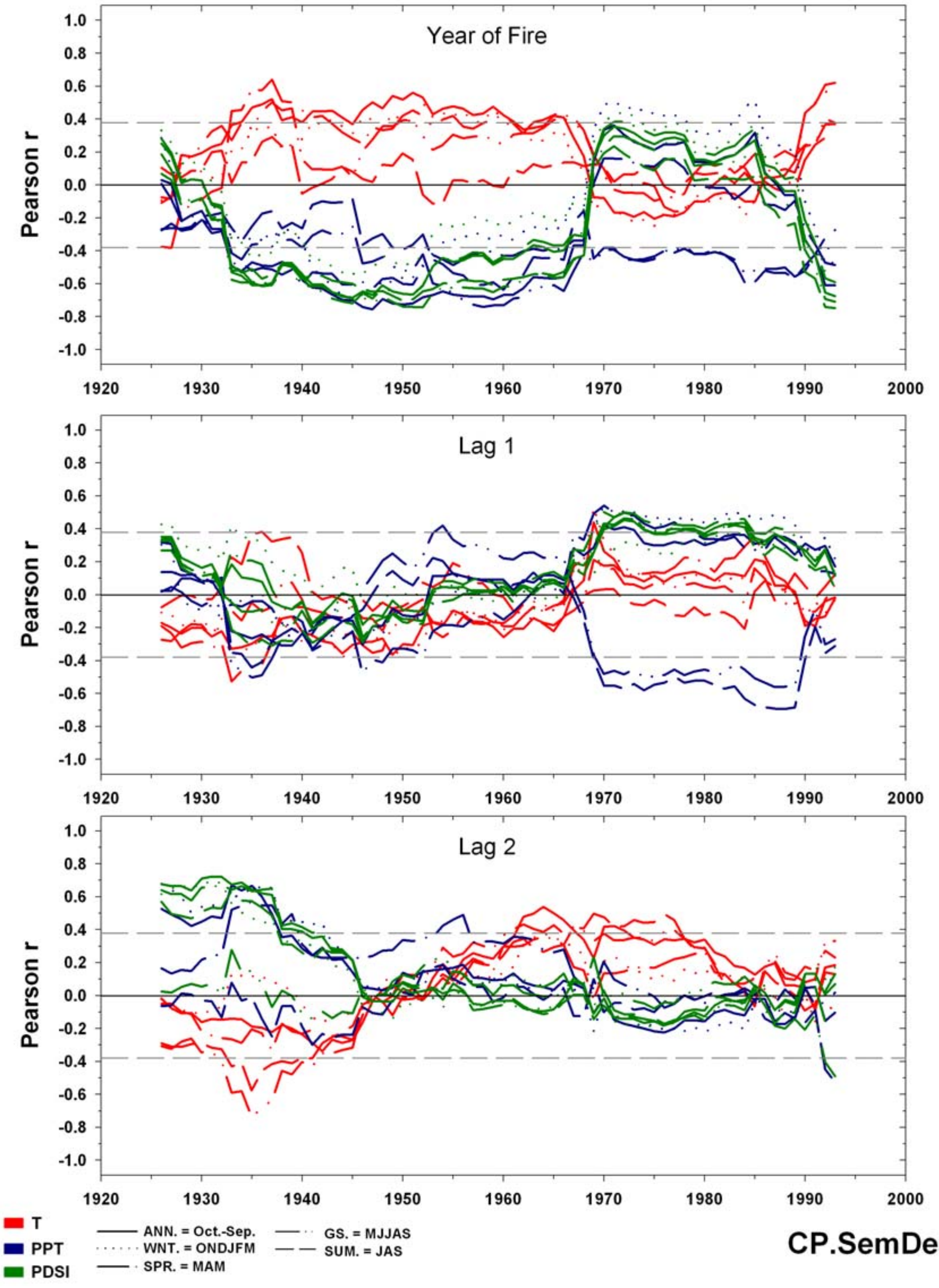
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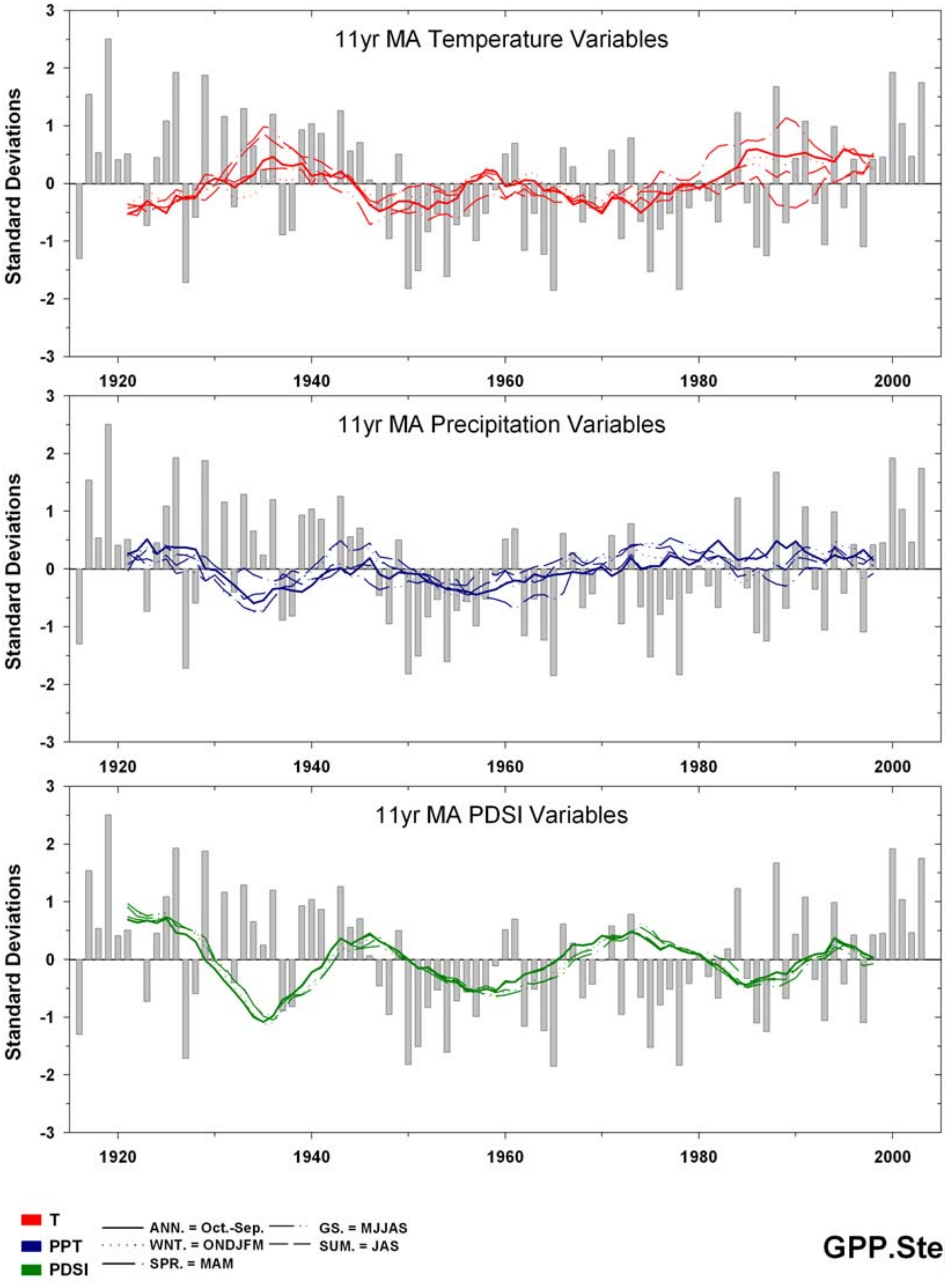
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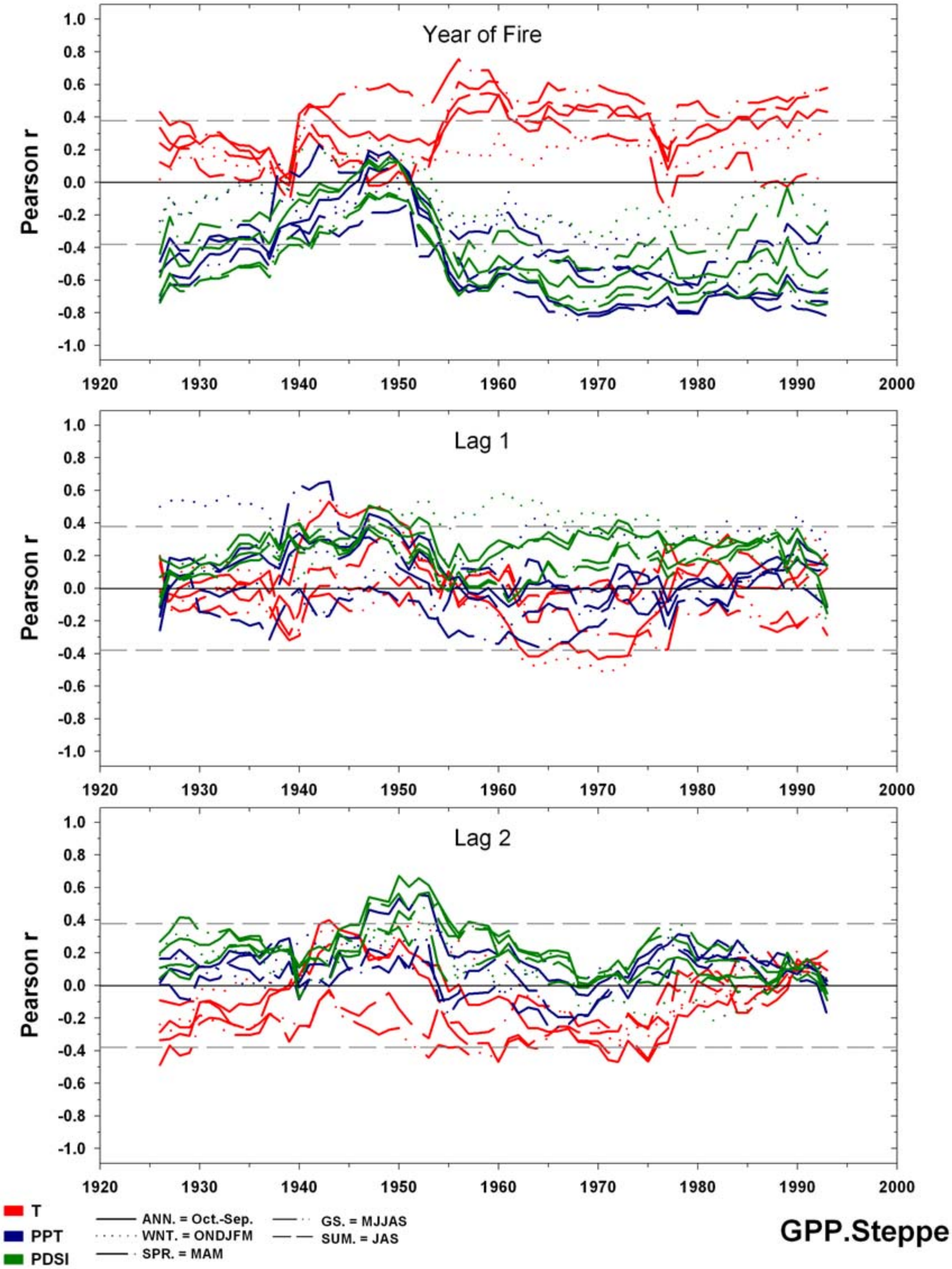
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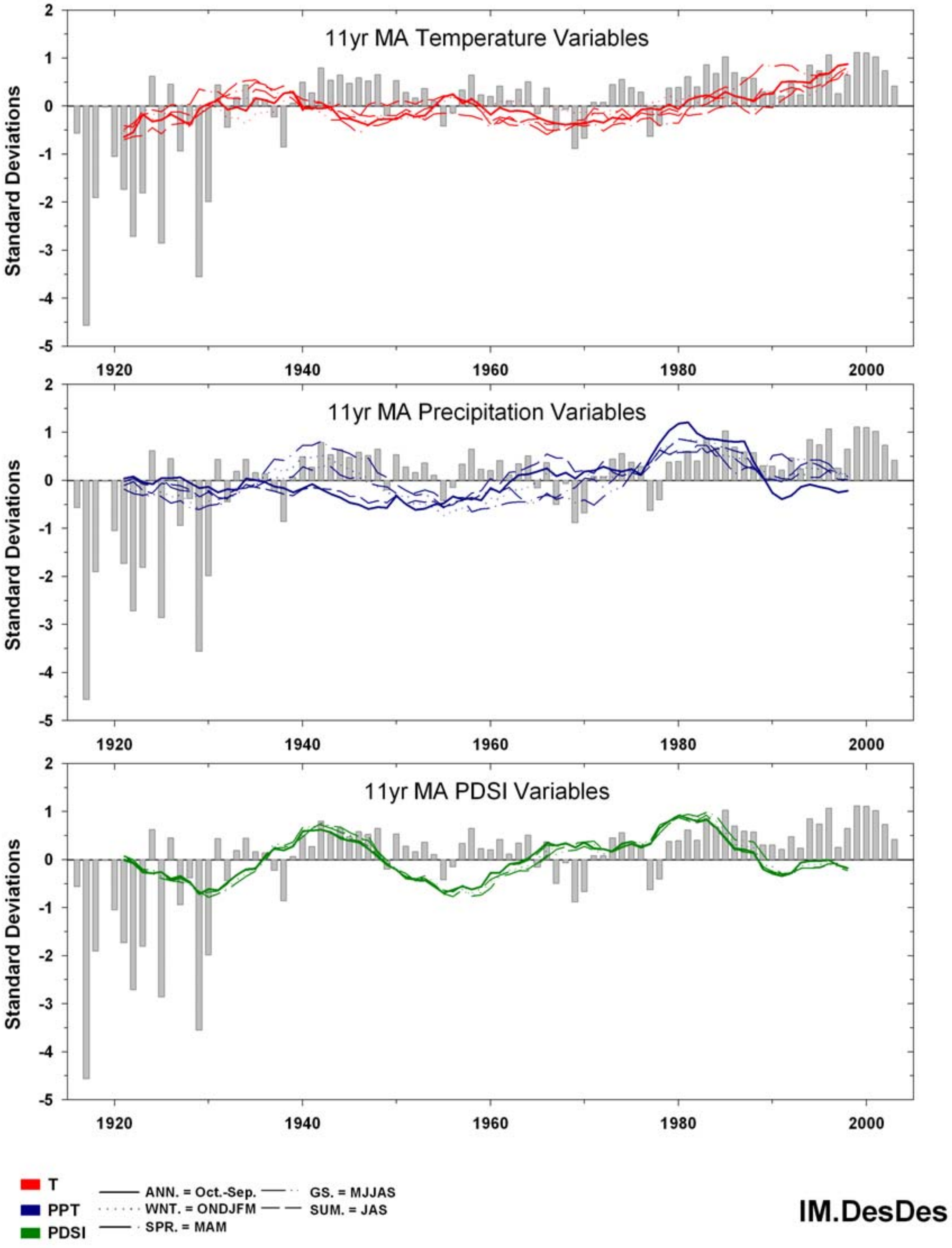
