Chapter 5: Change, Variability, Pattern and Scale

In this Chapter we discuss change, variability, pattern and scale relating fire to the major Earth system components (terrestrial ecosystems and the atmosphere/oceans) affecting it. Ecological classification systems, ecosystem disturbance theory and scale considerations are particularly useful for understanding the scales at which climate patterns influence ecosystem patterns and shape fire regimes (Bailey 1983; Bailey 2010; Turner 2010; Falk et al. 2011). Statistical measures of fire variability, such as Wildland Fire Area Burned (WFAB) and climate variability such as the Palmer Drought Severity Index (PDSI) are linked through use of ecological classification at appropriate scales (Maxwell and Soulé 2009; Littell et al. 2009). Ecological classification is also employed both in paleoecological studies to map the pattern and scales of ecosystem change in response to climate change and for designing the National Ecological Observing Network (NEON)[16] to monitor and map patterns of ecosystem responses to future climate change (Delcourt and Delcourt 1988; Adams and Faure 1997; Lowman, D'Avanzo, and Brewer 2009). Weather pattern classifications, which correlate synoptic scale[17] weather patterns with fire conditions, are the basis for fire weather forecasting (Schroeder et al. 1964). Severe fire conditions have long been associated with extended periods of hot, dry weather that are caused when normal day to day weather variation ceases as systems stagnate over a particular region and atmospheric Rossby Wave[18] blocking patterns set in (Beals 1916; Skinner et al. 2002; Stenseth 2002; Girardin et al. 2009; Lau and Kim 2011). Observed increases in the duration and intensity of summer heat waves and drought are likely an early example of 21st Century climate warming that are expected to amplify (Barriopedro et al. 2011; Diffenbaugh and Ashfaq 2010; Anderson 2011). Evidence is expanding that these regional scale patterns of interannual atmospheric variability are in turn manifestations of variability in larger scale patterns of coupled atmosphere-ocean (AO) circulation, with the El Nino Southern Oscillation (ENSO) as the best-known example (Alencar, Nepstad, and del Carmen Vera Diaz 2006; Hessl, McKenzie, and Schellhaas 2004; Schoennagel et al. 2005; Trouet, Taylor, et al. 2009). Variability and change of AO patterns affect fire in many areas of the world (Heyerdahl, Morgan, and Riser II 2008; Heyerdahl et al. 2008; Yocom et al. 2010). Better information about changes in the variability of ENSO and other coupled AO patterns is becoming available from improved satellite observation and GCM simulations (Giorgi and Francisco 2000; Tebaldi and Knutti 2007). Concepts of change, variability, pattern and scale help inform our understanding of how fire-atmosphere interactions impact fire regimes for specific fire prone regions of the United States (Abatzoglou and Kolden 2011; Moritz et al. 2010; Moritz and Stephens 2008; Swetnam and Anderson 2008). We consider these concepts in combination with fire regime and ecosystem classification to be

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[16] A map of ecological domains used in NEON can be found at http://www.neoninc.org/domains/overview

[17] The synoptic scale in meteorology (also known as large scale or cyclonic scale) is a horizontal length scale of the order of 1000 kilometres (about 620 miles) or more. http://en.wikipedia.org/wiki/Synoptic_scale_meteorology

[18] Atmospheric Rossby waves are large-scale meanders of the jet stream and a major influence on surface weather systems. These meanders govern cyclones and anticyclones that are responsible for day-to-day weather patterns at mid-latitudes.

critical components for applying fire history and climate change information in 21st Century fire planning and management.

Fire – Global Process, Regional Characteristics, Local Events

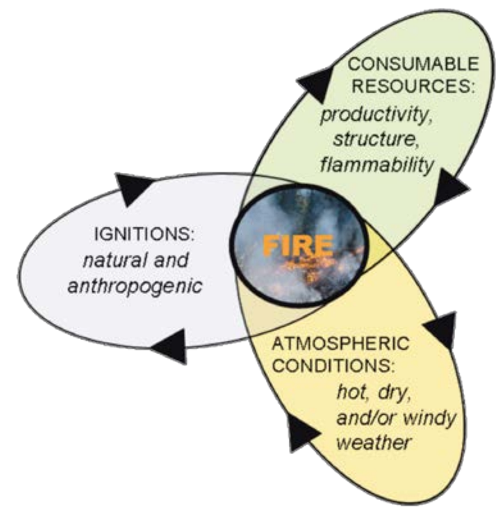

Figure 5.1: The pyrogeography framework includes vegetation resources to consume, atmospheric conditions, and ignition agents. Each of these components is spatially and temporally variable, as illustrated by arrows, and it is their coincidence that results in fire activity. Variation in their coincidence generates different fire regime types (e.g., frequent low-intensity surface fire versus infrequent high-intensity crown fire). Source: (Max A. Moritz, Krawchuk, and Parisien 2010)

Fire is a global ecosystem process consisting of local combustion events with organizing regional characteristics. Fire is an example of disturbance, or relatively discrete event disrupting an ecosystem, happening over relatively short intervals of time (hours to months) and altering ecosystem state and trajectory. Fires arise from a combination of abiotic (ignition source) and biotic (adequate fuel) conditions subject to climate forcing. Changes in both ignitions and fuel conditions are expected to result from 21st Century climate change (Hessl 2011). Disturbance **regimes**, in contrast to disturbance **events**, refer to the spatial and temporal dynamics of disturbances over a longer period of time. Disturbance regimes include characteristics such as spatial distribution, frequency, return interval, size, intensity, and severity (Turner 2010). Fire interactively links atmosphere, biosphere, and human Earth system components through time and at local, regional and global spatial scales (Lavorel et al. 2007). Those interactions may be categorized as top-down ($>10^4$ ha) and bottom-up (10^{-4} - 10^4 ha)[19] regulation respectively represented by 1) synchrony of fire- and non-fire years at regional and larger scales for climatically similar areas, and 2) spatial heterogeneity in fire occurrence, extent, or severity (Falk et al. 2011). This bimodal view is also reflected in weather/climate and fire event/fire regime couplings, and indicates the scale above which climate change information is likely to be most applicable for fire use.

Fuel availability and atmospheric components of the combustion process combine to make fire possible for some period of time at some location on Earth throughout the year. Throughout the fire history of Earth, characteristics (e.g. intensity, area burned, fuel consumed, carbon emitted) of fire events have been determined by local conditions existing at the time of the events.

[19] 10^4 hectares = 10^8 meters^2 approximates the boundary of Bailey Divisions and Provinces and centers on the mesoscale region used in paleoecology studies (Delcourt and Delcourt 1988)

However, those existing local fuel and atmospheric conditions are themselves variable in response to both local and larger scale forcing factors. The cumulative impacts of fire events, as described by fire regimes and fire statistics, vary over time in response to climate variability, climate change and other larger scale forcing factors. Paleoecological studies show that past climate variability has impacted fire regimes over large areas of the United States that are now expected to experience significant 21st Century drought (Swetnam and Anderson 2008; Stahle et al. 2011). Combining knowledge that 21st Century global climate change is altering fire regimes with knowledge that fire control mechanisms influenced by climate variability (such as ignition, fire spread, fuel moisture and fuel production) are likely to change, points to information pathways fire planners can follow (Flannigan et al. 2009; Gedalof 2011).

