PYROGEOGRAPHY OF THE SOUTHEAST USA: EXPLORING THE RELATIONSHIPS BETWEEN WILDFIRE AND CLIMATE

A Dissertation

by

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ABSTRACT

Wildfire plays a contradictory role as both a hazard and a necessary ecological process in certain ecosystems. A variety of factors influence wildfire, including fuel type and quantity, land management policies, and patterns of human activity. Climate, however, can often play a dominant role. Wildfires are often thought to occur only in the western United States; however, fires are common on the southeastern U.S. landscape. Despite the abundance of fires, limited fire climatology work has been performed in this region. This dissertation addresses a knowledge gap in Southeast fire climatology by examining how gradients in precipitation regimes, in particular precipitation variability, influence spatial patterns of wildfire. In addition, modern synoptic climatology techniques are used to examine the relationships between atmospheric circulation patterns and wildfire ignitions in the central Gulf Coast sub-region of the Southeast.

Chapter II characterizes precipitation regimes in Southeast national forests and associates mean annual ignition density and mean annual area burned with various precipitation metrics. Weak positive correlations were observed between daily precipitation variability and mean annual ignition density. Chapter III employs the Spatial Synoptic Classification (SSC) scheme to examine weather types associated with wildfire ignitions in the central Gulf Coast. Results show that dry tropical (DT) days occurred more often during years with higher numbers of ignitions in central Gulf Coast national forests, as well as in the 180, 90, and 30-day periods prior to a fire. DT weather types occurred most commonly in the fall and spring corresponding with peak fire seasons in much of the region. Particularly in the spring, DT variability was influenced by positive phases of the North Atlantic Oscillation (NAO), presumably increasing westerly flow and driving DT weather types farther east from their general source region. Finally, chapter IV developed eleven synoptic types using the Synoptic Typer Tool (STT). Principal Component Analysis (PCA) was applied to daily (18z) 500 mb geopotential height grids. Synoptic types were then linked with wildfire ignitions in the central Gulf Coast. Results suggested that troughs were associated with wildfire activity, as well as zonal flow and high pressure systems.

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NOMENCLATURE

AMO	Atlantic Multidecadal Oscillation
AO	Arctic Oscillation
BHI	Bermuda High Index
CV	Coefficient of variation
DEM	Digital elevation model
DM	Dry moderate
DP	Dry polar
DT	Dry tropical
ENSO	El Niño-Southern Oscillation
GHCN	Global Historical Climatology Network
IPO	Interdecadal Pacific Oscillation
LU/LC	Land use/land cover
MM	Moist moderate
MP	Moist polar
MT	Moist tropical
NAO	North Atlantic Oscillation
NCDC	National Climatic Data Center
NIFMID	National Interagency Fire Management Integrated Database
PCA	Principal component analysis
PDO	Pacific Decadal Oscillation

PDSI	Palmer Drought Severity Index
PNA	Pacific North American pattern
PRISM	Parameter elevation regression on independent slopes model
QBO	Quasi-Biennial Oscillation
SSC	Spatial Synoptic Classification
SSTs	Sea surface temperatures
STT	Synoptic Typer Tools
T	Transitional
TCs	Tropical cyclones

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CHAPTER I

INTRODUCTION AND LITERATURE REVIEW*

I.1 Introduction

Climate affects vegetation structure and composition, primary productivity, and spatial patterns of vegetation on the landscape (Shuman et al. 2004; Xiao and Moody 2004; Fang et al. 2002; Williams et al. 2004; Fay et al. 2003; Heisler-White et al. 2009; Breshears et al. 2008). Climatic patterns also help shape disturbance regimes, including ice storms, hurricanes, and tornadoes. In turn, disturbances can cause vegetation damage and mortality, influence species composition and biodiversity, and therefore, spatial patterns of vegetation (Harmon, Bratton, and White 1983; Bond and Keeley 2005; Platt and Connell 2003; Parker, Parker, and McCay 2001; Abrams and Scott 1989). Disturbances play an integral role in many ecosystems. Disturbances create gaps in the forest canopy allowing for changes in environmental conditions and altering the competitive dynamics as species compete to fill that space (Bonan 2008; Huston and Smith 1987). Ultimately, disturbance regimes create a mosaic of landscape patterns over time and space (Bonan 2008; Pickett and White 1985; Abrams and Scott 1989; Harmon, Bratton, and White 1983; Huston and Smith 1987).

Wildfire is a disturbance that is strongly controlled by climate (Parshall and Foster 2002; Krawchuk et al. 2009). Fire helps to shape vegetation structure and

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composition (Bond and van Wilgen 1996; Pyne 1982; Whelan 1995). While still scientifically debated, certain species of plants may be fire-adapted (Bond and Keeley 2005). Despite the debate, there are clear linkages between fire and plant traits (Bond and van Wilgen 1996; Bond and Keeley 2005; Lafon 2010), including enhanced flowering, seed germination, and seedling recruitment (Bond and van Wilgen 1996). For instance, the longleaf pine (*Pinus palustris*), once common to the southeastern United States coastal plain, exhibits a number of potentially fire-adapted traits including thick bark and a grass stage that allows the species to grow a deep root system and survive low to moderate intensity surface fires (Keeley and Zedler 1998).

While wildfires are a key component of many ecosystems, they are also a costly hazard (Hawbaker et al. 2013; Butry et al. 2001). Wildfires are responsible for the destruction of property and valuable natural resources and they can threaten communities. This makes understanding the climatic drivers of spatial and temporal patterns of wildfire an important, yet complex task (Hawbaker et al. 2013).

Despite the relatively common occurrence of wildfire in the southeastern USA, few studies have examined wildfire-climate relationships in this region. This dissertation addresses this knowledge gap by examining interactions between climate and wildfire in the Southeast. Specifically, it will examine how precipitation regimes influence wildfire patterns and identify the weather and atmospheric circulation patterns associated with wildfire events.