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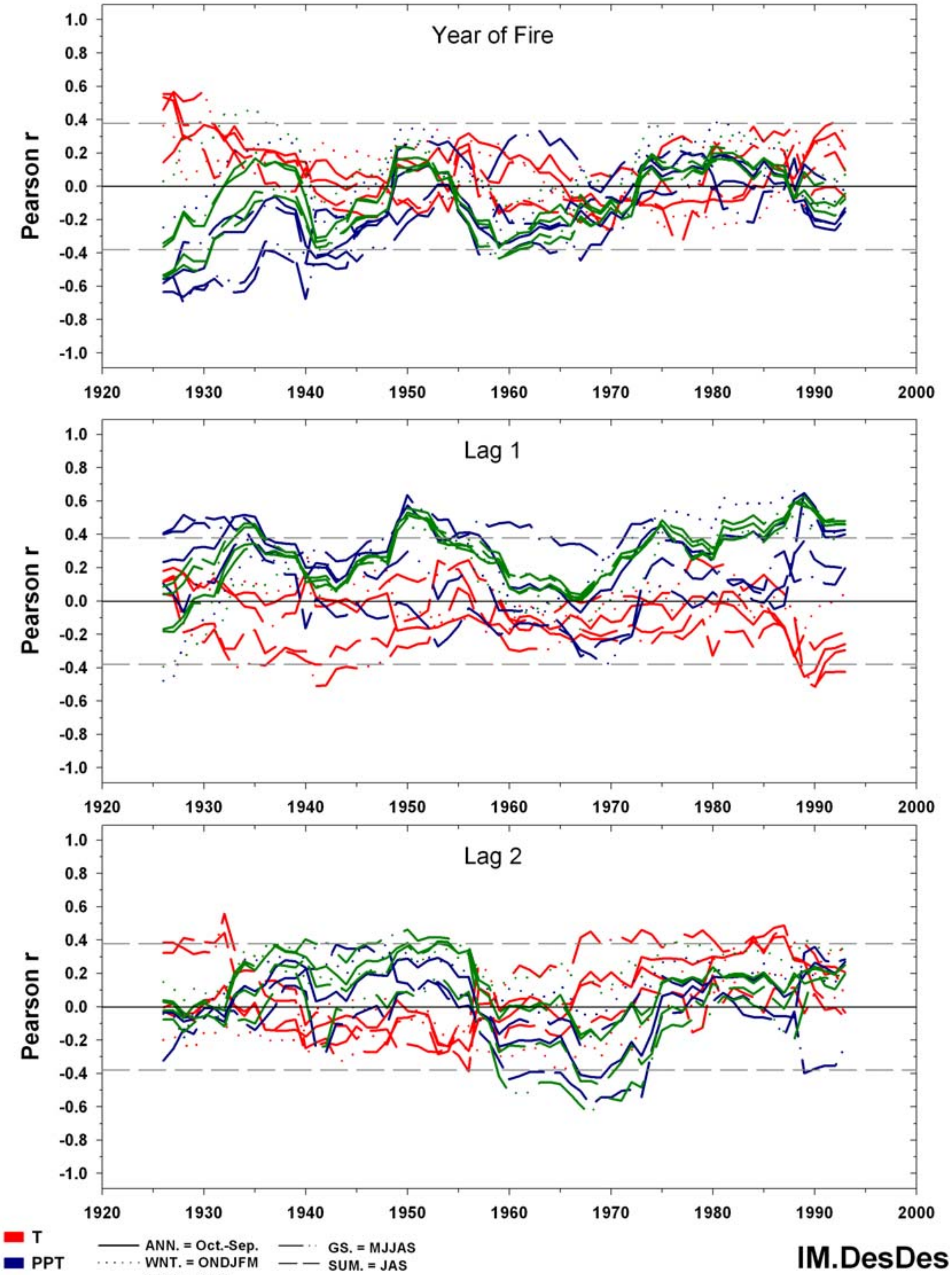
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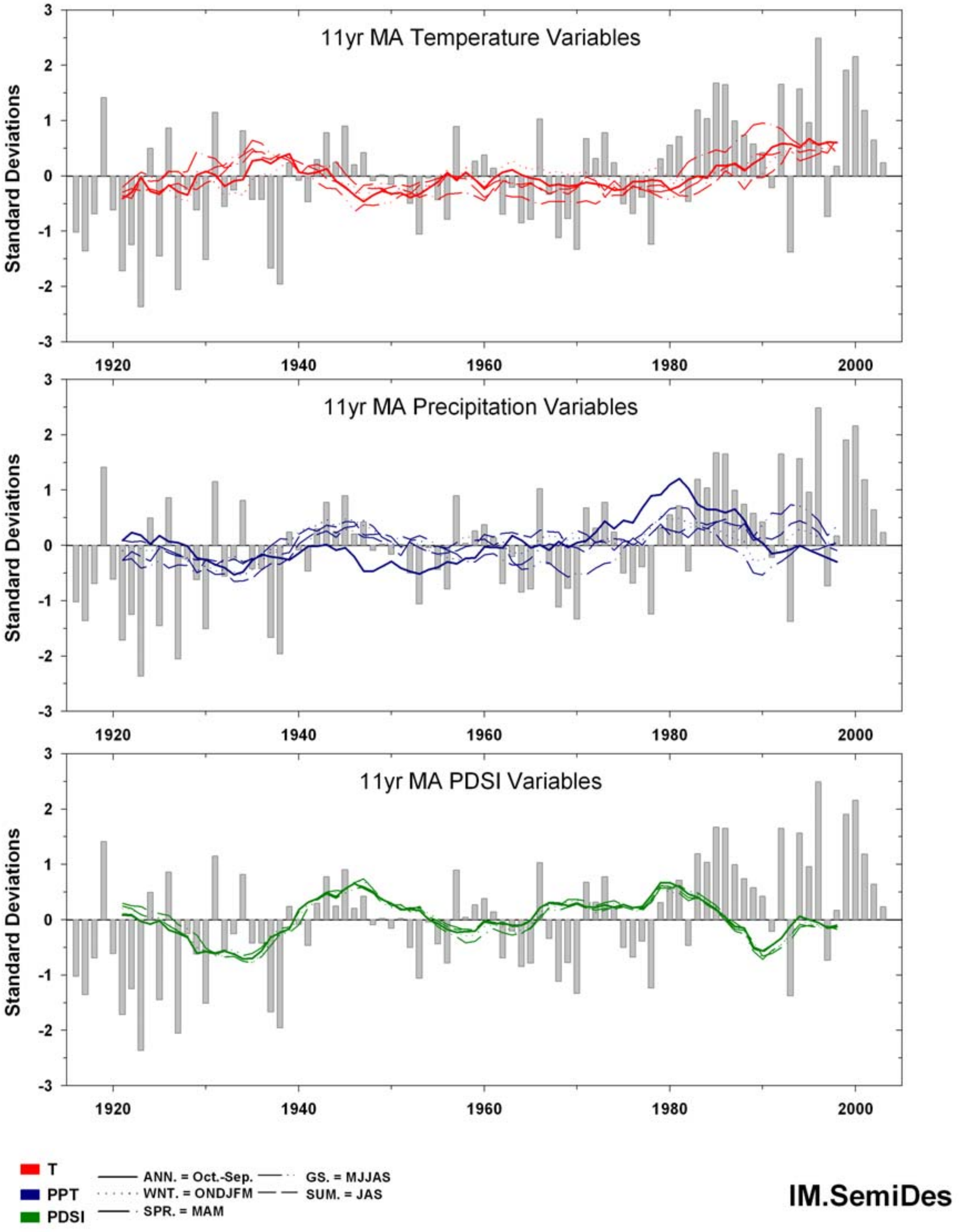
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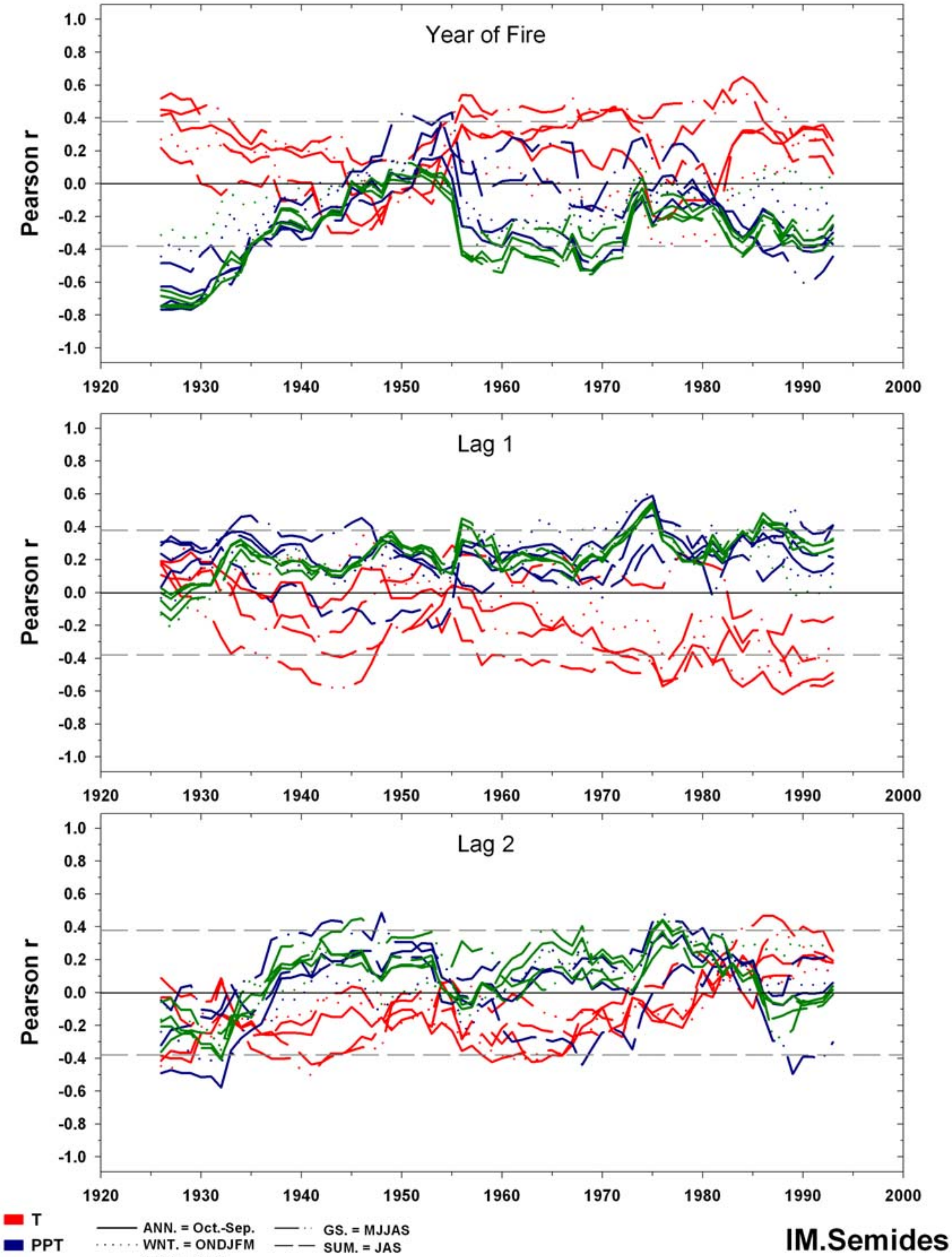