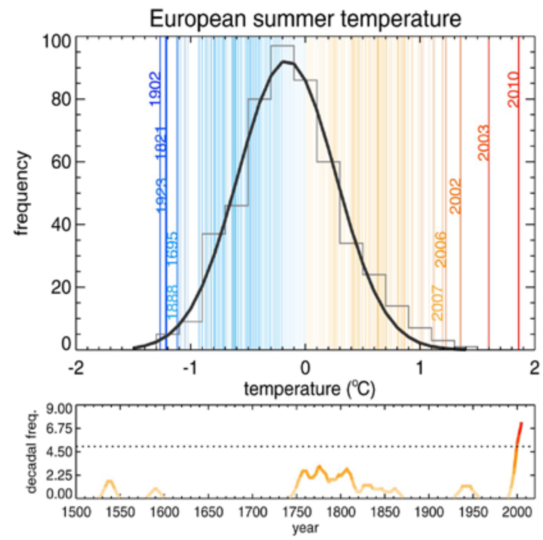

Figure 5.2: European summer temperatures for 1500-2010. The five warmest and coldest summers are highlighted. Grey bars represent the distribution for the 1500-2002 period with a Gaussian fit in black. The bottom panel shows the running decadal frequency of extreme summers, defined as those with temperature above the 95th percentile of the 1500-2002 distribution. A 10-yr smoothing is applied. Dotted line shows the 95th percentile of the distribution of maximum decadal values that would be expected by random chance. Source: (Barriopedro et al. 2011)

Numerical descriptions of interactions between weather and vegetation condition, such as the National Fire Danger Rating System (NFDRS), track developing fire potential (Bradshaw et al. 1984). When shown in map form[20], characteristic regional scale fire patterns display variability and change that help to inform fire planning. Planners use known seasonality of regional fire occurrence and severity risk (Roads et al. 2005), which on average vary for given regions of the Earth in cadence with annual global climate cycles modulated by interannual variability (Schultz 2002). Modulation of the average annual fire signal for a given region results when atmosphere-ocean systems (El Nino Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), Atlantic Multi-Decadal (AMO) and North Atlantic Oscillation (NAO) are examples) synchronize to produce extended periods of heat and drought that yield greater concentrations of vigorous fire events than usually experienced under average fire regime conditions for a given region (Carmona-Moreno et al. 2005).

Climate variability that increases normally experienced regional fire season lengths, through earlier starts and/or later closures, expands the seasonal fire risk window and has resulted in

[20] For example see http://www.wfas.net/images/firedanger/fd_class.png (last accessed June 1, 2011)

increases in overall fire activity and large fire events in recent years (Westerling et al. 2006; Spracklen et al. 2009). Since anthropogenic activities are modifying both the average state and variability of climate, we observe and project 21st Century climate change both as trends of atmospheric variables such average temperature and as temperature variability expressed by a change of the probability distribution of temperature (Sierra et al. 2010). Utilization of increasingly available climate change information for fire management and planning purposes will benefit from recognition of scale dependent patterns of atmospheric and ecosystem change and variability shown to impact fire regime characteristics.

Individual fire events result from the interaction of atmospheric and ecosystem components that supply the oxygen, ignition source (now often human supplied) and fuel needed to initiate and support combustion at a given place and time (Moritz, Krawchuk, and Parisien 2010; Pausas and Keeley 2009). These interactive linkages take place at different temporal and spatial scales, and are subject to variability in the component parts. Local conditions during the time and over the location of a fire determine ongoing event characteristics. Variability in those local conditions affects the vigor and impact of a given fire event, and is subject to larger scale forcing factors. When viewed globally, the accumulation of fire events over periods of years or longer is strongly correlated with ecosystem classifications and synchronized with seasonal climate and weather cycles (Bond, Woodward, and Midgley 2005). Observed variability may in turn prove to be a signal of change or simply variation that in time proves to be not statistically significant. Climate and fire regime "change" can thus only be attested to in hindsight, when sufficiently long record lengths (normally 30 years for climate) become available to account observed variability as statistical change. While local atmospheric and vegetative (weather and fuel) conditions drive fire behavior and other fire characteristics during fire events, those events, in turn, cause measurable and lasting variance in the atmosphere and vegetation. Over time, the cumulative effects of multiple fire events can result in changes in the atmosphere, ecosystems and fire regimes (Delcourt, Delcourt, and Webb III 1982; Page et al. 2002; Beerling and Osborne 2006; Arora and Boer 2005; Agee 1998; Johnstone et al. 2010; Bowman and Haberle 2010; Kasischke et al. 2010).

Pattern and Scale in Fire History

Paleo-fire history studies provide an increasingly comprehensive record of fire variability and change linked to climate and ecosystem variability and change (Belcher et al. 2010; Marlon et al. 2008; Enache and Cumming 2009). The combustion process itself has not changed since land plants began to diversify and evidence of fire appeared during the Silurian period (443 to 417 Mya) of Earth history (Pausas and Keeley 2009). Fire events have since been oxidizing biomass wherever vegetation grows. Fossil charcoal records, which had dated earliest fire to the late Devonian (417 to 354 Mya), now show that wildfires have been occurring on Earth for ~ 420 million years, since there was sufficient vegetation to serve as fuel and sufficient atmospheric oxygen to support the combustion process (Scott 2000; Scott 2008). Atmospheric O_2 concentration has varied during the 540 million years of the Phanerozoic[21] eon, resulting in significant variation in fire activity (Berner and Canfield 1989). Since terrestrial vegetation arose on Earth, the atmosphere has supplied the oxygen (current atmospheric O_2 concentration of

[21] The Phanerozoic is the current eon of geologic time, during which abundant animal life has existed. http://en.wikipedia.org/wiki/Phanerozoic

20% exceeds the minimum 13% required for combustion), and the lightning (currently estimated as ~ 44 flashes per second occurring globally) ignition source needed for combustion to be supported (Scott and Glasspool 2006; Christian et al. 2003). Paleoecology and paleoclimatogy studies combine to extend our understanding of antecedent conditions backward through the ~ 420 million years of Earth history where fire has functioned as a major shaper of ecosystem evolution (Bowman et al. 2009).

Fire has been a common but variable part of the evolution of existing terrestrial ecosystems, both shaping and shaped by changing ecosystems (Whitlock, Moreno, and Bartlein 2007; Bond and Keeley 2005). Fire history traditionally focused on one or more, local scale fire events, but has more recently expanded our knowledge of larger scale climate controls on vegetation composition and fire regimes (Whitlock and Bartlein 2003). The paleo record of fire history prior to 5,000 years ago (before human dominance), includes examples of occurrence of scale relevant fire regime change consistent with our current understanding. For example, recorded increases in charcoal deposits from increased burning of grasses are associated with grassland replacement of woodlands facilitated by increased fire size and frequency during a shift of climate conditions towards more monsoonal structures (Keeley and Rundel 2005). The paleo record associates the regional scale appearance 8 Mya of savannahs, as a major terrestrial biome, with climate-coupled fire accelerated forest loss and grassland expansion through multiple positive feedback loops that promoted drought and more fire (Beerling and Osborne 2006). During the Holocene, humans have increasingly changed the occurrence envelope of combustion events by supplying alternative ignition sources, among many other practices (Lavorel et al. 2007).