Climate plays a fundamental role in dictating spatial and temporal patterns of wildfire across the landscape (Krawchuk et al. 2009; Parshall and Foster 2002). While there are other factors contributing to wildfire, including vegetation structure and composition, land use/land cover, topography, and management practices (Bond and van Wilgen 1996; Pyne 1982; Krawchuk et al. 2009), climate is a dominant control of wildfire in many ecosystems (Meyn et al. 2007; Krawchuk et al. 2009) . Climate influences three of the requirements for wildfire – fuel type/quantity, fuel moisture, and lightning as an ignition source (Bond and van Wilgen 1996; Krawchuk et al. 2009). Long-term climate dictates the presence or absence of flammable vegetation that ultimately becomes the fuel type and quantity for a fire (Krawchuk et al. 2009; Bond and van Wilgen 1996). Climatic variability affects fuel moisture on daily to multidecadal timescales. Finally, lightning is a potential ignition source that is also controlled by the atmosphere (Bond and van Wilgen 1996).

I.1.1 Research Objectives

The purpose of this dissertation is to explore the linkages between spatiotemporal climatic variability and wildfire patterns in the southeastern United States. The following research objectives guide this research:

(1) Quantify the relationships between wildfire activity and the precipitation regime of the southeastern USA.

(2) Identify the weather type(s) associated with periods of high wildfire activity in the central Gulf Coast USA.

(3) Identify the synoptic type(s) associated with periods of high wildfire activity in the central Gulf Coast USA.

The Southeast is a sub-humid climate and therefore, a location with a variable precipitation regime in this region would be one in which intermittent dry periods were present. Locations with intermittent dry periods should experience increased ignition density and acres burned. This stands in contrast to arid/semi-arid climates with variable precipitation regimes that are interspersed with wet periods. Likewise, less variable precipitation regimes, for instance along the Northwest Pacific Coast, receive frequent, often low intensity precipitation events. Consequently, it is hypothesized that drier locations, as determined by mean precipitation and locations with more variable precipitation regimes, will be more prone to wildfire activity (Objectives 1). Similar hypotheses have been proposed by Sauer (1950), Meyn et al. (2007), and Parisien and Mortiz (2009) regarding the environmental conditions required for fire. Studies exploring the spatial distribution of fire as a function of environmental gradients is necessary, but to date have been lacking (Parisien and Moritz 2009). Objective 1 of this dissertation represents a step in the direction of addressing that gap concerning gradients in precipitation regimes. Large-scale weather patterns, circulation features, and atmospheric-oceanic oscillations often drive precipitation variability and drought (Ropelewski and Halpert 1986; Horel and Wallace 1981). Atmospheric circulation patterns have a significant influence on the conditions necessary to promote burning (e.g. Trouet et al. 2009, Skinner et al. 2002). Dry and/or warm to hot air masses, along with high pressure systems should be conducive to such conditions and therefore be associated with increased ignition density and acres burned. Objectives 2 and 3 will address weather type and circulation patterns associated with wildfire.

Prior to delving into the main chapters of this dissertation, a synopsis of the main characteristics and features of the Southeast hydroclimate follows. After a review of the hydroclimate, previous wildfire-climate literature is reviewed with a particular emphasis on focus on the Southeast follows. Chapters II, III, and IV discuss the data, methods, and results of the three research objectives. Chapter II of the dissertation quantifies the relationship between metrics of precipitation regimes (mean precipitation and precipitation variability) and wildfire activity (ignitions and area burned). Chapter III focuses the on the central Gulf Coast and identifies weather types associated with high wildfire activity. In addition, chapter III also identifies potential large-scale teleconnections, such as El Niño-Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO) that explain an increase in particular air masses. Chapter IV classifies synoptic atmospheric circulation patterns associated with wildfire ignitions throughout the central Gulf Coast, defined as the states of Mississippi, Alabama, and the panhandle of Florida. A summary with major conclusions of this dissertation is provided in Chapter V, along with potential directions for future research.

I.1.2 Merit and Impacts

Wildfires pose a significant threat to timber resources, ecosystem functioning, and rural, and in some cases, urban communities, costing billions of dollars in suppression costs alone (Hawbaker et al. 2013). For instance, fires in Florida in 1998 cost $600 million, approximately equivalent to a category-2 hurricane making landfall in the state (Butry et al. 2001). Yet at the same time, wildfires are a natural and required component for many ecosystems throughout North America (Pyne 1982; Pyne, Andrews, and Laven 1996; Bond and van Wilgen 1996). Wildfires influence vegetation structure and composition, as well as wildlife habitat (Whelan 1995; Bond and van Wilgen 1996) and can play an important role in habitat maintenance and restoration (Beckage, Platt, and Panko 2005). The dual role as both a hazard and a critical ecosystem process makes balancing these roles a challenge (Hawbaker et al. 2013) and understanding drivers of wildfire not only a complex task, but an important one.

There are many factors that influence spatial and temporal patterns of wildfire on the landscape from vegetation structure and fuel composition to patterns of human habitation and forest management policies (Bond and van Wilgen 1996; Pyne 1982; Pyne, Andrews, and Laven 1996; Krawchuk et al. 2009). Climate is one of the main factors that influences wildfire patterns over time and space (Krawchuk et al. 2009).

As is often depicted in the media, wildfires are perceived to occur most frequently in western North America. However, the southeast USA has a large number of wildfires each year with both the climate and vegetation to support such fires (Pyne 1982; Andreau and Hermansen-Báez 2008). Despite the frequency of wildfires in the Southeast, studies detailing wildfire-climate relationship in this region are limited. While some excellent studies have been completed in the field of Southeast wildfire climatology, there are still a number of issues that have not been fully addressed. Specifically, modern synoptic climatological methods have not been applied towards understanding the atmospheric circulation patterns associated with wildfire. Previous work in synoptic climatology and Southeast wildfire provides guidance for such research (i.e. Brotak and Reifsnyder 1977, Heilman 1995); however these studies are dated and there have been many advances in synoptic climatology techniques since the publication of these studies (Yarnal 1993). Many of these techniques have been applied in western North America (i.e. Trouet et al. 2009, Crimmins 2006), but again, not in the Southeast. This dissertation employs two synoptic techniques that have not been previously used to assess weather and synoptic types in the context of wildfire, namely the Spatial Synoptic Classification (SSC) scheme and the Synoptic Typer Tools (STT).

The spatial distribution of wildfires along environmental gradients is not well understood (Parisien and Moritz 2009). An improved understanding of the major controls of wildfire patterns will assist in understanding the drivers of current and future patterns under changing climatic conditions (Parisien and Moritz 2009). In particular, this dissertation examines precipitation variability, which has been identified as an important component of future climate change in the Southeast, but has not been fully assessed to explain spatial patterns of wildfire (Wang et al. 2010; Groisman and Knight 2008; Karl and Knight 1998). The results of this dissertation will help to address the knowledge gap that exists in Southeast USA fire climatology. Finally, the relationships uncovered in this dissertation are applicable to other ecosystems and climatic regions and beneficial for management and restoration efforts outside of the Southeast (Beckage, Platt, and Panko 2005).