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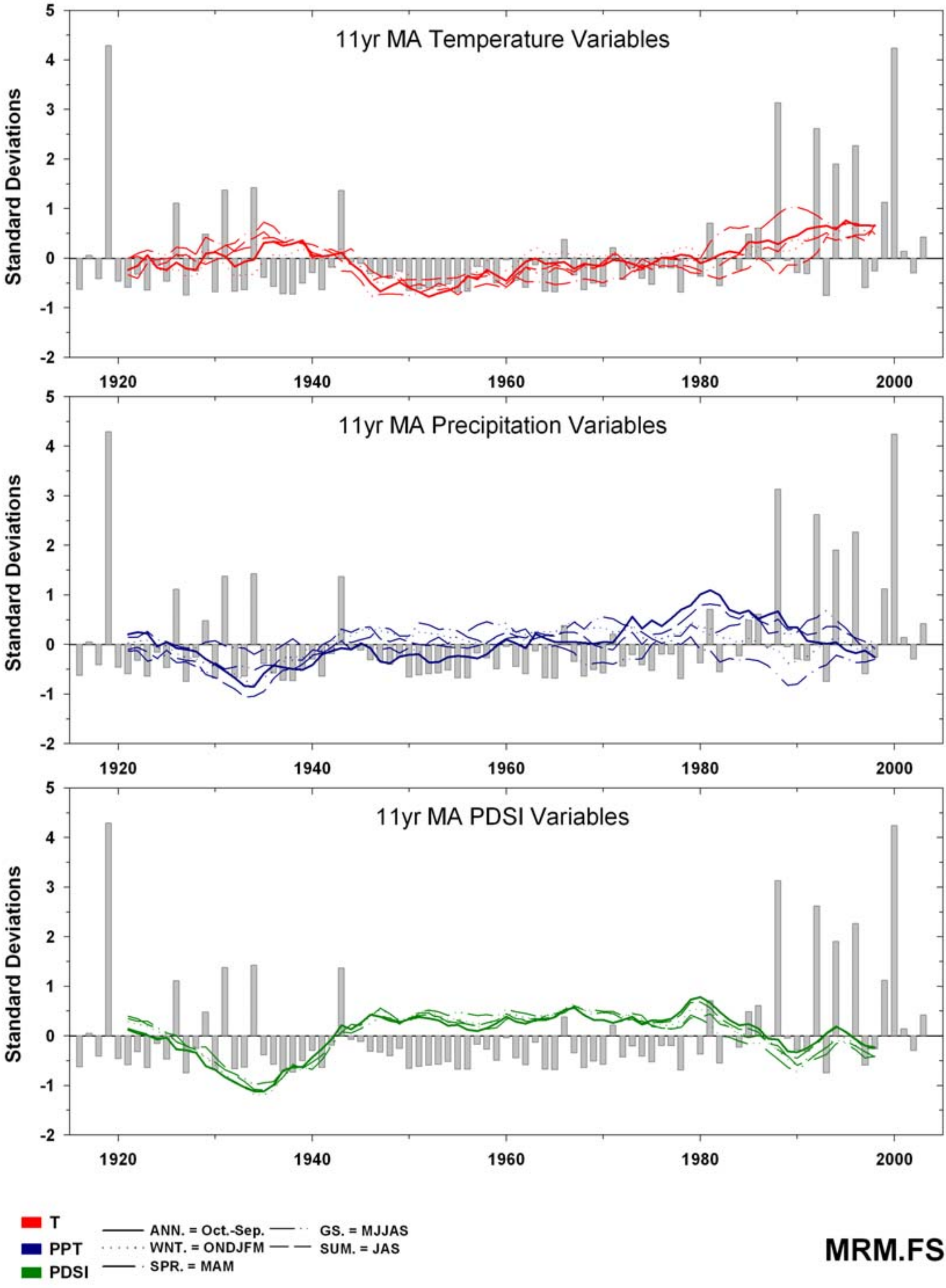
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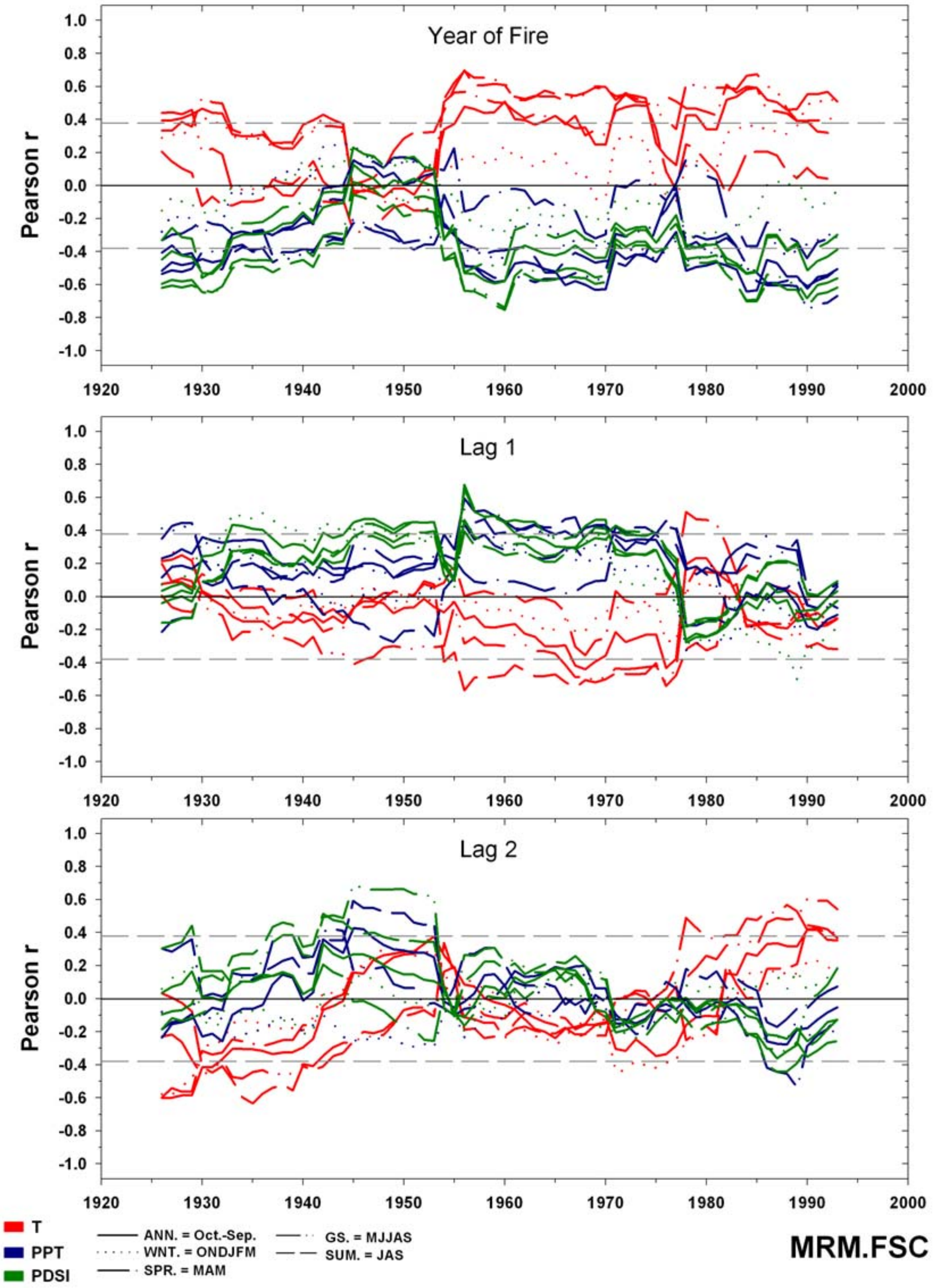
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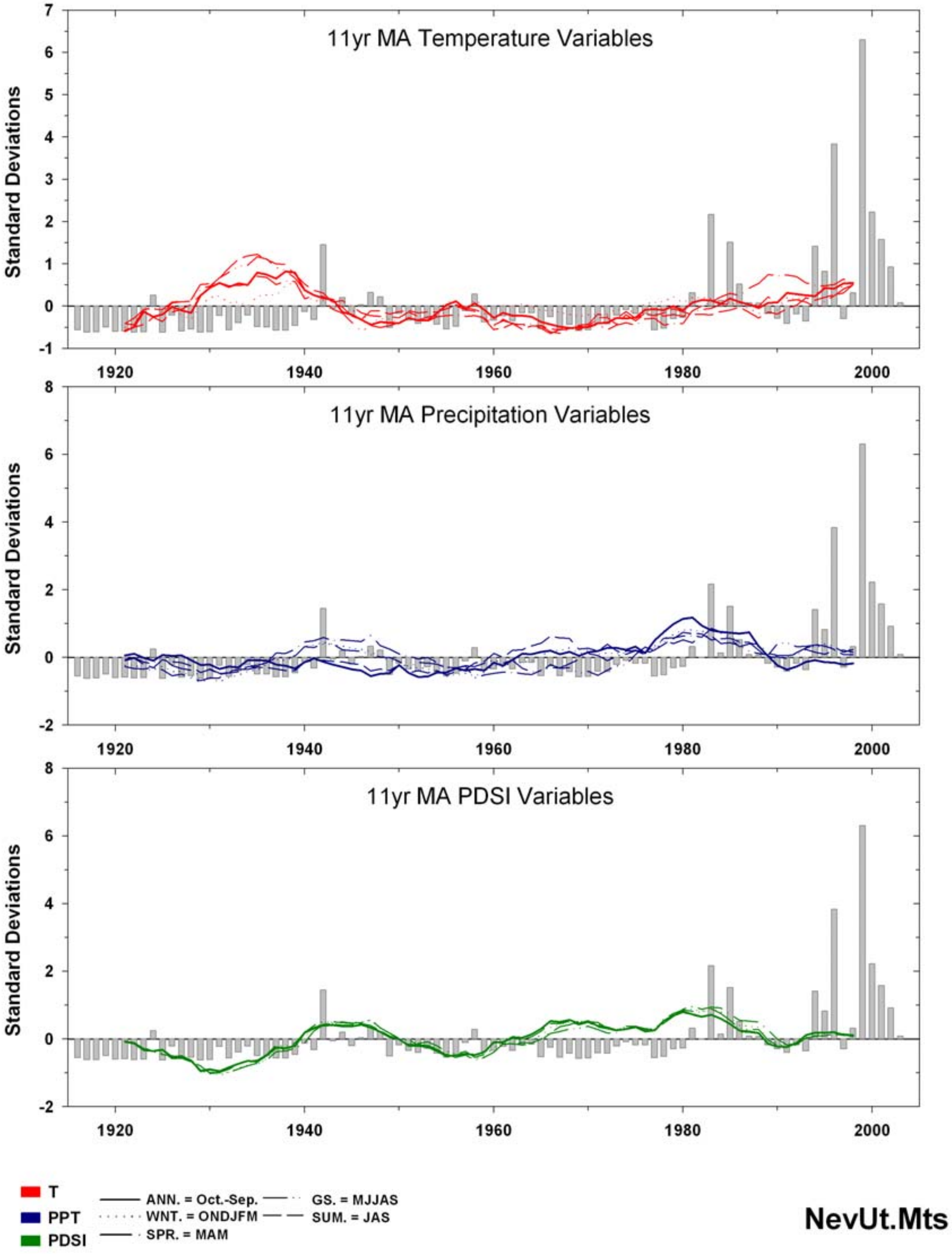
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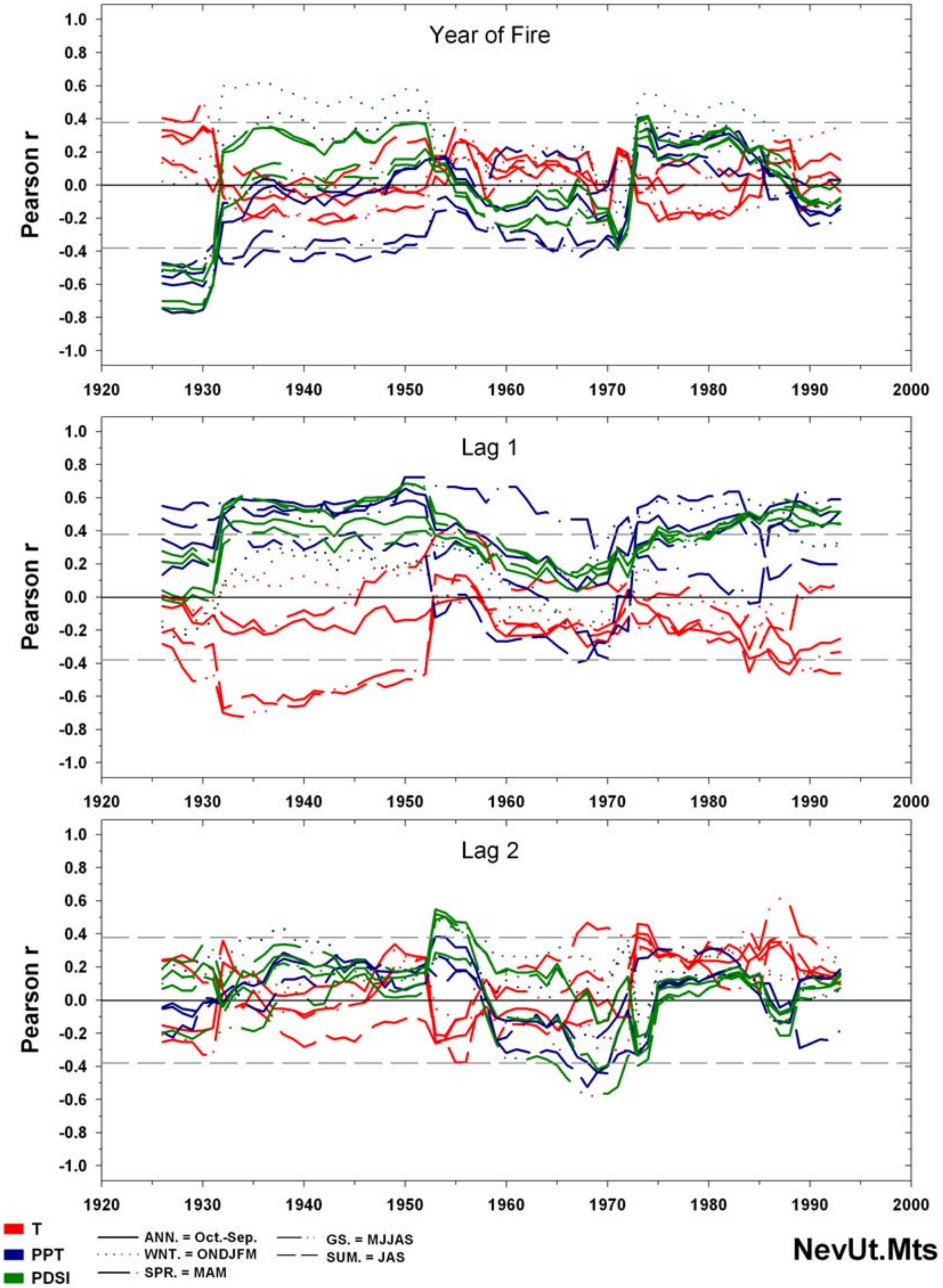