Individual fire events add up to a fire history on Earth that has been closely aligned with regional to global scale climate variability and change through geologic time, as recorded in tree ring and other paleo records (Scott 2000; Swetnam and Betancourt 1998; Bowman et al. 2009). Paleo studies have proven to be an invaluable source for increasing our understanding of the historic relations between climate and fire (Marlon 2009). Early breakthrough paleo studies, for example of fusains and fire scars, while limited in ability to provide spatial and temporal scale information by sample size and analytical resolution, form the scientific foundation for what is now a growing catalogue of paleo records relating past fire and climate (Crickmay 1935; Dieterich and Swetnam 1984). Paleo information about both climate and fire is providing increasingly wider spatial coverage and finer temporal resolution that correlates fire with atmospheric conditions present when combustion took place (Stahle et al. 2011; Swetnam and Anderson 2008; Marynowski and Simoneit 2009).

While each fire event results from the local scale interaction of atmosphere and ecosystem components at the time of the event, antecedent and post-ignition conditions, deriving from a variety of scale dependent interactions of atmosphere and ecosystems components, govern the eventual impact of each fire (Hostetler, Bartlein, and Holman 2006). Scale dependent atmosphere-ecosystem interactions also govern post-ignition fire development and ecosystem impacts (Flannigan et al. 2005; Randerson et al. 2006; Abatzoglou and Kolden 2011). Those interacting atmosphere and ecosystem components in turn display ongoing temporal and spatial variability and change. McKenzie et al (McKenzie, Miller, and Falk 2011) note: "…*spatial and temporal scales of fire are intuitively observable and comprehensible by humans, although* *reconciling them quantitatively with the spatiotemporal domain of "normal" ecosystem processes introduces profound challenges, chiefly because of the different rates and scales at which processes occur. Planning at scales that are too fine will fail to account for disturbances that arise outside small management units; planning at scales that are too coarse…will not account for local patterns of spatial and temporal variability.... fires occur as "events" over time spans of days to months, the postfire ecosystem response can unfold over decades to centuries.*" 21st Century climate change is a forced global scale disturbance that, by definition, arises outside of management units and interacts with ecosystems to yield impacts realized at all scales of/on those management units. This is the tension inherently faced by managers/observers seeking to employ past, present and future climate variability and change information to inform place based fire planning under 21st Century climate change.

Observer Perspective

Discussions of scale, variability and change can relate to the scale of observer, the process observed and the scientific framework employed by the observer. As we look backward or forward in time, and upward in spatial scale, from the fire event, discussion becomes more dependent on atmospheric and ecosystem observations, processes and frameworks. Fire scientists are expanding knowledge of fire history from past local scale fire events to patterns with regional to larger scale linkages to past climate (Swetnam and Baisan 2003; Swetnam and Anderson 2008; Whitlock, Moreno, and Bartlein 2007; Whitlock et al. 2010). Climate scientists are, in turn, providing knowledge of the underlying atmospheric pattern drivers that forced past warming periods, such as the Medieval Climate Anomaly (MCA) (Trouet, Esper, et al. 2009; Xoplaki et al. 2011; Graham et al. 2007; Bird et al. 2011). Increased occurrence, duration and amplitude of these atmospheric forcing patterns will likely be a manifestation of 21st Century climate change (Schär et al. 2004; Xie et al. 2010; Liang Xu et al. 2011; Woodhouse et al. 2010). Correlating fire history and other ecosystem histories with past climate change, such as observed high fire occurrence associated with severe summer

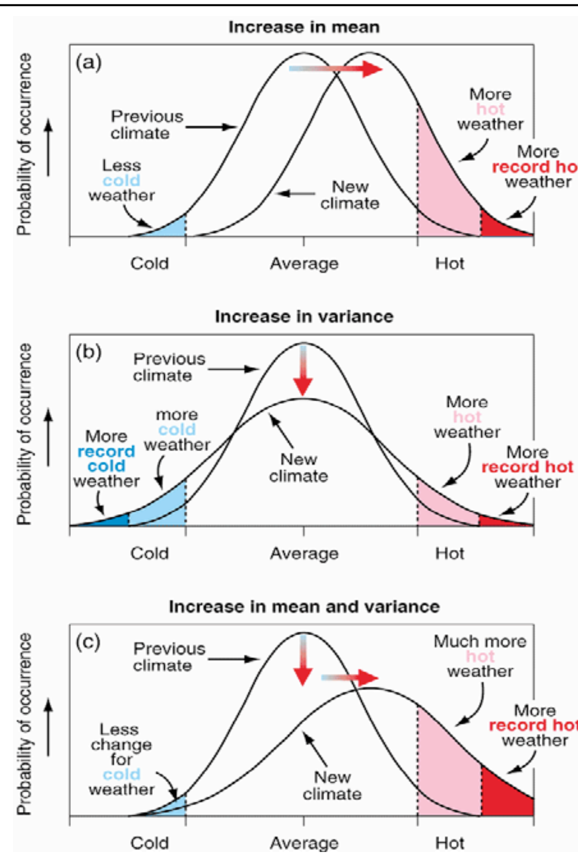

Figure 5.3: Schematic showing the effect on extreme temperatures when (a) the mean temperature increases, (b) the variance increases, and (c) when both the mean and variance increase for a normal distribution of temperature. Source: (IPCC WG I 2001)

droughts in the northern Rockies during the MCA, informs our understanding of fire-climate interaction at regional and larger scales (Umbanhowar Jr. 2004; Miao et al. 2007; Whitlock, Shafer, and Marlon 2003; Brunelle et al. 2005). Recent fire outbreaks and regional scale vegetation desiccation, with resulting ecosystem impacts, have similarly been associated with atmospheric patterns that force increased occurrence, duration and amplitude of record-breaking summer heat waves (Pereira et al. 2005; Della-Marta, Haylock, et al. 2007; Yurganov et al. 2011; Xu et al. 2011; Lewis et al. 2011; Barriopedro et al. 2011; Lau and Kim 2011). These observations of both lengthier periods of hot weather and increased numbers of record hot weather events demonstrate statistical climate change in the making, with both increasing mean and variance of recorded temperature (Schär et al. 2004; Della-Marta, Haylock, et al. 2007; Kuglitsch et al. 2010).