I.2 Hydroclimatology of the Southeastern USA

I.2.1 Introduction

The Southeastern USA has a humid subtropical climate with hot summers, mild winters, and generally high amounts of precipitation throughout the year. According to the USA Census Bureau (2013), the Southeast is home to over 50 million people, and this figure is on the rise. Several large urban centers have climatic conditions that are largely regarded as favorable, including Charlotte, Memphis, Nashville, Jacksonville, Miami, Tampa Bay, and Atlanta, and in recent decades many areas of the Southeast have seen an increase in urban land use/land cover (LU/LC, Nowak et al. 2005). With the increasing population, particularly in these metropolitan areas, comes an increased demand for water resources to supply industry, energy, agriculture, and municipalities. Also, pollution degrades water resources, leaving less clean water available for ecosystems and human consumption (Dyer 2008). Future climatic changes may cause substantial changes in spatial and temporal patterns of the availability of water resources, making it more difficult to meet water demands in the region. In addition to population growth and urban development, hydroclimatic variability is increasing and extreme wet and dry events are becoming more common (Karl and Knight 1998; Groisman and Knight 2008; Wang et al. 2010). It is therefore important to characterize the hydroclimatology of the Southeast and to understand its controls.

To date, no comprehensive review of the hydroclimate of the Southeast has been performed. A review by Soulé (1998) is the most recent paper that addresses the climate of the Southeast. Soulé (1998) focuses on describing how factors such as latitude, elevation, air masses, tropical cyclones (TCs), mid latitude cyclones, and convective activity influence the climate of the Southeast. The present study describes general hydroclimatic patterns in the Southeast, including mean precipitation and variability, flooding, and drought. It also reviews the primary, large-scale seasonal to interannual controls on the hydroclimate of the Southeastern USA, including El Niño/Southern Oscillation (ENSO), the Pacific North American (PNA) pattern, the Bermuda High, and TCs. In addition, a brief overview of recent significant hydroclimatic events in the region are presented, including the near record setting drought in 2007, the severe Atlanta floods in 2009, and examples of TCs that alleviated drought conditions.

The Southeastern USA is defined here as consisting of the following states: Virginia, North Carolina, South Carolina, Georgia, Florida, Alabama, Mississippi, and Tennessee (see Figure 1). This area encompasses the region covered by the Southeast Regional Climate Center with the addition of Mississippi and Tennessee. Others have defined the Southeast in a similar fashion, including Soulé (1998). It is acknowledged that defining regions is somewhat subjective and that others may choose to define the Southeastern USA differently.

I.2.2 Hydroclimatic Patterns

I.2.2.1 Precipitation Regimes

Mean annual precipitation from 1895 to 2011 is depicted in Figure 1A. Locations in the eastern half of the region (generally east of the Appalachian Mountains) are drier, and western and southern areas are wetter. While station resolution is insufficient to adequately characterize precipitation regimes in the Appalachians, it is clear that the mountain range has an effect. The highest mean annual precipitation occurs in far western North Carolina near the Great Smoky Mountains (2,103 mm). The lowest mean annual precipitation is in northwestern Virginia (894 mm).

Low coefficient of variation (CV) values tend to occur in the northeastern half of the region, particularly in a band running from the North Carolina and Virginia coast into central Tennessee, as depicted in Figure 1B. Highest CV values are found in isolated patches throughout the study area, particularly in the central Gulf Coast states, but also along coastlines. Figure 2 presents mean monthly precipitation at selected stations throughout the region from 1895 to 2011. While September, October, and November tend to be drier, precipitation is evenly distributed throughout the year. One exception is Bartow, Florida where there is a pronounced wet and dry season. Mo and Schemm (2008a) maintain that the lack of seasonal precipitation cycles in the Southeast reduces drought persistence.

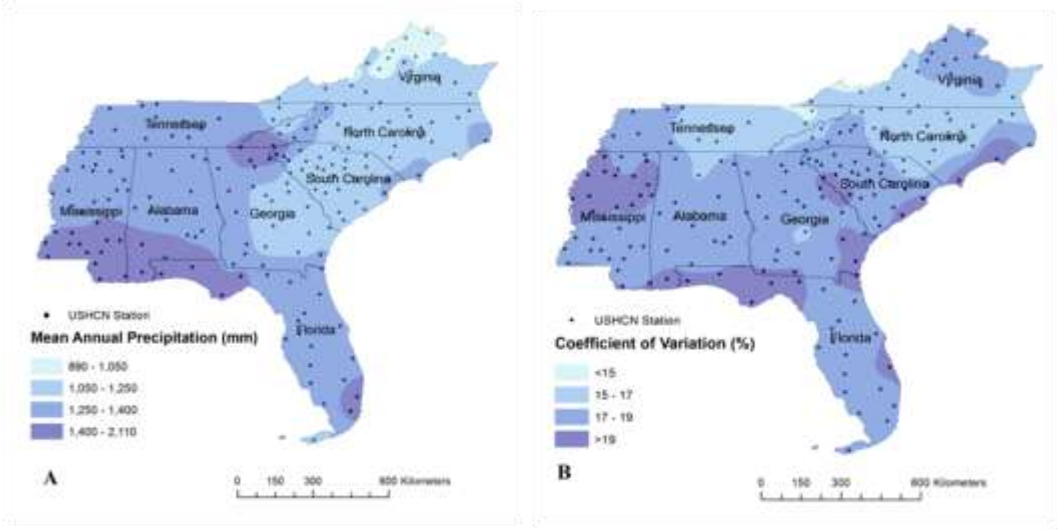


Figure 1. Mean annual precipitation (A) and coefficient of variation (CV) of annual precipitation (B) for 1895-2011. Data are obtained from the US Historical Climatology Network (USHCN; http://cdiac.ornl.gov/epubs/ndp/ushcn/ushcn.html) from 1895-2011. Interpolation completed using ordinary kriging.