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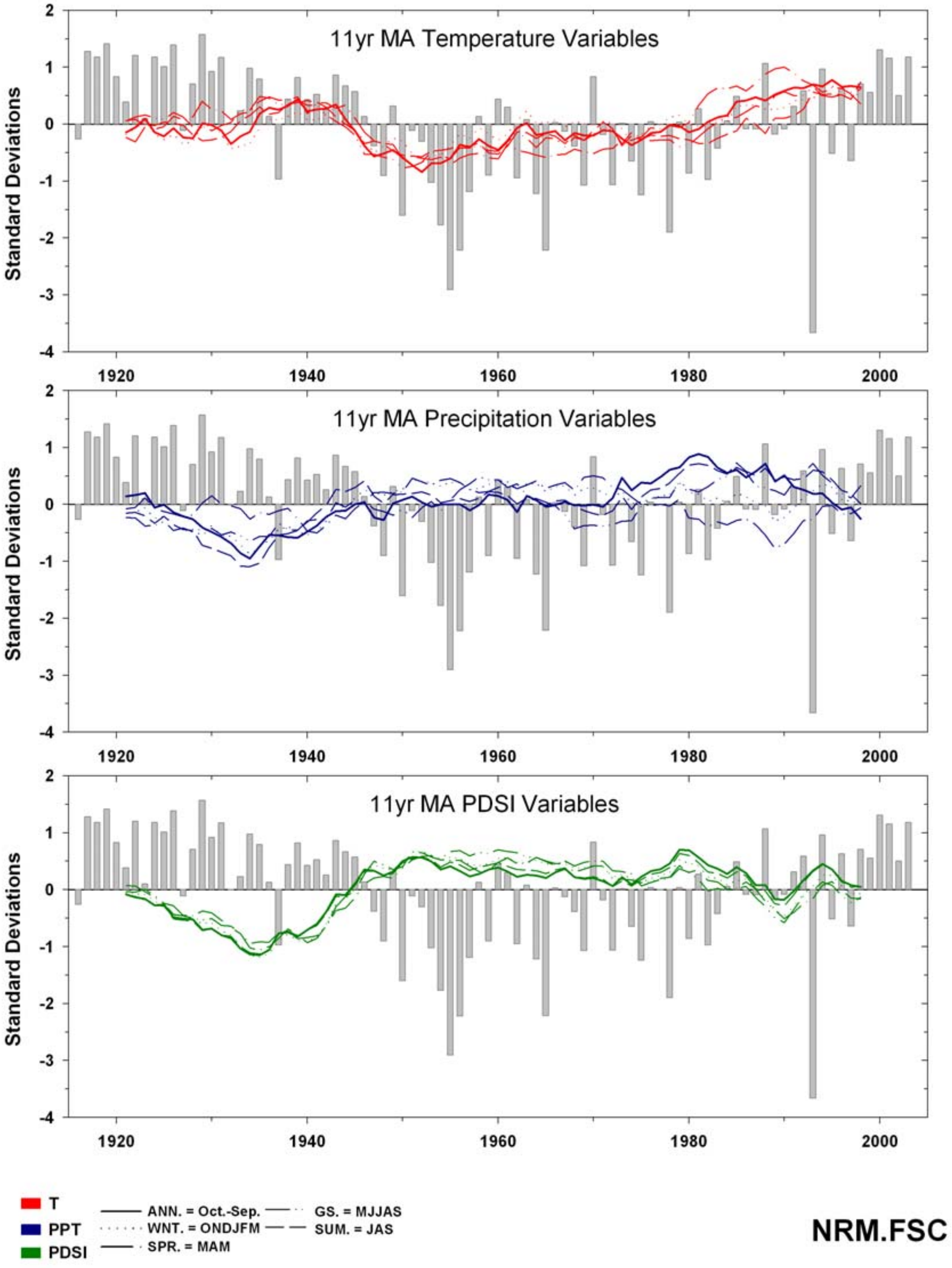
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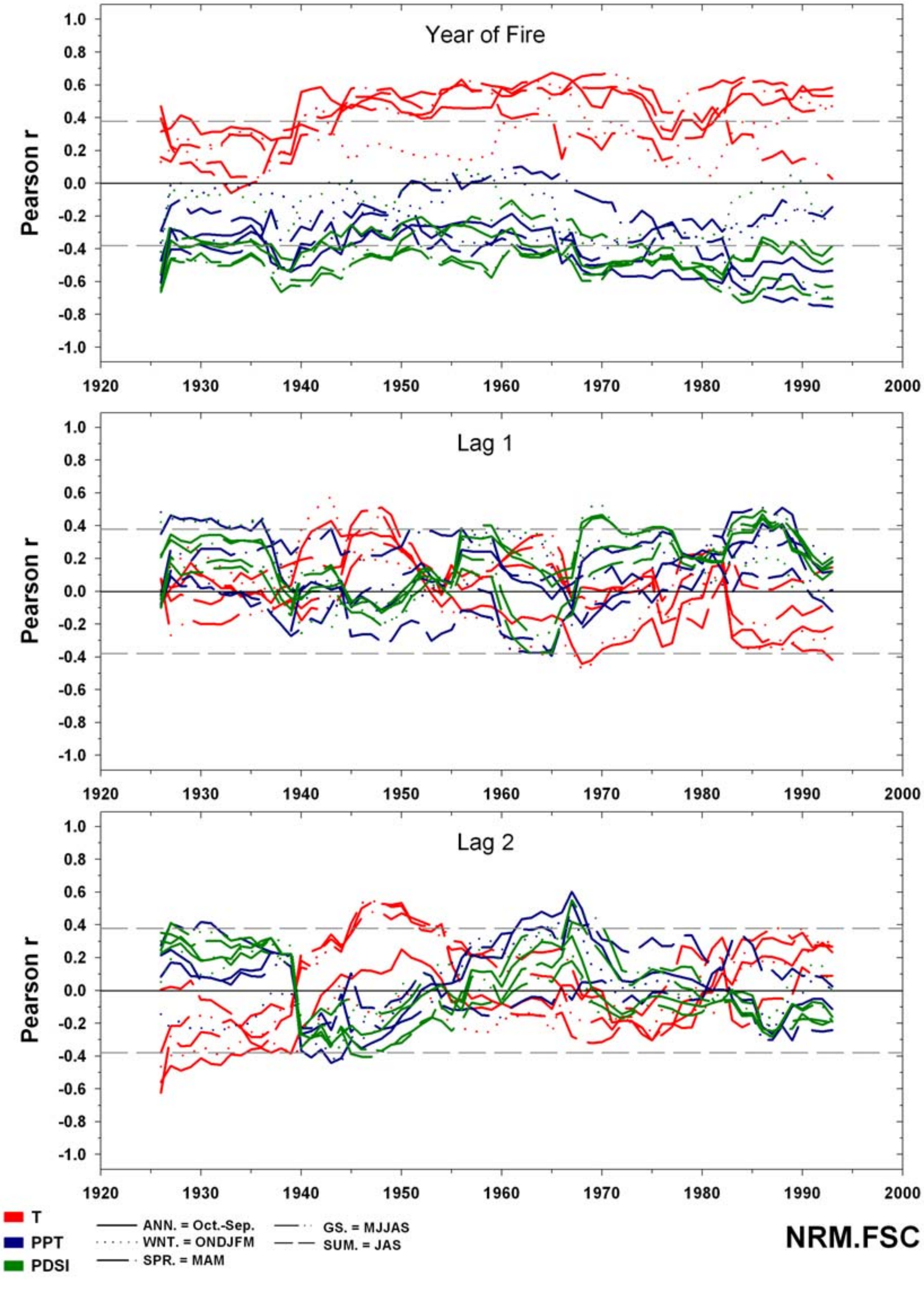
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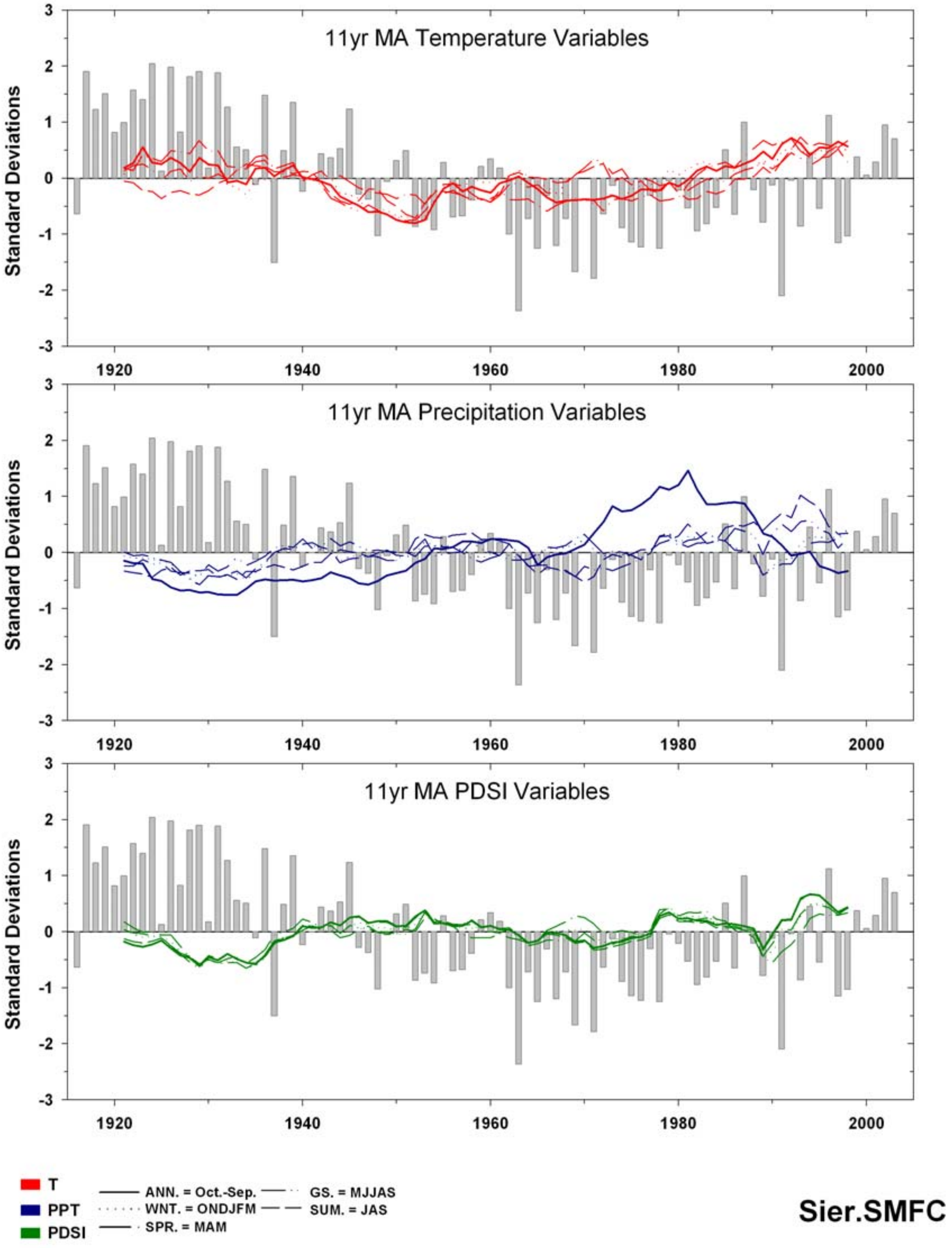