Fire and Weather Patterns

Fire history informs our understanding of antecedent forcing of current conditions. Large fires and fire complexes have long been known to be associated with regional scale drought and synoptic scale weather patterns (Beals 1916; Crimmins 2006; Schroeder and Buck 1970; Skinner et al. 2002; Pereira et al. 2005). Even though large fires result from only a very small percentage of total fire ignitions, they are the cause of high fire suppression costs, result in large area burned, significantly impact the atmosphere, serve as ecosystem shapers, and display strong climatic forcing (Calkin et al. 2005; Balshi et al. 2009; Abatzoglou and Kolden 2011; Wiedinmyer and Neff 2007; Fromm et al. 2010; Bond, Woodward, and Midgley 2005; Yang, He, and Gustafson 2004; Moritz 1997; Heyerdahl, Brubaker, and Agee 2002). Large fires in extreme fire years drive area burned statistics (a surrogate measure of fire impacts) and correlate with atmospheric circulation patterns and climatic processes (Abatzoglou and Kolden 2011; Gedalof, Peterson, and Mantua 2005). Statistically significant regional scale increases in large fire activity in the western United States starting in the mid-1980s are associated with climate change forcing from warmer spring and summer temperatures and earlier spring snowmelt (Westerling et al. 2006). We have now accumulated sufficient data to view two regional scale climate variations (increased frequency, intensity and duration of summer heat waves and earlier spring snowmelt) as manifestations of ongoing

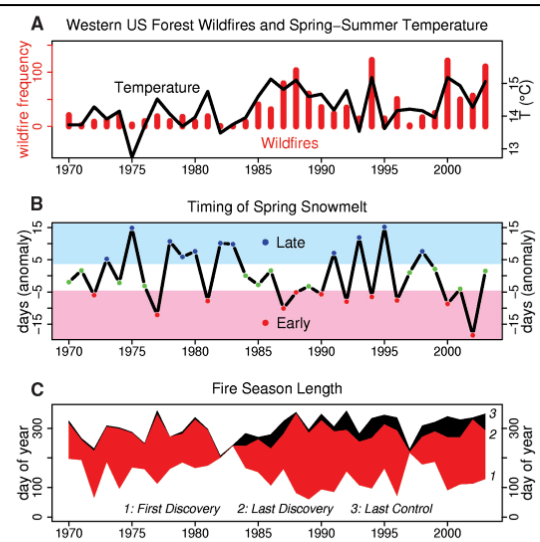

Figure 5.4: A) Annual frequency of large (9400 ha) western U.S. forest wildfires (bars) and mean March through August temperature for the western United States (line). (B) First principle component of center timing of streamflow in snowmelt dominated streams (line). Low (pink shading), middle (no shading), and high (light blue shading) tercile values indicate early, mid-, and late timing of spring snowmelt, respectively. (C) Annual time between first and last large-fire ignition, and last large-fire control. Source: (Westerling et al. 2006)

climate change that fire history associates with increased fire activity.

Pattern and Scale Concepts

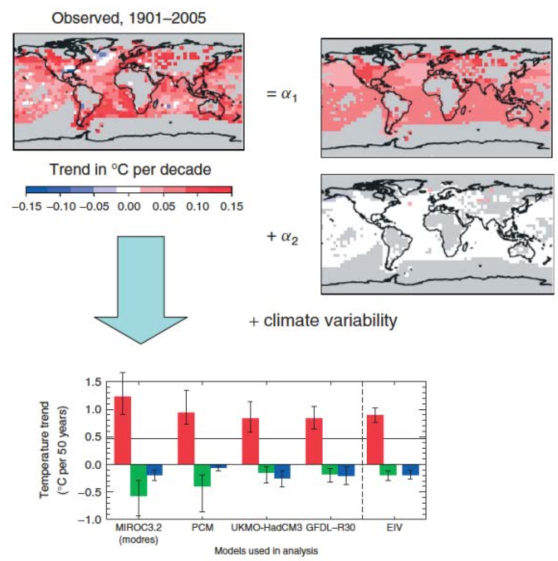

Figure 5.5: Schematic for detection and attribution. The observed change (shown here: pattern of temperature change over the 20th century, left) is composed of a linear combination of fingerprints for all forcings combined (top, right) and for natural forcings only (center right, this combination allows rescaling of natural vs anthropogenic fingerprints in simulations of the 20th century) plus residual, unexplained variability. Source: (Hegerl and Zwiers 2011) (Reprinted with permission from Ref 2. Copyright 2007 Cambridge University Press)

The concepts of pattern and scale are central to our understanding of: ecosystem processes, ecosystem classification, invasive species and biodiversity, weather and climate, demographic influences, fire history and fire regimes (Levin 1992; Gosz and Sharpe 1989; Holdridge 1947; Adams and Faure 1997; Bailey 1985; Powell, Chase, and Knight 2011; Lorenz 2006; O'Neill et al. 2010; Delcourt, Delcourt, and Webb III 1982; Grissino Mayer and Swetnam 2000; Morgan et al. 2001). Scale considerations are thus necessary for understanding how present climate influences ecosystems and fire, for interpreting fire history recorded during past climate conditions, and for applying fire history knowledge to describe expected changes in fire regimes resulting from 21st Century climate change (Whitlock and Bartlein 2003; Whitlock, Moreno, and Bartlein 2007; Whitlock et al. 2008; Whitlock et al. 2010). A scaling issue inherent in providing and applying climate change information useful to fire managers is that while climate change is an integrative global scale response to GHG and other forcings, biological systems respond to local conditions (Parmesan et al. 2011). Those local conditions describe the sum of measured component parts that are themselves subject to variation and change in space and time. Local and regional conditions existing at the time of an individual disturbance event (a fire for example) influence responses to the event, which may be quite different to responses that would be experienced under a new disturbance regime, or at different local and regional scales (Clark 1996; Powell, Chase, and Knight 2011). Disturbances, with fire being a ubiquitous example, play important roles in landscape ecology, an ecology subfield that focuses on the reciprocal interactions between spatial pattern and ecological processes (Hessburg and Agee 2003; Turner 2005). Processes operating at various temporal and spatial scales generate landscape patterns (Urban, O'Neill, and Shugart Jr 1987). Fire has been an important process coupling biotic and abiotic ecosystem components, for example insect outbreaks and snow pack retention in evolving landscape patterns for over millions of years of Earth history, while the combustion process itself has not undergone change (Pugh and Small 2011; Clow 2010; McKenzie, Miller, and Falk 2011).

Atmosphere and Ecosystem Change and Variability

Concepts that relate event variability to regime change are similar for the atmosphere and ecosystems. Fires and weather are the respective events, or realizations, whose ensemble[22] statistics define fire regimes and climate, and whether or not they are changing over time. You can not reverse calculate from the climate or fire regime statistics to get the actual distributions of fire and weather events that produced them, although some information can be gained by applying power law approaches (McKenzie, Miller, and Falk 2011). Climate change projections based on ensemble forecasts[23] provide envelopes containing multiple projected outcomes (events), which derive from slightly varying initial condition inputs (Tebaldi and Knutti 2007). We can use future climate and fire regime projections as envelopes that inform us about the shape, based on historical distributions, of future weather and fire event statistics. In doing so, we need to assure that pattern scaling information used to describe future variability and change of fire, atmosphere and ecosystem interactions applies reasonably linearly across the scales that are used (Mitchell 2003). Climate scientists attribute observed and projected climate change signals to parts due to external forcing and internal variability, with such factors as GHG emissions, solar cycles and orbital variation assigned to external forcing and ENSO, PDO, and NAO assigned to internal variability (Hegerl and Zwiers 2011). We can likewise view the Bailey classification system scale transition from Division to Province as a transition in dominance from external climate forcing to internal variability (due to terrain and other factors), or a division between Macro (10^{11} m^2) and Meso (10^9 m^2) ecosystems (Bailey 1983; Bailey 1985; Rowe and Sheard 1981). This line of reasoning points to an expectation that GCM climate change predictions resulting from GHG and other external forcing factors will reasonably allow for projection of change and variation of Bailey Division scale patterns through the 21st Century. Province and smaller scale change and variation will require climate information associated with ENSO and other factors that contribute to internal climate variability.