During recent decades (1978 to 2007), the Southeastern USA region has witnessed an increase in summer precipitation variability with more frequent drought and pluvial events compared to 1948-1977 (Wang et al. 2010). Other studies also confirm the findings of Wang et al. (2010). For example, over the last century precipitation has increased in the Southeast due to increases in heavy and extreme precipitation (Karl and Knight 1998; Groisman, Knight, and Karl 2001). Groisman and Knight (2008) observed an increase in the mean duration of warm season dry periods in the eastern USA during the past 40 years accompanied by a decrease in return intervals from 15 to 6-7 years for these dry events. Consequently, it seems that the Southeastern precipitation regime is becoming more variable, with both longer and more frequent dry periods and more heavy to extreme precipitation events.

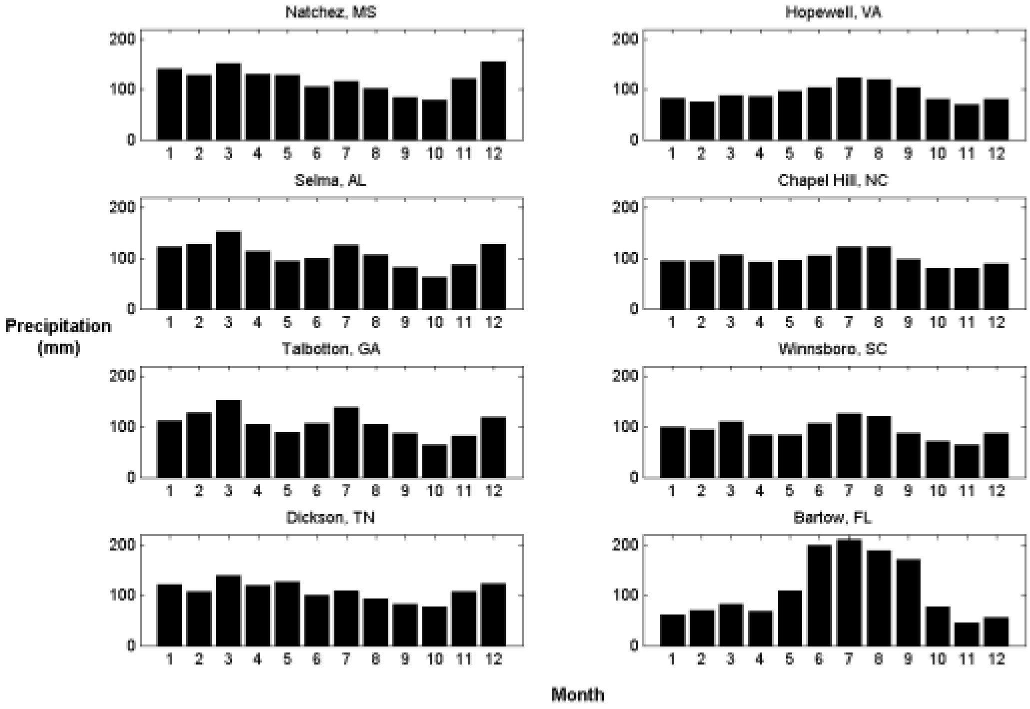


Figure 2. Mean monthly precipitation for selected Southeast stations for 1895-2011. Data are obtained from the US Historical Climatology Network (USHCN; http://cdiac.ornl.gov/epubs/ndp/ushcn/ushcn.html) from 1895-2011.

Heavy or extreme precipitation events are characteristic of Southeastern climatology. Keim (1997) examined spatial and temporal variability of heavy precipitation events, defined as 76.2 mm over a period of 2 consecutive days. The central

Gulf Coast regions experienced the highest number of annual events on average, followed closely by peninsular Florida (Keim 1997), results also broadly supported by Faiers and Keim (2008) when examining 3 and 24 hour storm magnitudes. Heavy precipitation events were less common in the western extremes and in the interior of the region (Keim 1997). Keim (1997) found that the trend in the number of heavy precipitation events increased over time in band extending from Texas to the Tennessee Appalachians.

I.2.2.2 Flooding

Given the prevalence of heavy precipitation events, along with the compounding factors of local topography and LU/LC, the Southeast is susceptible to flooding. Gamble (1997) examined flood seasonality in the Southeast, identifying 5 distinct regions with similar seasonalities, and suggested potential mechanisms behind the homogenous regions. Winter is the primary flood season in Tennessee, northern Mississippi, and northern Alabama due to the prevalence of extratropical cyclones in the season. Along the Gulf Coast into central Mississippi, through Alabama, and northern Georgia and into South Carolina, floods primary occur during the spring. Such floods are also attributable to extratropical cyclones. In Peninsular Florida, floods are most prevalent in the fall because this is associated with the peak in tropical cyclone activity. Coastal Georgia and portions of northern Florida have a spring flood season. Interestingly, no dominant flood season is found in North Carolina and Virginia, possibly due to the variety of geographic (i.e. Appalachian Mountains and proximity to Atlantic Ocean) and synoptic factors, such as damming of cold air along the eastern slopes of the Appalachians and weakening of storm systems in proximity to the western portion of the mountain range, as reported in Keeter et al. (1995). Lecce (2000) found similar results when performing a cluster analysis on streamflow data in the Southeast. The states of Mississippi, Alabama, Georgia, and Tennessee have a late winter/spring flood season. Like Gamble (1997), Lecce (2000) suggests that the northern portion of this region experiences most floods in winter, and the southern portion, closer to the Gulf Coast, experiences most floods in the spring. Florida experiences floods in both spring and late summer/early fall with over half occurring in the months of August, September, and October. Finally, similar to Gamble’s (1997) findings, Lecce (2000) found that the Carolinas have no true dominant flood season. However, flooding was slightly more common in the months of January through April (Lecce 2000). In a follow-up study to Gamble (1997), Gamble and Meentemeyer (1997) examined extreme unseasonable flooding, defined as the 10 highest magnitude flood events from 1950 to 1990 during the season of lowest flood frequency (summer). Gamble and Meentemeyer (1997) found that localized storm systems rarely produce unseasonable extreme flooding, but instead large-scale extratropical and tropical systems are more associated with these events, and land surface characteristics also play a role.