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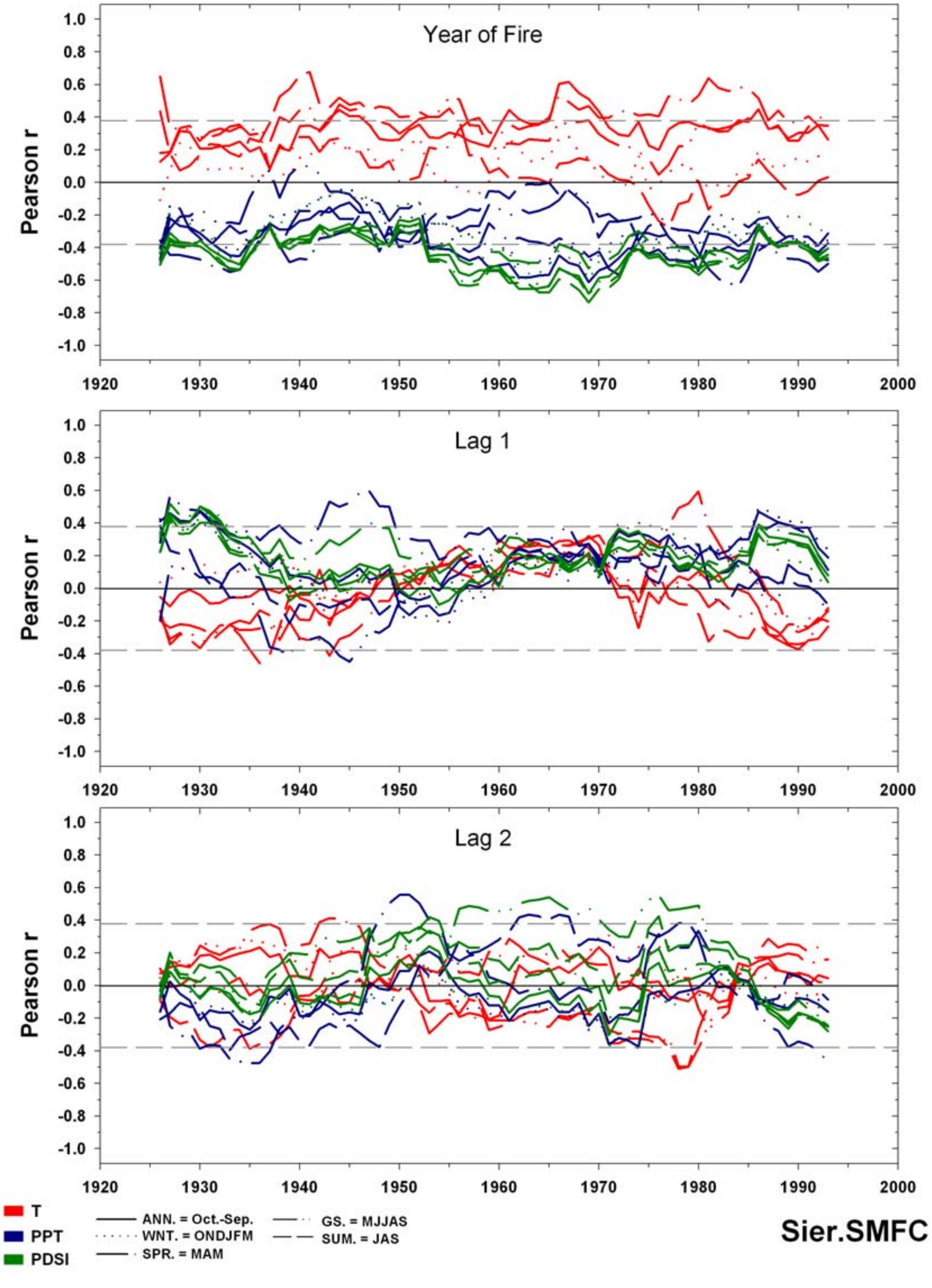
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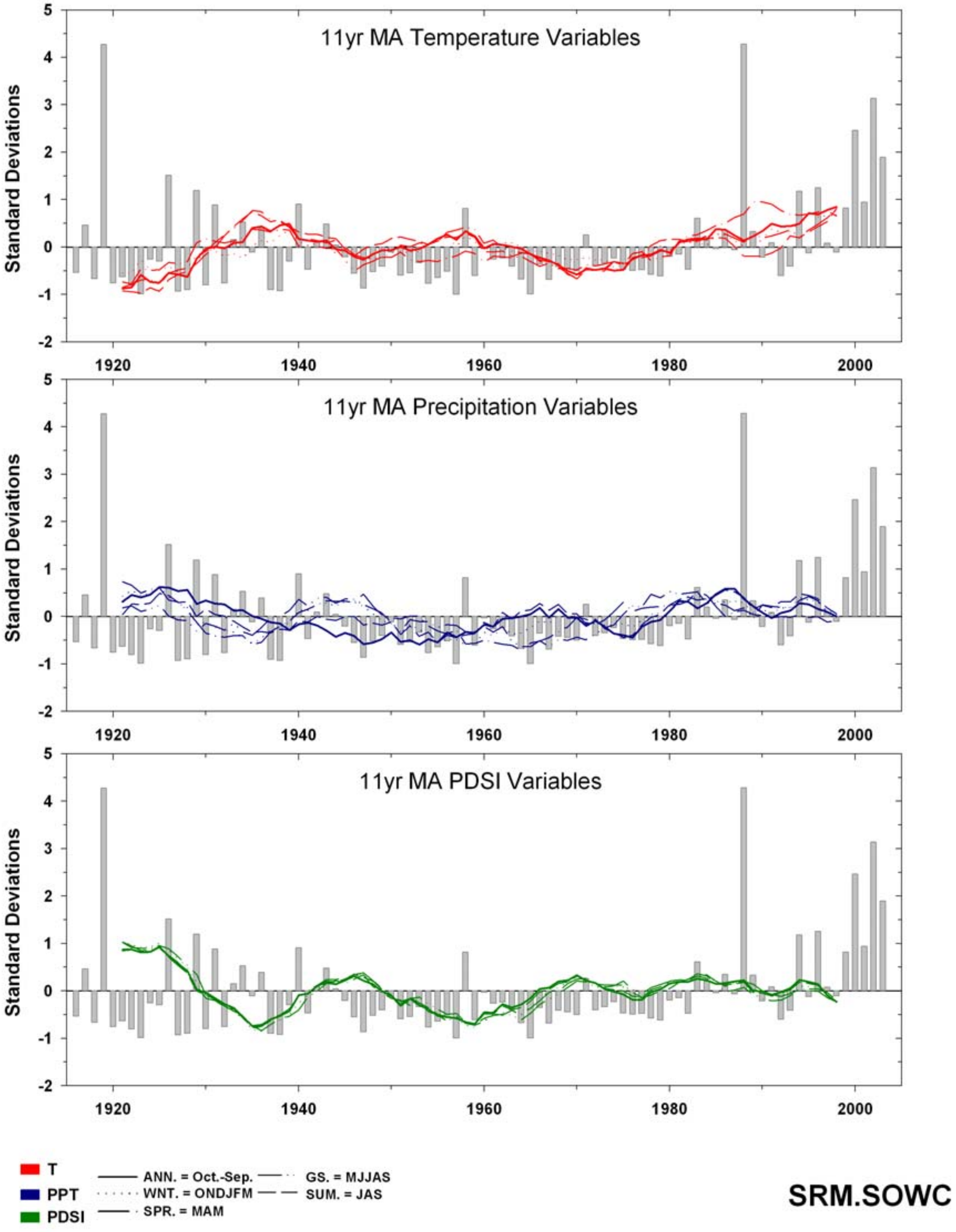
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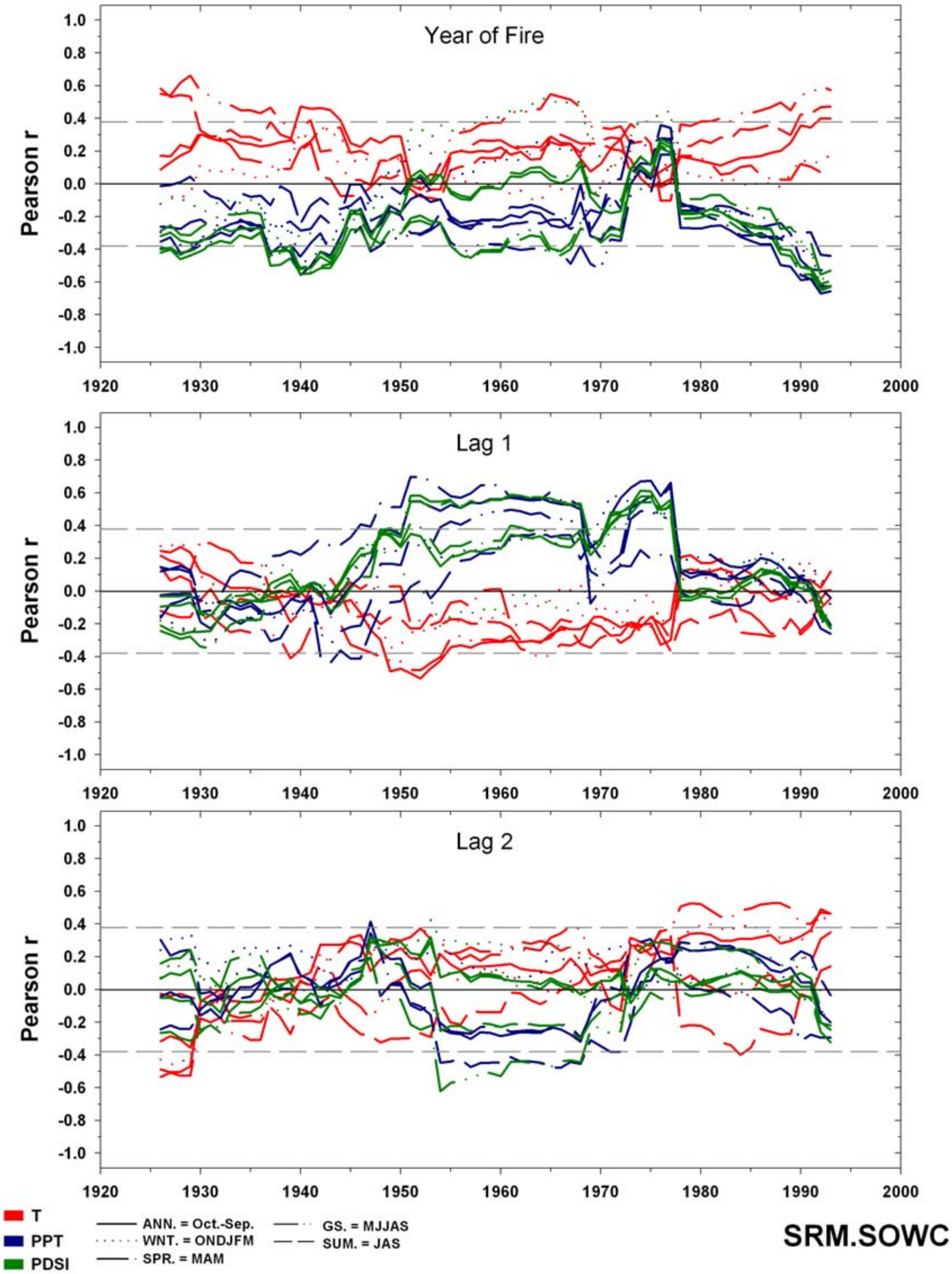
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APPENDIX 2.