Since fire is a nexus of coupled atmospheric and ecosystem processes, the scale concepts governing fire and these contributing processes guide our application of information needed to describe fire regime changes resulting from climate change. Scale recognition is also critical when applying this information for fire planning and management, since information may only be available at scales that are not normally preferred for a particular fire activity (Saxon et al. 2005). While scale considerations are necessary, they can also be complex and confusing when they traverse multiple disciplines and uses. In view of this inherent communication problem, we sought a practical common ground, for discussion and information display, in the widely used

[22] An ensemble (also statistical ensemble or thermodynamic ensemble) is an idealization consisting of a large number of mental copies (sometimes infinitely many) of a system, considered all at once, each of which represents a possible state that the real system might be in. http://en.wikipedia.org/wiki/Statistical_ensemble

[23] Ensemble forecasting is a numerical prediction method that is used to attempt to generate a representative sample of the possible future states of a dynamical system. http://en.wikipedia.org/wiki/Ensemble_forecasting

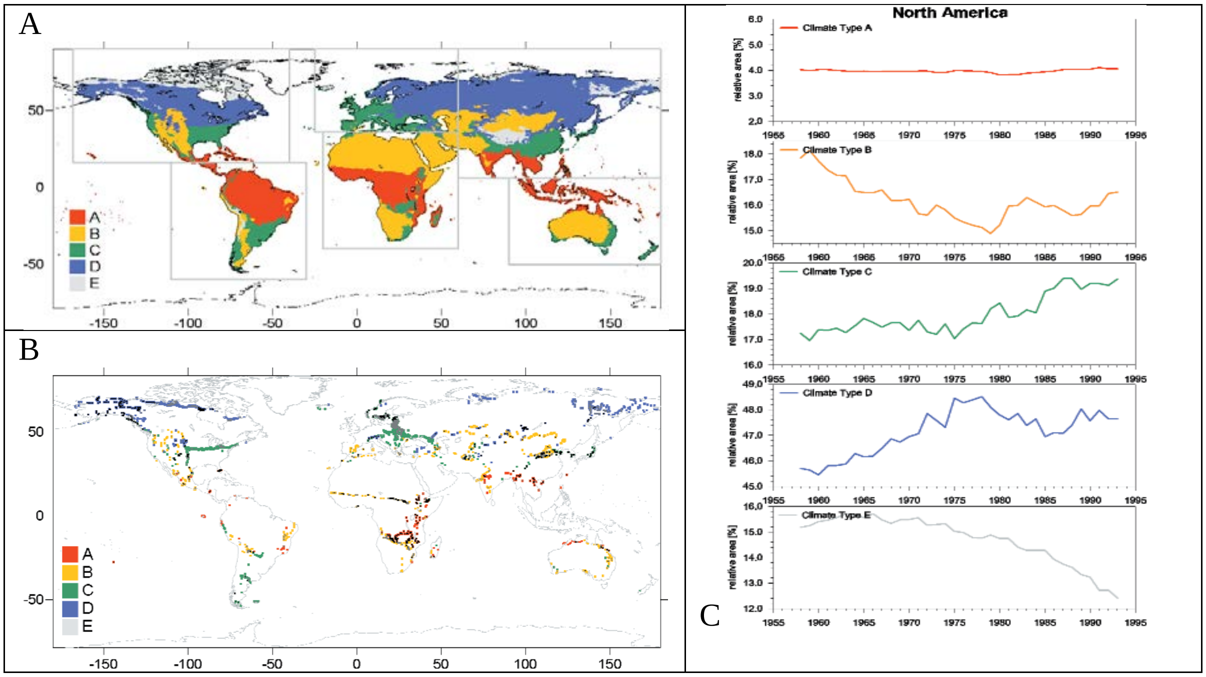

Figure 5.6: Characterizing Global Climate Change by means of Köppen Climate. a: Spatial distribution of the five main Köppen climate types determined for the period 1951 – 2000. Rectangles indicate the continental sub-regions for which selected results are presented. b: Köppen climate types for the period 1986 - 2000 for gridcells with different Köppen climates within the periods 1951 – 2000 and 1986 – 2000, respectively. c: Time series of the relative area (percentage of the resp. continental land area excluding Greenland and Antarctica) occupied by the main Köppen types. Source: (Beck et al. 2005)

Bailey system[24] for classifying ecosystems. Consensus agreement reached at our February 2010 Workshop (see Appendix A) was that fire history and climate information at the Bailey Division level would serve as a useful and sufficient scale for information focus, while information at the Domain level was useful only for broad discussion purposes, and information, when available, at the Province level would be most preferred.

To illustrate the information scale consequences involved in Domain-Division-Province discussions (see Figures 5.5a, b, c), consider that Bailey's system is derived from the Köppen climate classification system with the Bailey Division equivalent to the Köppen climatic type (Bailey 1983; Ackerman 1941; Kottek et al. 2006; von Köppen 1931; von Köppen and Geiger 1930). Beck et al. (2005) applied 50 years (1951-2000) of digitized climate data in sliding 15-year intervals using the five main Köppen climate types (which are equivalent to Bailey Domains - see Figure 5.5d). He demonstrated the temporal variability in the mapped types (see Figure 5.5e) and graphing (see Figure 5.5f) changes in relative climate type area for each continent (see Figure 5.5g for North America). Beck found "…*Most striking for North America appear distinct reductions of polar E and as well dry B climates. Simultaneously the area occupied by the temperate C and boreal D climate types increases.*"

[24] http://www.fs.fed.us/land/ecosysmgmt/index.html

How do the Bailey Domain, Division and Province level scales compare with scales employed in paleoecology, atmospheric and fire fields? A recent study of wildfire area burned (WFAB) in the western United States from 1916 to 2003 employed Palmer Drought Severity Index (PDSI) and WFAB statistics at the Bailey Province level (Littell et al. 2009; Karl 1986). They concluded that WFAB is substantially controlled by climate, with current season temperature and dryness having the greatest effect in most Provinces but previous year moisture and PDSI drought being better WFAS predictors in others. For managers, knowledge of climate-fuel interactions at the Bailey Province level will help refine larger scale (Division and Domain level) information deriving from climate change patterns. For example, the management impacts of fire related ecosystem change that result from the interaction of elevated CO_2 levels, warmer temperatures, nitrate deposition and fire on invasive species competition are informed by integrating global scale external forcing (e.g. CO_2 growth) with internal climate variability (e.g. ENSO) through Province/Section scale (fire event) processes (Dukes et al. 2011). Even the largest individual fire events rarely burn beyond or cross more than one or two Bailey Provinces.