It is also important to compare the patterns of flooding in the Southeast with flooding patterns in the continental USA. Michaud, Hirschboek, and Winchell (2001) examined peak discharges throughout the USA to contrast spatial patterns of floods. Analysis of the median and 25 year floods suggests that portions of the central and western Southeast into the Great Plains experience the largest floods (Michaud, Hirschboeck, and Winchell 2001). However, when the analysis focuses on the most rare flood events, the spatial pattern shifts westward, with events in the Southeast generally smaller than the rest of the country (Michaud, Hirschboeck, and Winchell 2001).

While extratropical and tropical cyclones certainly play a role in flooding, it is the interaction between atmosphere and local land surface characteristics that dictate flood duration and severity. Studies have demonstrated that heavy precipitation is not the sole cause of flooding, and even moderate amounts of precipitation can cause flooding, suggesting an interaction with the local land surface (Gamble and Meentemeyer 1997). LU/LC, topography, watershed characteristics, vegetation, baseflow conditions, temperature and antecedent rainfall all interact to induce flooding (LaPenta et al. 1995; Gamble 1997; Gamble and Meentemeyer 1997). Studies suggest that antecedent soil moisture is of particular importance in determining flooding (LaPenta et al. 1995; Gamble and Meentemeyer 1997; Legates et al. 2011).

The flood event in Atlanta, Georgia, in September 2009 provides an example of how multiple factors can contribute to flood conditions. Severe flooding took place in the greater Atlanta area, which in some cases exceeded the 500 year flood (Shepherd et al. 2011). Shepherd et al. (2011) suggest significant antecedent precipitation from a stalled cut-off low aided in setting the stage for the Atlanta flood event. Previous studies have documented the connection between these systems, heavy precipitation, and flooding, but research involving these systems is limited in the Southeast (Shepherd et al. 2011). In addition, moisture advection from Tropical Storms Marty and Fred may have also contributed to the flood event on 20 to 22 September. It is clear from the analysis of Shepherd et al. (2011) that soils in the region were at or near field capacity prior to the actual flooding event. Topography and urban LU/LC may have also enhanced the precipitation events and certainly influenced runoff and infiltration processes (Shepherd et al. 2011). Other studies pertaining to Atlanta flood hydrology have identified urbanization-related land cover changes as an important factor (e.g. Shepherd, Pierce, and Negri 2002, Wright et al. 2012) and may play a role in other large Southeast cities as well (Shepherd, Pierce, and Negri 2002).

I.2.2.3 Drought

Despite the generally humid and wet climate, the Southeastern USA is prone to periodic droughts, which are an important feature of the hydroclimatology of the region (Seager, Tzanova, and Nakamura 2009). Doublin and Grundstein (2008) examined drought from the standpoint of soil moisture deficits from 1895 to 2005. They used principal component analysis (PCA) to regionalize annual accumulated warm season soil moisture deficit and identified 5 distinct regions in the southern USA, including from the Southeast the eastern region (Carolinas, Georgia, much of Tennessee, and northeast Florida), the Gulf Coast (Alabama, panhandle of Florida, the southeastern half of Mississippi, and Louisiana), and southern Florida. Others have also found central and southern Florida to be isolated in terms of drought behavior, possibly due to the influence of land-sea breezes (Henry and Dicks 1988). Average soil moisture deficits were highest in Texas and areas west of the Mississippi River, and decreased eastward where south Florida had the lowest average soil moisture deficits (Doublin and Grundstein 2008). Different regionalizations are possible depending on how drought is quantified, and on the methodology used to define homogenous regions. For instance, Ortegren et al. (2011) found that most of the Southeast, with the exception of Mississippi, far west Tennessee, and eastern Virginia, behaved similarly when examining warm season Palmer Hydrological Drought Index data. Others have also performed similar analyses, creating regionalizations based on drought conditions, including Eder, Davis, and Monahan (1987) using the Palmer Drought Severity Index (PDSI).

Tree ring-based reconstructions are commonly used to put contemporary droughts into historical context. A number of reconstructed datasets have been created for both drought and precipitation in the Southeast using baldcypress (*Taxodium distichum*). These reconstructions show variability in both intensity and duration of wet and dry periods in the region (Stahle, Cleaveland, and Hehr 1985, 1988; Stahle and Cleaveland 1992, 1994) and some suggest an approximate 30 year cycle between wet and dry periods (Stahle, Cleaveland, and Hehr 1988; Stahle and Cleaveland 1992). Generally speaking, no significant long-term trend exists in the instrumental record (Karl and Heim 1990; Doublin and Grundstein 2008), but decadal cycles do seem to exist with the 1920s, 1950s, and 1980s being dry and the 1940s and 1970s being wet (Doublin and Grundstein 2008). However, some studies have noted trends towards a wetter climate on smaller spatial scales (e.g. Yin 1993 with climate divisions). The drought measure, spatial scale, and instrumental record length all have a large influence on whether trends in drought conditions are detected.

Not surprisingly, drought in the Southeast is associated with above normal temperatures and below normal precipitation (Doublin and Grundstein 2008), unlike other climatic regimes where temperature is not as strongly associated with drought (e.g. Northeast USA; Leathers, Grundstein, and Ellis 2000). In a study of warm season drought, potential evapotranspiration and precipitation were found to be strongly correlated with soil moisture deficits, particularly in more inland regions such as northwestern Mississippi into western Tennessee (Doublin and Grundstein 2008), suggesting possible land-atmosphere feedbacks. However, studies examining these feedbacks in the Southeast are limited. Droughts also tend to be more strongly associated with decreases in precipitation event frequency than with decreases in precipitation intensity (Doublin and Grundstein 2008).

Impacts from severe droughts are often thought to be mostly limited to the Great Plains and western USA, but droughts also represent a serious threat to water resources in the Southeast. For instance, drought conditions in the Southeast have been implicated in the demise of the settlements at Jamestown and Roanoke in the late 16th and early 17th centuries (Stahle et al. 1998). The most recent severe drought began during the winter of 2005-2006, continuing through to the fall/winter of 2007-2008 and was responsible for significant economic losses due to crop failures, lack of hydropower generation, wildfires, and water shortages (Manuel 2008; Maxwell and Soulé 2009). The drought also reignited tensions between Georgia, Alabama, and Florida over the use of limited water from Lake Sidney Lanier, Atlanta’s main municipal water supplier (Manuel 2008). Figure 3 depicts the PDSI, temperature anomalies, and 500 mb geopotential height anomalies for the fall months of 2007. As expected positive temperature anomalies dominated much of the impacted region during this time period, along with positive geopotential height anomalies. A thorough explanation of the atmospheric conditions leading to the 2007 drought is provided by Maxwell and Soulé (2009).