Plot Location, Physical Description, and Chronology Statistics

APPENDIX 2. Plot location, physical description, and selected tree-ring statistics. Map numbers correspond to Figure 3.1 sample watersheds. Trees is the number of sampled trees included in the final chronology. Standard deviation, mean sensitivity, and the first order autocorrelation describe the nature of the chronology. The expressed population signal (EPS) refers to the statistical quality of the chronology and is calculated over the common period, 1900-2003. The number of trees required to exceed an EPS of 0.85 is included in the last column.

Map #	Water-shed	N/S		Lat. (N)	Long. (W)	Elev. (m)	Slope (deg)	Aspect (deg)	Trees	Std dev	Mean sens.	AC1	EPS	EPS # 0.85
1	Sol Duc ONP	N	LO	47.95	123.82	639	29	345	8	0.18	0.135	0.55	0.87	7
			MID	47.94	123.82	809	32	5	10	0.17	0.128	0.57	0.80	>10
			HI	47.93	123.82	1031	40	21	10	0.18	0.128	0.62	0.87	9
		S	LO	47.95	123.81	743	31	206	11	0.19	0.128	0.64	0.85	11
			MID	47.96	123.81	896	46	208	9	0.18	0.140	0.53	0.86	8
			HI	47.96	123.81	1256	48	196	10	0.21	0.142	0.64	0.88	8
2	Hoh River ONP	N	LO	47.83	123.98	285	23	325	10	0.18	0.134	0.56	0.86	9
			MID	47.82	123.97	560	29	7	13	0.17	0.138	0.49	0.89	5
			HI	47.82	123.97	830	40	18	12	0.17	0.130	0.53	0.87	6
		S	LO	47.82	124.02	200	39	172	10	0.23	0.174	0.60	0.73	>8
			MID	47.83	124.02	583	43	174	14	0.19	0.139	0.60	0.88	12
			HI	47.84	124.03	778	46	186	12	0.20	0.135	0.62	0.90	7
3	Quinault ONP	N	LO	47.53	123.70	249	45	346	13	0.18	0.138	0.59	0.90	8
			MID	47.52	123.70	737	45	353	10	0.16	0.107	0.66	0.85	10
			HI	47.52	123.70	960	21	348	11	0.16	0.115	0.60	0.83	>10
		S	LO	47.57	123.66	162	6	106	12	0.17	0.117	0.62	0.86	11
			MID	47.58	123.68	443	48	177	14	0.15	0.106	0.64	0.86	13
			HI	47.58	123.68	633	41	176	9	0.17	0.142	0.47	0.87	8