Ongoing research is helping us to better determine patterns of where and when the relative weight of human influence is greater than that of past climate change, or where human influence is a major factor in observed changes in historical patterns of global biomass burning (Ruddiman, Kutzbach, and Vavrus 2011; McWethy et al. 2010; Marlon et al. 2008). While fully acknowledging the importance of human influences, we concentrate this synthesis on fire as it relates to atmospheric and ecosystem process interactions described at different time and space scales. Descriptions of the pattern and scale of ecosystem (and fire regime) responses to past

<u>IPCC (IPCC WG I 2001) Definitions</u>

Climate change: Climate change refers to a statistically significant variation in either the mean state of the climate or in its variability, persisting for an extended period (typically decades or longer). Climate change may be due to natural internal processes or external forcings, or to persistent anthropogenic changes in the composition of the atmosphere or in land use.

Climate variability: Climate variability refers to variations in the mean state and other statistics (such as standard deviations, the occurrence of extremes, etc.) of the climate on all temporal and spatial scales beyond that of individual weather events. Variability may be due to natural internal processes within the climate system (internal variability), or to variations in natural or anthropogenic external forcing (external variability).

Patterns and Indices of Climate Variability – *"Climate variability is not uniform in space; it can be described as a combination of some "preferred" spatial patterns. The most prominent of these are known as modes of climate variability, which affect weather and climate on many spatial and temporal scales. The best known and truly periodic climate variability mode is the seasonal cycle. Others are quasi-periodic or of wide spectrum temporal variability. Climate modes themselves and their influence on regional climates are often identified through spatial teleconnections, i.e., relationships between climate variations in places far removed from each other."* (A. Kaplan in Blunden, J., D. S. Arndt, and M. O. Baringer, Eds., 2011: State of the Climate in 2010. *Bull. Amer. Meteor. Soc.*, **92** (6), S20–S26) climate change better inform our understanding of how fire regimes are likely to change in response to 21st Century climate change (Guetter and Kutzbach 1990; Flannigan et al. 2005; Spracklen et al. 2009). Such descriptions help us understand the patterns and scales of interaction between atmosphere and ecosystem processes (Mitchell 2003). Bailey classifications and fire regimes are well correlated (Malamud, Millington, and Perry 2005; Bailey 2010).

The terms "variability" and "change" also depend on the scale of the process described, and the processes themselves. Climate variability (see box for IPCC Definition) refers to variations in the mean state and other statistics of the climate on all temporal and spatial scales beyond that of individual weather events. Climate change refers to a statistically significant variation either in the mean state of the climate or in its variability, persisting for an extended period (typically decades or longer). Weather (temperature, wind direction and speed, humidity, sky cover, etc.) "changes" minute to minute, hour to hour, day to day and location to location. But unless the statistical envelope that describes the long term mean and variability of those weather components changes over time, what we call changeable weather in our every day language is just inherent variability in weather patterns and component variables. The Intergovernmental Panel on Climate Change (IPCC)[25] and The American Meteorological Society (AMS)[26] provide online glossaries for reference. The IPCC defines climate change as referring to *"…a change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer."* It defines climate variability as referring to"… *variations in the mean state and other statistics --- of the climate on all spatial and temporal scales beyond that of individual weather events."* No comparable glossaries are as readily available from the ecological community to offer definitions of the terms "change" and "variability". For fire, we often observe that fire behavior, spread, intensity, fuel consumption and all other fire variables "change" over the period of a fire event or incident, when "variation" is a more accurate description of what is going on.

Time Scales of atmospheric Effects on Fire

Atmospheric and fire processes are coupled across time and space scales used to describe patterns of climate, weather, ecosystems and fire (Macias Fauria, Michaletz, and Johnson 2011). Climate can impact fire by changing the three components of the pyrogeography framework (see Figure 5.1) affecting fire through changes in weather, ignition and fuel (Hessl 2011). She examines a broad array of factors, including influences on fuel, to derive general relationships of fire-climate-vegetation interaction at different time scales. At short time scales (several hours to days) local weather conditions, temperature, relative humidity, precipitation and wind speed influence how fires burn by affecting fuel conditions and heat transfer for combustion of those fuels (Albini 1976; Anderson 1982; Rothermel 1983). On time scales of weeks to months, meteorological variables may influence the duration of the fire season, frequency of lightning ignitions, and the abundance of fine fuels (Goldammer and Price 1998; Wotton and Flannigan 1993). On scales of years to decades, climate may influence fire regimes by altering net primary

[25] Intergovernmental Panel on Climate Change (IPCC) AR4 Annex 1 Glossary (last accessed June1, 2011 http://www.ipcc.ch/pdf/glossary/ar4-wg1.pdf

[26] American Meteorological Society (AMS) Glossary of Meteorology (last accessed June 1, 2011) http://amsglossary.allenpress.com/glossary/browse

productivity, decomposition, vegetation structure, vegetation composition, density, fuel loading, and fuel connectivity across a landscape (Meyn et al. 2007).

Given that climate and weather clearly interact with wildfire over a range of spatial and temporal scales, Gedalof (Chapter 4 in McKenzie, Miller, and Falk 2011) conceptually models climate interaction with processes of vegetation development and topography, to characterize regimes and patterns of wildfire throughout North America.

Gedalof described timescales of atmospheric effects on fire,

- Short (synoptic to seasonal)
  - Fine fuel moisture,
  - Ignition frequency, and
  - Rates of wildfire spread,
- Intermediate (annual to interannual)
  - Relative abundance and continuity of fine fuels, as well as
  - The abundance and moisture content of coarser fuels,
- Long (decadal to centennial)
  - Assemblage of species that can survive at a particular location,

These are a useful construct for conveying information about climate/weather impacts on fire, and one we now employ to transition to considerations of atmosphere/climate/weather scale, variability and change of import to fire. Adapting the Gedalof timescales to atmospheric processes yields

- Short (synoptic to seasonal)
  - Traditional fire weather (Schroeder and Buck 1970)
  - Seasonal fire planning aids (Roads et al. 2005);
- Intermediate (annual to interannual)
  - El Nino Southern Oscillation (ENSO) (Schoennagel et al. 2005)
  - Pacific Decadal Oscillation (PDO) (Le Goff et al. 2007)
  - Atlantic Multidecadal Oscillation (AMO) (Sibold and Veblen 2006)
  - North Atlantic Oscillation (NAO) (Goodrick and Hanley 2009); and
- Long (decadal to centennial)
  - Climate induced ecosystem changes that cause revisions of Bailey ecosystem Domain, Division and Province maps (Saxon et al. 2005).