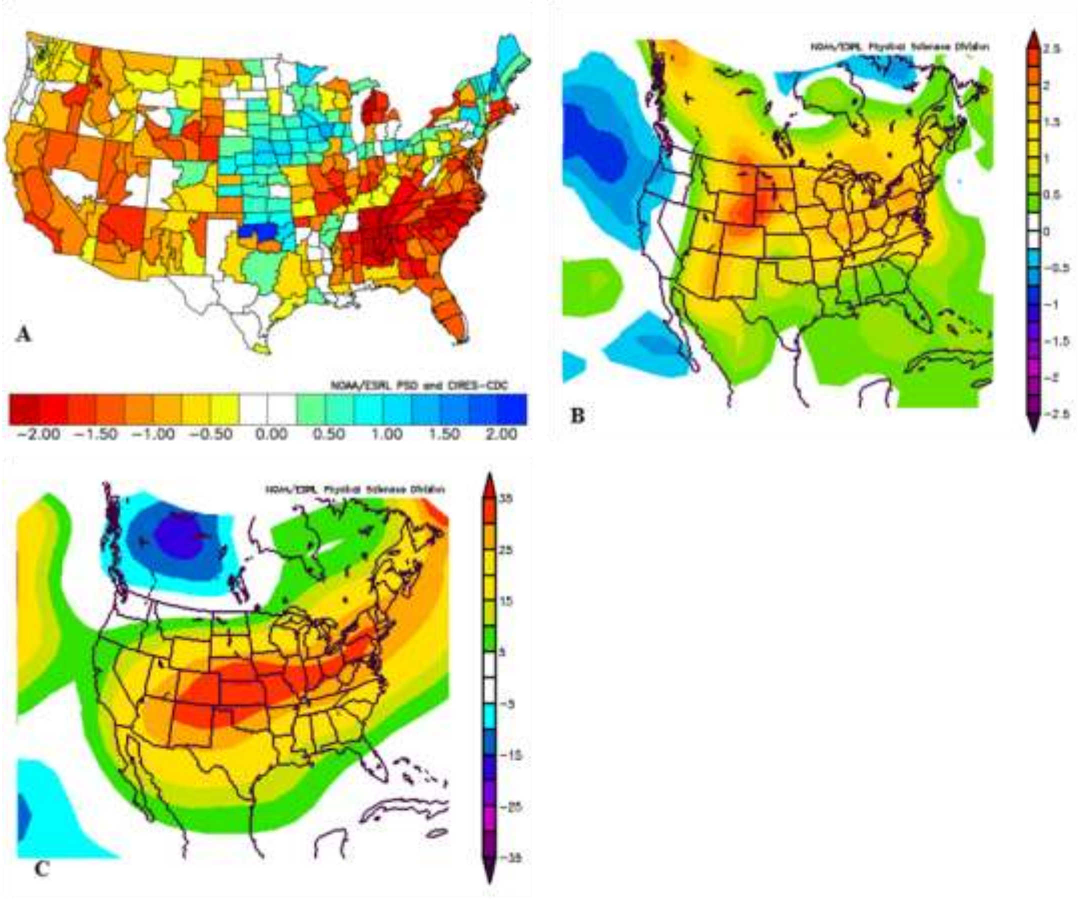


Figure 3. September, October, and November 2007 (A) PDSI, (B) surface air temperature anomalies, and (C) 500 mb geopotential height anomalies. All variables are relative to the 1981-2010 climatology. Data are obtained from NCEP/NCAR reanalysis data. Figures created using Earth System Research Laboratory Plotting and Analysis Tool (www.esrl.noaa.gov). For more information, see Maxwell and Soulé (2009).

During the 2007-2008 drought the Southeast experienced some of the driest conditions on record (relative to the period 1895-2007), underscoring the necessity of proper planning, management and conservation (Maxwell and Soulé 2009). From a historical standpoint, this recent drought was not particularly unusual (Maxwell and Soulé 2009; Seager, Tzanova, and Nakamura 2009). While drought conditions in November 2007 were the worst witnessed by many climate divisions during the instrumental record, the drought was relatively localized. Recurrence intervals for climate divisions in November 2007 show that only 2 of these climate divisions (one in northeast Alabama and one in western South Carolina) witnessed a >100 yr drought event (Maxwell and Soulé 2009). Drought reconstructions suggest that events of this magnitude and duration are a relatively common feature of the hydroclimatic regime in the region, and more severe and longer duration droughts are found in the paleo-record (Pederson et al. 2012). Especially important is the suggestion that many water management policies were put into place during some of the wettest years on record. This underscores the need for current and future water management policies to take into account hydroclimate variability on longer timescales (Pederson et al. 2012).

Tree-ring reconstructions provide important information on moisture conditions prior to the instrumental record. Pederson et al. (2012) reconstructed PDSI in the Apalachicola-Chattahoochee-Flint river basin and found that from 1696 to 1820 droughts were frequent and long lived. Interestingly, the tree-ring record identifies the 1986 drought as one of the most severe and rare drought events on record (Cook, Kablack, and Jacoby 1988; Pederson et al. 2012). Cook, Kablack, and Jacoby (1988) estimates the recurrence interval of the 1986 drought to be ~287 yr. Using the shorter instrumental record, Karl and Young (1987) confirm the severity of the 1986 drought in terms of impacts on agriculture, but suggest that the drought was not unprecedented in terms of streamflow.

I.2.3 Major Atmospheric Controls on Hydroclimatology

There are many controls on the hydroclimatology of the Southeastern USA that range in scale from local surface heating that gives rise to convective thunderstorms to hemispheric/global-scale teleconnections that influence the position of the jetstream. This paper emphasizes large-scale processes and does not deal with smaller scale processes, although they are also important for the hydroclimatology of the Southeast. There are also processes that influence the hydroclimate of the Southeastern USA on different timescales (i.e. daily, decadal, and longer). This review limits the discussion to those features and processes that are important on a seasonal to interannual scale.