Map #	Water-shed	N/S		Lat. (N)	Long. (W)	Elev. (m)	Slope (deg)	Aspect (deg)	Trees	Std dev	Mean sens.	AC1	EPS	EPS # 0.85
4	Gray Wolf ONP	N	LO	47.91	123.24	759	49	4	11	0.18	0.144	0.53	0.92	6
			MID	47.91	123.25	1102	36	53	10	0.15	0.131	0.44	0.89	5
			HI	47.90	123.26	1491	40	336	9	0.15	0.130	0.35	0.88	7
		S	LO	47.92	123.25	794	39	206	10	0.16	0.136	0.42	0.91	6
			MID	47.93	123.25	1098	32	179	9	0.17	0.141	0.45	0.91	6
			HI	47.94	123.25	1474	30	231	12	0.17	0.145	0.39	0.92	6
5	Dosewal-lips ONP	N	LO	47.74	123.21	616	42	11	12	0.17	0.145	0.45	0.92	6
			MID	47.74	123.21	1025	39	354	12	0.15	0.123	0.53	0.87	11
			HI	47.73	123.21	1340	33	350	9	0.17	0.126	0.48	0.87	8
		S	LO	47.75	123.21	680	46	183	12	0.16	0.128	0.50	0.85	12
			MID	47.76	123.21	1083	28	193	12	0.16	0.123	0.56	0.90	8
			HI	47.77	123.20	1455	42	169	12	0.19	0.137	0.59	0.90	8
6	Chil-liwack NCNP	N	LO	48.93	121.39	813	19	2	10	0.14	0.103	0.56	0.90	7
			MID	48.93	121.39	1063	49	359	13	0.18	0.123	0.63	0.91	7
			HI	48.93	121.39	1233	36	354	15	0.17	0.126	0.52	0.93	6
		S	LO	48.95	121.40	821	35	126	12	0.24	0.144	0.65	0.88	9
			MID	48.95	121.41	1027	29	137	13	0.16	0.123	0.52	0.90	9
			HI	48.95	121.42	1258	32	159	13	0.15	0.126	0.39	0.91	7
7	Thunder Creek NCNP	N	LO	48.71	121.14	455	28	276	10	0.24	0.154	0.68	0.90	7
			MID	48.70	121.13	701	35	2	11	0.19	0.122	0.68	0.89	8
			HI	48.70	121.12	913	9	270	11	0.21	0.156	0.59	0.86	6
		S	LO	48.67	121.07	465	26	243	9	0.18	0.148	0.44	0.89	5
			MID	48.67	121.06	727	32	267	10	0.24	0.168	0.60	0.91	6
			HI	48.66	121.05	1065	23	278	10	0.23	0.178	0.51	0.92	6

Map #	Watershed	N/S		Lat. (N)	Long. (W)	Elev. (m)	Slope (deg)	Aspect (deg)	Trees	Std dev	Mean sens.	AC1	EPS	EPS # 0.85
8	Park Creek NCNP	N	LO	48.42	120.95	792	23	349	10	0.16	0.126	0.49	0.85	10
			MID	48.41	120.95	952	58	34	9	0.18	0.124	0.64	0.85	9
			HI	48.41	120.95	1124	33	358	10	0.19	0.133	0.59	0.89	7
		S	LO	48.43	120.92	767	25	184	9	0.22	0.169	0.52	0.85	9
			MID	48.44	120.91	1083	52	174	9	0.21	0.183	0.47	0.85	9
			HI	48.44	120.92	1378	48	232	11	0.22	0.163	0.56	0.91	7
9	Desol-ation Peak NCNP	N	LO	48.87	121.01	738	39	270	13	0.27	0.201	0.64	0.89	8
			MID	48.87	121.00	1122	31	326	17	0.25	0.153	0.72	0.87	7
			HI	48.87	120.99	1319	49	23	12	0.22	0.173	0.50	0.91	5
		S	LO	48.88	121.02	659	55	185	12	0.23	0.169	0.58	0.89	8
			MID	48.88	121.01	916	50	189	13	0.22	0.196	0.39	0.93	5
			HI	48.88	121.01	1067	21	202	13	0.31	0.218	0.60	0.90	7
10	Bridge Creek NCNP	N	LO	48.46	120.78	1027	27	349	10	0.33	0.172	0.89	0.81*	>7
			MID	48.46	120.78	1182	35	359	9	0.27	0.163	0.74	0.88*	7
			HI	48.45	120.78	1340	45	9	9	0.20	0.154	0.48	0.89*	7
		S	LO	48.46	120.83	1008	28	179	11	0.19	0.138	0.61	0.79	>8
			MID	48.47	120.81	1200	43	201	10	0.20	0.159	0.48	0.87	4
			HI	48.47	120.80	1424	43	174	11	0.21	0.156	0.51	0.93	5
11	Stehekin NCNP	N	HI	48.31	120.68	444	41	63	12	0.17	0.119	0.62	0.89	8
			LO	48.31	120.69	754	33	352	10	0.13	0.116	0.42	0.79*	>9
			MID	48.30	120.69	1382	22	47	13	0.18	0.129	0.57	0.90	9
		S	LO	48.31	120.65	522	43	218	9	0.15	0.139	0.34	**	
			MID	48.31	120.63	1250	45	216	10	0.18	0.170	0.30	0.90	6
			HI	48.31	120.61	1700	40	247	11	0.17	0.155	0.32	0.92	6

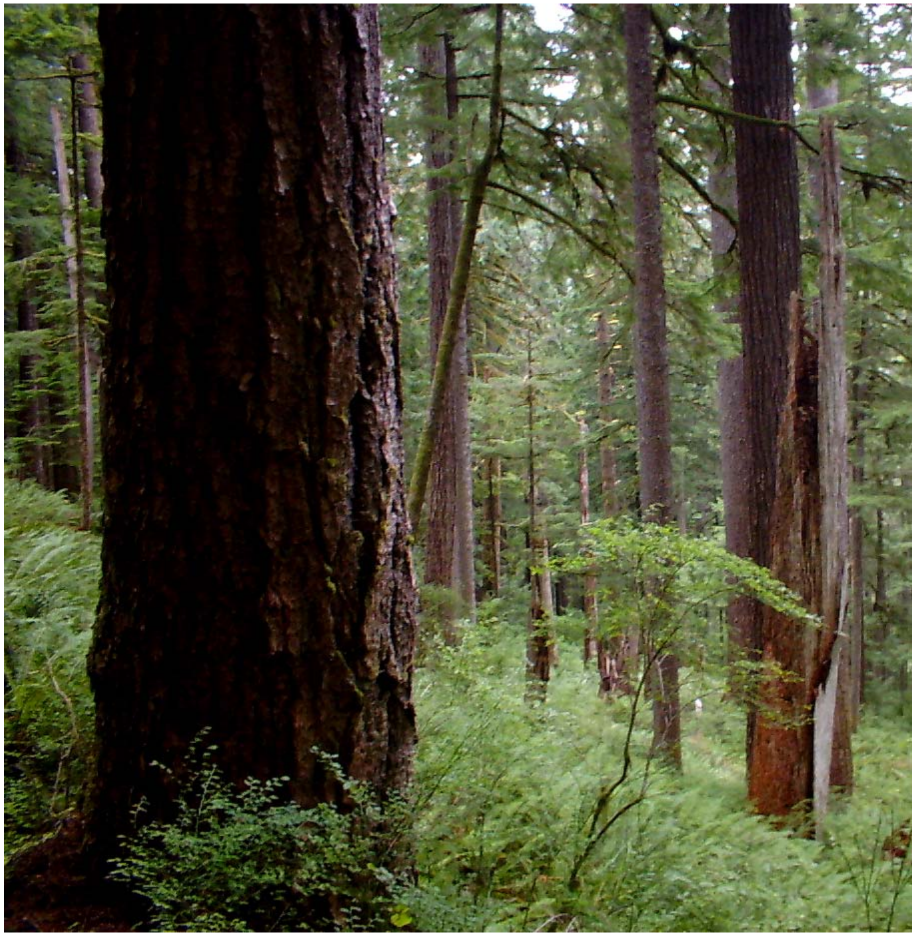
Map #	Watershed	N/S		Lat. (N)	Long. (W)	Elev. (m)	Slope (deg)	Aspect (deg)	Trees	Std dev	Mean sens.	AC1	EPS	EPS # 0.85
12	Boundary Mt. IPNF	N	LO	48.99	116.60	748	35	354	13	0.22	0.185	0.48	0.92*	6
			MID	48.98	116.60	969	40	334	11	0.30	0.234	0.62	0.84	>7
			HI	48.97	116.60	1412	22	356	12	0.17	0.132	0.53	0.87	10
		S	LO	48.99	116.66	1052	38	177	11	0.24	0.192	0.55	0.89	8
			MID	48.99	116.65	1295	42	179	11	0.27	0.210	0.56	0.91	6
			HI	49.00	116.65	1603	27	185	12	0.28	0.223	0.55	0.93	5
13	Trout Creek IPNF	N	LO	48.83	116.46	951	49	347	11	0.32	0.204	0.68	0.85	9
			MID	48.82	116.46	1113	42	339	12	0.28	0.198	0.61	0.89	6
			HI	48.82	116.46	1368	41	338	12	0.24	0.203	0.48	0.91	5
		S	LO	48.83	116.46	1103	42	155	10	0.31	0.229	0.59	0.87	5
			MID	48.83	116.47	1368	34	170	11	0.31	0.232	0.57	0.92	6
			HI	48.84	116.46	1699	29	180	14	0.26	0.204	0.53	0.95	5
14	Round Prairie IPNF	N	LO	48.95	116.23	986	27	329	10	0.28	0.259	0.47	0.88	6
			MID	48.95	116.22	1187	43	17	10	0.23	0.215	0.33	0.93*	4
			HI	48.94	116.22	1444	10	351	11	0.31	0.211	0.63	0.93	4
		S	LO	48.97	116.25	985	32	165	13	0.36	0.277	0.55	0.95	4
			MID	48.97	116.25	1201	37	146	13	0.35	0.250	0.59	0.94	5
			HI	48.98	116.25	1500	24	180	11	0.24	0.187	0.54	0.94	5
15	Leonia Knob IPNF	N	LO	48.62	116.06	694	50	357	10	0.24	0.181	0.48	0.78	>4
			MID	48.62	116.06	810	13	326	11	0.29	0.201	0.56	0.86	6
			HI	48.61	116.07	978	23	319	12	0.35	0.224	0.69	0.85	8
		S	LO	48.62	116.07	791	31	171	11	0.30	0.208	0.66	0.84	>6
			MID	48.62	116.08	989	24	112	11	0.27	0.207	0.57	0.84	>7
			HI	48.62	116.08	1124	20	160	13	0.29	0.217	0.59	0.92	5