The various Intermediate scale atmosphere-ocean coupled circulation patterns (referred to as "oscillations" by atmospheric scientists – see box and Appendix E) drive fire activity trends on a multi-year basis, underlie fire-weather teleconnections, and are increasingly recognized as critical links for understanding year to year regional weather "anomalies", including those associated with prolonged summer heat waves and drought (Cooke et al. 2007; Simard, Haines, and Main 1985; Mote and Kutney 2011; Della-Marta, Luterbacher, et al. 2007; Della-Marta, Haylock, et al. 2007). 21st Century changes in these Intermediate scale circulation patterns are seen as key elements leading to increased summer heat waves and droughts and help us to better understand historic patterns of fire-ecosystem interactions (Meehl and Tebaldi 2004; Diffenbaugh and Ashfaq 2010; Kaye 2011). Short time scale atmospheric prediction derives from Numerical Weather Prediction (NWP) technology (see Chapter 2 discussion) with improving accuracy in multi-day fire weather forecasts that inform fire event management, and extended length forecasts inform seasonal fire planning (Pereira et al. 2005; Roads et al. 2005). Long time scale atmospheric prediction derives from General Circulation Model (GCM) technology (see Chapter 2 discussion) with improving resolution (space and time) and increasingly realistic modeling of contributing Earth system component interactions that determine climate change.

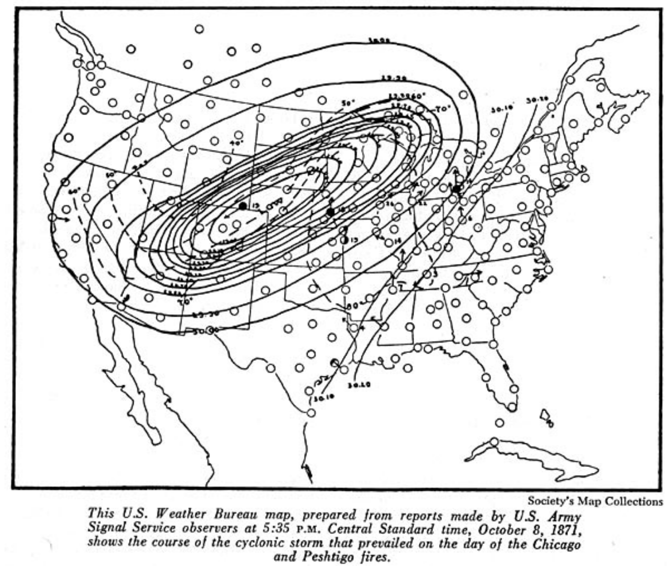

Figure 5.7: U.S. Weather Bureau Map for 5:35 pm CST October 8, 1871. Source: This image courtesy of the [Wisconsin Electronic Reader]

Much of our discussion of ecosystem scale, both in the present and in the past, has had a spatial focus, whereas discussion of atmospheric scaling places more focus on temporal scale issues. This is because if weather and/or climate never changed with time or place we would have little concern with them, although biodiversity and other ecosystem components would be different (Cadena et al. 2011). Initial human observation of weather/climate was from a small fixed place orientation in space over hours to years of time. It was not until commercial 18th Century ocean spanning navigation took hold that we began to place our locally observed time varying weather and climate in a global context of moving atmospheric systems that could be monitored and tracked in space and time (see Chapter 2). The advent of meteorological instrumentation and the telegraph provided the opportunity to display in map format moving pressure driven weather systems. The deadliest fire in American history (Peshtigo, Wisconsin) and the most infamous urban fire (Chicago) started on the same October 8, 1871 evening, both driven by the same synoptic weather system (Flesch 2009; Schroeder et al. 1964). Schroeder (1964) analyzed surface and upper-air weather patterns and computed daily fire load indexes for a 10-year period (1951-1960) using a pre-cursor of the NFDRS to categorize critical fire weather patterns for the contiguous 48 States aggregated into 14 regional groups. Schroeder concluded, *"…periods of critical fire weather are associated with a relatively few synoptic weather patterns and types."* A high amplitude example of one of those types created the drought, high temperatures and high winds that produced the Peshtigo and Chicago fires (Lorimer and Gough 1988; Schulte and Mladenoff 2005).

In the ensuing five decades after Schroeder's pioneering work, synoptic weather typing produced comprehensive information about synoptic scale weather patterns related to fire activity in various regions of the world (Schroeder et al. 1964; Crimmins 2006; Amiro et al. 2004; Skinner et al. 2002; Pereira et al. 2005; Takle et al. 1994; McCutchan 1978; Benson, Roads, and Weise 2008). By having linked synoptic scale weather patterns to various aspects of the fire business, improvements in general weather forecasting, resulting from advancements in Numerical Weather Prediction (NWP) (see Chapter 2), satellite observation, radar, lightning detection and other incremental improvements, have lead directly to improved fire weather information. For fire planners, improved accuracy of 24 to 96 hour range forecasts and progression into seasonal outlooks[27] were of critical importance. Those seasonal outlooks are transitional between the Short (synoptic to seasonal) and Intermediate (annual to interannual) timescales.

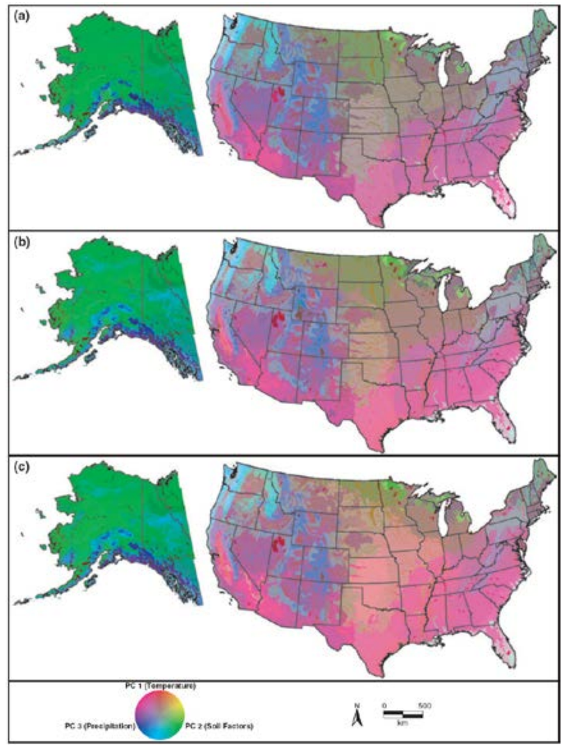

Figure 5.8: Five hundred domains in the continental USA and north-western Canada are depicted in colours reflecting the relative dominance of temperature factors (red), edaphic factors (green) and precipitation (blue). Colour assignments are consistent regardless of when or where each domain occurs. (a) Current conditions. (b) Scenario B2, moderate greenhouse gas increases. (c) Scenario A2, rapid greenhouse gas increases. Source: (Earl Saxon, Barry Baker, et al. 2005)

PDSI is a variable familiar to the fire community that is subject to large multi-year to decadal variations with demonstrated United States summer drought teleconnections to ENSO (Taylor and Beaty 2005; Dai, Trenberth, and Karl 1998; Rajagopalan et al. 2000). A recent study of global drought during the last millennia statistically links United States drought to ENSO with expected 21st Century increases in aridity. While the United States has avoided prolonged drought during the last 50 years, persistent droughts are expected during the next 20 to 50 years (Dai 2011). Monitoring variability and change of PDSI patterns over the next several decades will provide a crucial linkage between patterns of climate change that manifest through changes in ENSO (and other Intermediate scale atmospheric patterns) variability and ensuing changes in Intermediate to Long scale ecosystem and fire patterns. Several studies have found relationships among regional fire history, PDSI and Intermediate scale atmospheric oscillatory patterns, although for some fire regimes short (synoptic) scale factors are more dominant (Trouet et al. 2006; Trouet et al. 2009; Hessl, McKenzie, and Schellhaas 2004; Keeley 2004).