I.2.3.1 El Niño-Southern Oscillation (ENSO)

The dominant mode of climatic variability in the tropics, and the most well-studied, is ENSO (Curtis 2008). ENSO has been used to examine a number of other phenomena in the Southeast, including wildfires (e.g. Harrison and Meindl 2001; Beckage et al. 2003), vegetation health (e.g. Mennis 2001; Peters, Ji, and Walter-Shea 2003), and crop yields (e.g. Royce, Fraisee, and Baigorria 2011) among others. ENSO involves changes in the interactions between oceanic (El Niño) and atmospheric (Southern Oscillation) circulation components that influence the Walker Circulation in the equatorial Pacific (Bjerknes 1969; Curtis 2008). El Niño periods consist of anomalously warm sea surface temperatures (SSTs) in the eastern tropical Pacific along with anomalously low sea level pressure (Curtis 2008; Bjerknes 1969). La Niña periods, on the other hand, are indicative of anomalously cool SSTs in the eastern Tropical Pacific and higher sea level pressures (Curtis 2008). While phases of the ENSO are often referred to as opposites of one another, research shows that atmospheric-oceanic oscillations are frequently non-linear, and that this assumption is therefore not appropriate (Sheridan and Lee 2012).

Cold and warm phases of ENSO differentially impact precipitation patterns across the globe (Kiladis and Diaz 1989; Curtis 2008). Ropelewski and Halpert (1986) first identified the primary USA regions where precipitation consistently responded to ENSO, including the Southeast from October through March. Warm phase El Niño events are associated with increased precipitation throughout much of the Southeast into Mexico, and cold phase La Niña events are associated with drier than normal conditions (Kiladis and Diaz 1989). Eichler and Higgins (2006) also suggest increased precipitation east of the Appalachians during El Niño winters as the storm tracks on the Atlantic Coast become enhanced. With increased precipitation comes increased streamflow, which has also been linked to ENSO phases in the Southeast (Kahya and Dracup 1993).

The aforementioned studies take a continental to global-scale perspective, but these same relationships have also been observed on smaller scales within the Southeast. Douglas and Englehart (1981) found that wet winters in Florida were typically preceded by warmer SSTs and increased precipitation in the ENSO region and vice-versa, suggesting that cyclogenesis increases in the Gulf of Mexico with El Niño phases. This same relationship has also been seen in terms of surface hydrology and groundwater recharge (Sun and Furbish 1997). Senkbeil et al. (2012) performed a manual and automated classification of extratropical cyclones in the Southeast and found that moderate to strong warm ENSO phases generally resulted in the strongest associations with extratropical cyclones. In particular, stronger El Niño phases provided for a tendency to produce more intense extratropical cyclones (Senkbeil et al. 2012). In an analysis of weather type occurrences between winter phases of ENSO in New Orleans, McCabe and Muller (2002) found statistically significant differences during La Niña events as certain wet weather types became less frequent and dry weather types became more frequent. They also found precipitation for 'stormy weather types', such as Gulf Return, Frontal Gulf Return, and Frontal Overrunning, to be greater during El Niño events than for neutral or La Niña events (McCabe and Muller 2002). McCabe and Muller (2002) suggest that this reflects a shift in the position of storm tracks between ENSO phases, further demonstrating the link between ENSO, cyclogenesis, and precipitation suggested by Ropelewski and Halpert (1986). Curtis (2006) reports that during winter El Niño periods, cyclogenesis is common in the western Gulf of Mexico and the Atlantic Coast around North Carolina. In addition, storm counts in the Southeast increase along with the number of intense storms (Curtis 2006).

ENSO has also been shown to influence drought events in the Southeast. Studies suggest that winter drought is most commonly associated with La Niña phases (Mo and Schemm 2008b). There is, however, disagreement over the controls on interannual variability of summer drought in the Southeastern USA. Some have argued that summer drought is controlled by internal atmospheric processes and is only weakly associated with ENSO (Seager, Tzanova, and Nakamura 2009), while others argue that oceanic-atmospheric conditions in the North Atlantic also play a significant role (Enfield, Mestas-Nunez, and Trimble 2001; McCabe, Palecki, and Betancourt 2004; Ortegren et al. 2011).

I.2.3.2 Pacific North American (PNA) Pattern

Horel and Wallace (1981) suggested a mechanism by which ENSO effects could be propagated to North America. During warm phases in the equatorial Pacific, geopotential heights in the North Pacific and the Southeastern USA tend to be anomalously low while anomalously high geopotential heights reside over western Canada (this was later termed the PNA). The PNA relates geopotential height anomalies between the northern Pacific and the North American continent (Horel and Wallace 1981; Leathers, Yarnal, and Palecki 1991). During a positive phase of PNA, meridional flow dominates while zonal flow is characteristic of the negative phase (Leathers, Yarnal, and Palecki 1991). Studies relating the PNA and spatiotemporal patterns of precipitation are limited in the Southeast, despite the region being one of the primary centers of action (Leathers, Yarnal, and Palecki 1991). Henderson and Vega (1996) demonstrate that there is significant spatial variability in the impacts of PNA on precipitation variability in the Southeast. During the winter when the teleconnection is most prevalent, positive PNA patterns often lead to positive precipitation anomalies in much of the region with the exception of northern portions of the region west of the Appalachians as cyclones tend to form and traverse east of the mountain range

(Henderson and Vega 1996). The reverse occurs during a negative PNA phase, as much of the region experiences negative precipitation anomalies (Henderson and Vega 1996). Potential evapotranspiration and soil moisture deficits during the warm season have also been linked with PNA phases, as positive phases, advect cooler air into the region and decrease atmospheric demand (Doublin and Grundstein 2008).

PNA may also influence the number of cyclones that traverse the Southeast, as evidenced by the work of Henderson and Robinson (1994). Henderson and Robinson (1994) found meridional flow to be linked with less frequent winter cyclones and more frequent cyclones in the summer. Results also show that the longer duration cyclones that generate greater amounts of precipitation tend to be associated with meridional flow east of the Appalachians, supporting the results of Henderson and Vega (1996). This suggests that the Southeast is far from a homogenous climate and does not respond uniformly to climatic variability. Furthermore, this demonstrates the importance of the Appalachian Mountains in generating climatic spatial variability.