Map #	Watershed	N/S		Lat. (N)	Long. (W)	Elev. (m)	Slope (deg)	Aspect (deg)	Trees	Std dev	Mean sens.	AC1	EPS	EPS # 0.85
16	Bowman Lake GNP	N	LO	48.83	114.19	1291	17	339	12	0.35	0.199	0.75	**	
			MID	48.82	114.19	1363	25	325	14	0.29	0.189	0.72	0.95	4
			HI	48.81	114.19	1506	25	327	12	0.22	0.172	0.54	0.91*	4
		S	LO	48.87	114.16	1260	24	152	11	0.20	0.161	0.55	0.77*	>11
			MID	48.88	114.17	1628	51	153	13	0.24	0.191	0.55	0.95*	4
			HI	48.88	114.17	1872	38	170	15	0.20	0.151	0.59	0.88*	9
17	Lake MacDonald GNP	N	LO	48.58	113.90	1018	27	314	14	0.22	0.173	0.57	0.90	9
			MID	48.55	113.94	1258	24	329	11	0.22	0.206	0.29	0.89	8
			HI	48.56	113.91	1410	24	352	11	0.21	0.174	0.45	0.89	8
		S	LO	48.61	113.86	1100	15	225	13	0.21	0.160	0.55	0.93	6
			MID	48.61	113.85	1461	46	187	16	0.25	0.201	0.55	0.95	6
			HI	48.62	113.84	1713	17	237	12	0.29	0.194	0.66	0.92	6
18	Soldier Mt. GNP	N	LO	48.34	113.53	1425	43	330	10	0.16	0.147	0.32	0.84	>10
			MID	48.34	113.53	1580	55	1	11	0.24	0.188	0.52	0.92	5
			HI	48.34	113.52	1801	30	335	10	0.20	0.183	0.39	0.89	7
	Salvage Mt. GNP	S	LO	48.35	113.53	1420	26	166	9	0.22	0.179	0.48	0.92	4
			MID	48.36	113.53	1604	54	181	10	0.24	0.202	0.42	0.92	5
			HI	48.36	113.53	2000	45	189	9	0.29	0.226	0.50	0.79	>5
19	Belly River GNP	N	MID	48.93	113.74	1564	58	57	10	0.44	0.319	0.70	0.67	>6
		S	LO	48.93	113.75	1634	37	192	10	0.33	0.273	0.57	0.84	6
			MID	48.93	113.75	1675	38	238	8	0.26	0.212	0.45	0.81	>7
			HI	48.93	113.75	1768	39	217	9	0.20	0.181	0.35	0.77	>7

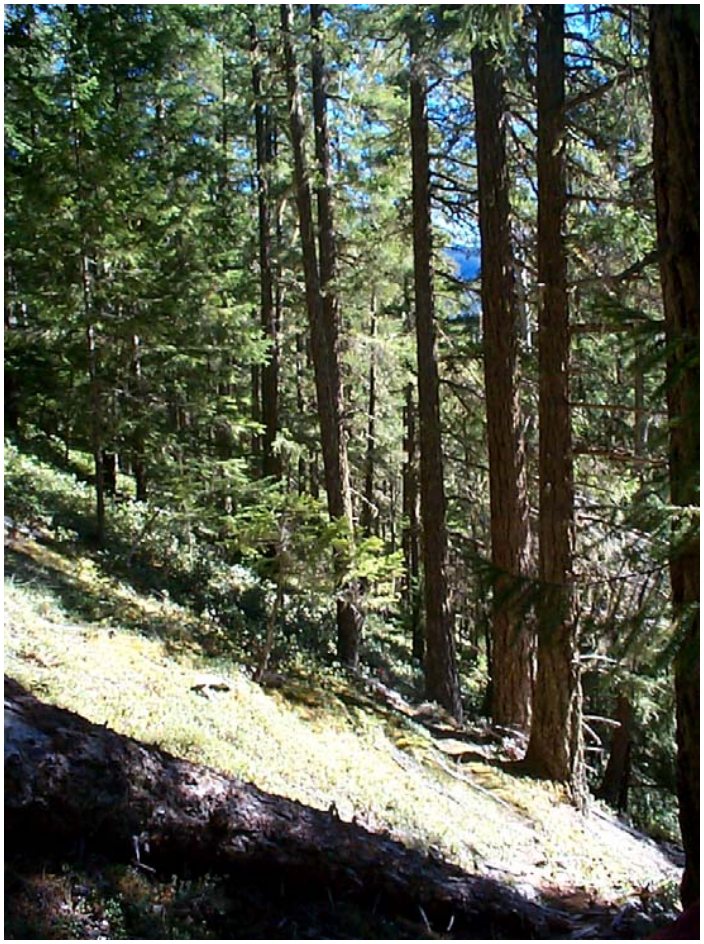
Map #	Watershed	N/S		Lat. (N)	Long. (W)	Elev. (m)	Slope (deg)	Aspect (deg)	Trees	Std dev	Mean sens.	AC1	EPS	EPS # 0.85
20	Saint Mary GNP	N	LO	48.68	113.51	1412	36	330	9	0.26	0.204	0.51	0.79	>7
			MID	48.66	113.60	1468	12	348	12	0.30	0.249	0.55	0.89	8
			HI	48.68	113.51	1541	53	12	11	0.29	0.234	0.55	0.87	8
		S	LO	48.69	113.53	1406	9	180	13	0.33	0.255	0.53	0.94	5
			MID	48.70	113.53	1566	10	207	9	0.24	0.197	0.45	0.88	6
			HI	48.71	113.52	1717	41	139	12	0.25	0.182	0.59	0.89	9
21	Two Medicine GNP	N	LO	48.47	113.38	1605	6	347	11	0.25	0.212	0.45	0.83	>7
			MID	48.47	113.38	1656	17	316	12	0.24	0.184	0.54	0.89	5
			HI	48.47	113.38	1748	27	11	11	0.37	0.296	0.60	0.81	>6
		S	LO	48.51	113.34	1600	6	145	10	0.24	0.226	0.37	0.84*	>5
			MID	48.52	113.34	1806	36	189	12	0.21	0.158	0.54	0.86	11
			HI	48.52	113.34	1915	59	141	12	0.27	0.181	0.61	0.87	9

APPENDIX 3.

Example Stand Photos



Western Olympic National Park (Quinault River North)*



Eastern Olympic National Park (Graywolf South)

Western North Cascades National Park (Thunder Creek North)

Eastern North Cascades National Park (Park Creek South)

North Facing (Trout Creek), Idaho Panhandle National Forest

South Facing (Boundary), Idaho Panhandle National Forest

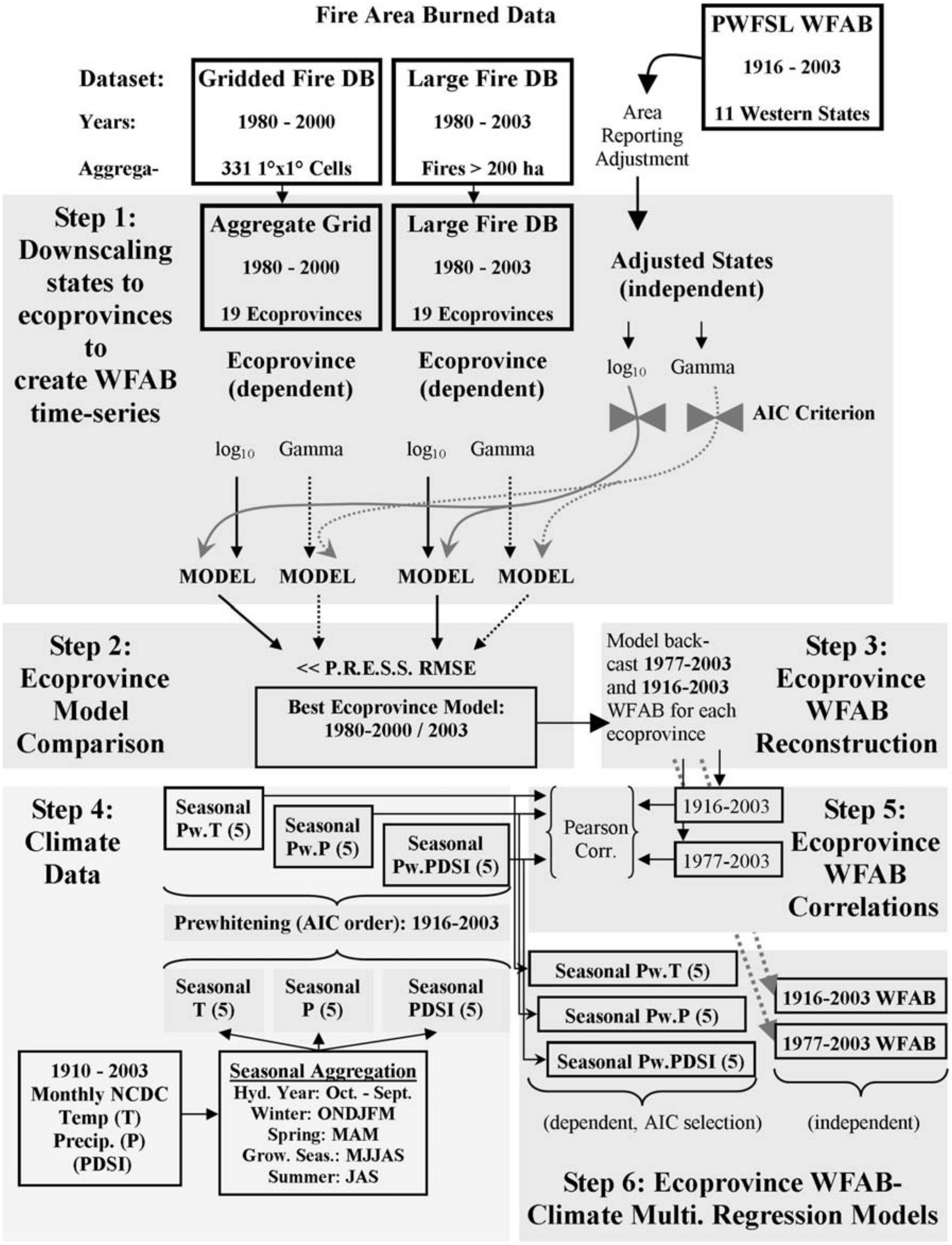
Western Glacier National Park (Salvage Mountain)

Eastern Glacier National Park (Belly River North

APPENDIX 4.

Workflow Diagrams

Data Handling and Analysis for Climate-Wild Fire Area Burned Chapter



VITA

Jeremy S. Littell

My research generally focuses on the impacts of climate change and climate variability on forest ecosystems. Specifically, I use modern and tree-ring records of ecological processes such as tree-growth, recruitment, and disturbance by fire to examine the mechanistic relationships between the climate system and ecosystem responses at a variety of spatial and temporal scales. I seek employment in a research program where my analytical skills as a climate change ecologist will contribute to collaborative research in global change biology.

Education:

Ph.D. (expected) August 2006. Forest Ecosystem Analysis, College of Forest Resources, University of Washington. Dissertation Title: **Climate Impacts to Forest Ecosystem Processes: Douglas-fir Growth in Northwestern U.S. Mountain Landscapes and Area Burned by Wildfire in Western U.S. Ecoprovinces.** David Peterson, advisor**.**

M.S. 2002. Land Resources and Environmental Science, Montana State University. Thesis title: **Determinants of fire regime variability in lower elevation forests of the northern greater Yellowstone ecosystem.** Lisa Graumlich, advisor.

B.S. 1998. Environmental Science; emphasis in Terrestrial Ecology. Huxley College of the Environment, Western Washington University. David Wallin, advisor.