Long scale (decadal to centennial) patternsof climate forced ecosystem change resulting from a

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[27] See National Wildland Significant Fire Potential Outlook http://www.predictiveservices.nifc.gov/outlooks/monthly_seasonal_outlook.pdf - last accessed June 1, 2011

21st Century doubling of CO_2 concentrations are projected to affect a substantial portion of global forests and Bailey ecoregion patterns (Melillo 1999). Holocene records (see Chapter 4 discussion) demonstrate ecoregion variability and change associated with climate change. GCM outputs for CO_2 scenarios have been used to model future eastern U.S. forest tree distribution patterns with substantial resultant, yet variable, change (Iverson and Prasad 2002). Iverson and colleagues have since refined and expanded their efforts, with increasing tree mortality attributed to drier and hotter conditions (Iverson and Prasad 1998; Iverson et al. 2010). With the rate of 21st Century climate change outstripping previous Holocene change rates, *"…the rate of migration typical of the Holocene period (50 km/century in fully forested condition), less than 15% of the newly suitable habitat has even a remote possibility of being colonized within 100 years."* (Iverson, Schwartz, and Prasad 2004). Considering (see Chapter 2 discussion) that global GHG emissions continue to exceed those envisioned in the IPCC scenarios used by GCM, with irreversible climate change and a potential quadrupling of CO_2 concentrations by the end of the 21st Century, significant ecosystem change will inevitably result. While fire is well understood in regard to Short (synoptic to seasonal) atmosphere patterns, and is increasingly being understood in relation to Intermediate (annual to interannual) scale atmospheric forcing, fire is not generally incorporated in models of Long (decadal to centennial) term climate forcing of ecosystem change (Solomon et al. 2010). It is recognized that *"…climate change can effect forests by altering the frequency, intensity, duration, and timing of fire, drought, introduced species, insect and pathogen outbreaks, hurricanes, windstorms, ice storms, or landslides"*, and fire regimes are likely to change in response to Long-term climate forcing, there has been little or no work that explicitly incorporates fire as an expediter of decadal to centennial scale ecosystem adjustment to 21st climate change (Dale et al. 2001; Flannigan et al. 2009).

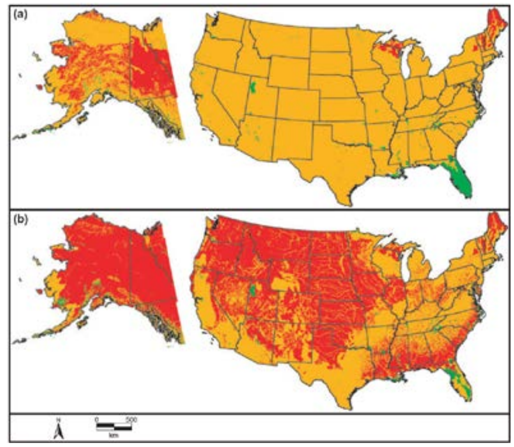

Figure 5.9: Current locations of domains that disappear from the study area are shown red, those that decrease are shown orange and those that increase are shown green. (a) Scenario B2, moderate greenhouse gas increases. (b) Scenario A2, rapid greenhouse gas increases. Source: (Earl Saxon, Barry Baker, et al. 2005)

21st Century Patterns

What patterns can we expect to see for U.S. ecosystems by the end of the 21st Century as they respond to climate change? Saxon et al. (2005) considered that question by mapping the distribution of 500 environmental domains in the year 2100 for GCM projections under the IPCC A2 (reaching concentrations of 735–1080 ppm CO_2 in 2100) and B2 (reaching concentrations of 545–770 ppm CO_2 in 2100) scenarios (see Chapter 2 discussion and (Nakićenović and Swart 2000)), with the A2 scenario concentrations more closely matching CO_2 emissions trajectories currently being experienced. The 500 environmental domains used are based on climatic, edaphic and topographic attributes that are the foundation of Bailey and other widely used biogeographic ecoregions, but, unfortunately for our purposes, are not identical. They determined *"…that 500 domains are enough to separate large uniform areas, such as the south-*

eastern Atlantic seaboard, without creating excessive numbers of units in small heterogeneous areas, such as the Rocky Mountains." Their results (see Figures 5.8, 5.9, 5.10) show significant environmental domain change for B2 scenario projections and almost nationwide domain change for A2 scenario projections by the year 2100.

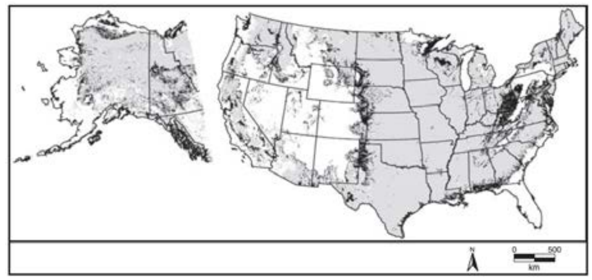

Figure 5. 10: Future locations of domains that have no current analogue in the study area. (White) Future locations of domains that currently exist, although not necessarily at these locations (Grey) Non-analogue domains that appear under both Scenario A2 and Scenario B2. (Black) Addition non-analogue domains that appear under Scenario A2 only. Source: (Saxon et al. 2005)

In this Chapter we have attempted to provide an overview of the change, variability, pattern and scale considerations that influence fire and its interactions with the atmosphere and ecosystems. We have noted the importance of fires that have occured through a considerable period of Earth history as local events and that fit within a larger context of fire as global process. Fire has exhibited regional scale patterns in time and space that relate to climate change and variability. We suggest that that the Bailey Division scale is currently the most appropriate spatial scale for which meaningful climate change information is likely to be available for fire planning use. We further suggest that it is useful to consider atmospheric information at the Short (synoptic to seasonal), Intermediate (annual to interannual), and Long (decadal to centennial) scales suggested by Gedalof (McKenzie, Miller, and Falk 2011). There is a long and valuable record of information on fire-atmosphere interactions that can inform our understanding of the factors governing fire events, their cumulative impact over time, and how they are being affected by 21st Century climate change. Our understanding of variability, change, pattern and scale gained from long observation of fire-atmosphere interaction at the Short scale is helping us to identify how Intermediate scale atmospheric patterns, such as those associated with ENSO, effect patterns of annual through interannual fire variability. At Long time scales, we remain dependent on knowledge of historic changes in ecosystem pattern and variability in response to climate change to infer that fire (and other disturbances) will play an increasing role in the future. Future ecosystem changes can be mapped and monitored at the Bailey Division level.