I.2.3.3 Atlantic Subtropical High/Bermuda High

The Atlantic subtropical high pressure center, also termed the Bermuda High or Azores High (Davis et al. 1997), influences the climate of the Southeastern USA throughout the year, but it is most important during the spring and summer. The Atlantic subtropical high/Bermuda High is also a part of a larger oceanic-atmospheric oscillation termed the North Atlantic Oscillation (NAO). The 2 centers of action in the NAO are the Icelandic Low and the Azores High and together they represent the main circulation feature in the Atlantic (Serreze and Barry 2009). A positive NAO indicates that both centers are anomalously strong and tend to shift poleward and a negative NAO indicates that both centers are anomalously weak and tend to shift equatorward (Serreze and Barry 2009). Storm tracks are influenced by the strength and positioning of positive and negative phases, which play a significant role in eastern USA winters (Marshall et al. 2001). Positive NAO phases have been shown to result in increased moisture advection into the eastern USA (partially as a result of the Bermuda High circulation to be discussed; Hurrell 1995). On the other hand, a negative NAO results in weaker zonal flow allowing for intrusions of colder, dryer air in the Southeast (Hurrell 1996; Yin 1994). There is also debate surrounding whether the NAO is simply a regional manifestation of the Arctic Oscillation (e.g. Thompson and Wallace 1998); however, this is beyond the scope of this paper. With this in mind, the focus of this section will remain on the Bermuda High.

In an examination of the characteristics of the Atlantic subtropical high, Sahsamanoglou (1990) calculated the mean annual central pressures from 1873 to 1980 and found it to be 1023.5 hPa, with very little variation (standard deviation of 1.2 hPa). The semi-permanent anticyclone migrates on a seasonal basis from ~30°N, 25°W near the Azores (Azores High) during the winter to ~30°N, 40°W near Bermuda (Bermuda High) during the middle of the summer (Sahsamanoglou 1990; Barry and Carleton 2001). From this location, the high pressure cell moves north to 35°N in late summer and then to 20° W by the middle of fall (Sahsamanoglou 1990; Barry and Carleton 2001). However, Davis et al. (1997) show that these changes can occur suddenly, and therefore a smooth, seasonal progression does not always occur. The Bermuda High central pressure values are highest in January and July and reach the minimum values in March and October (Sahsamanoglou 1990). Similarly, Davis et al. (1997) report peak intensities in January over the Southeastern USA and in July over the central Atlantic, with the spring and fall acting more as transitional periods. The Atlantic subtropical high also influences weather from the eastern half of the USA to portions of Europe and northwest Africa (Davis et al. 1997). For a more thorough explanation of the characteristics and significance of this circulation feature, see Davis et al. (1997).

The strength and positioning of the Bermuda High has a strong influence on moisture conditions in the Southeast, particularly during the spring and summer. Typically, tropical easterlies flow south of the Bermuda High bringing warm, moist, unstable air masses from the Atlantic and Gulf of Mexico onshore along the Atlantic Coast and Florida (Coleman 1988; Keim 1997). However, when summer temperatures are higher than normal, a contrasting situation develops where the Bermuda High intensifies and expands due to an increased gradient between land and sea temperatures (Coleman 1988). This situation leads to subsidence of more stable air as the tropical easterlies are forced westward, and consequently drier conditions occur in Florida (Coleman 1988). Research from Stahle and Cleaveland (1992) confirms this mechanism with composite analyses of sea level pressure during the 10 driest and 10 wettest periods from the early 20th century to the mid-1980s along the Atlantic Coast, showing westward ridging during dry extremes and contraction eastward during wet extremes.

Trends in the strength and positioning of the Bermuda High and the implications for summer precipitation in the Southeast have also been examined. Using 850 hPa geopotential heights from National Centers for Environmental Prediction (NCEP) and European Centre for Medium Range Weather Forecasts (ECMWF) ERA-40 reanalysis datasets, Li et al. (2011) show that the center of the Bermuda High has shifted westward and the intensity has increased since the late 1970s. The north-south position of the western ridge also influences precipitation, and Li et al. (2011) suggest that the ridge has expanded over the last 30 years. During periods when the western ridge is positioned in a more northerly location, Southeast summer precipitation decreases, and when it is positioned towards the south, summer precipitation tends to increase (Li et al. 2011). However, other studies (e.g. Diem 2013) have contradicted these findings and consequently continued research is warranted.

The Bermuda High has been quantified with the Bermuda High Index (BHI) (Stahle and Cleaveland 1992). The BHI is defined as the difference between normalized sea level pressures in Bermuda and New Orleans, Louisiana (Stahle and Cleaveland 1992) where positive values are indicative of strong southerly flow in the western Atlantic and increased moisture advection into the Southeast, along with reduced atmospheric stability (Henderson and Vega 1996). Negative values indicate weaker southerly flow in the western Atlantic (Henderson and Vega 1996).

While studies relating precipitation and BHI are somewhat limited in number, conclusions drawn from these studies tend to agree. Henderson and Vega (1996) showed strong correlations between the BHI and seasonal precipitation in the southern USA, suggesting that even during the winter, subtropical circulation patterns are important in determining precipitation patterns in the Southeastern USA. During the spring, positive correlations between BHI and precipitation indicate that a stronger Bermuda High results in increased moisture advection into the region. Similar results based on reconstructed spring precipitation were found for North Carolina, South Carolina, and Georgia (Stahle and Cleaveland 1992), as well as relationships with soil moisture deficits in the southern USA (Doublin and Grundstein 2008) and drought variability (Ortegren et al. 2011). Diem (2006) examined wet versus dry 13-day periods from 1953 to 2002 in the greater Atlanta metropolitan area, and found that wet periods are associated with troughing and negative geopotential height anomalies in the Midwest and Southeast, and dry periods are associated with ridging and positive geopotential height anomalies in the interior Southeast. However, the BHI was more strongly correlated with dry than with wet period frequency (Diem 2006). While these studies provide evidence of the importance of subtropical circulation as a factor in precipitation regimes of the Southeast, research by Keim (1997) shows a very weak relationship between BHI and seasonal heavy precipitation events. As Keim (1997) suggests, precipitation patterns are not solely explained by the existence of precipitable water, and it is important to consider other factors.

I.2.3.4 Tropical Cyclones

Tropical cyclones (TCs) are a common occurrence in the Southeast region during the hurricane season (June through November). Spatial and temporal patterns of landfalling TCs in the Southeast have been studied by multiple sources and results can be dependent on the methods used to identify landfalling locations (Muller and Stone 2001; Keim, Muller, and Stone 2007; Elsner and Kara 1999; Simpson and Lawrence

1971). The most active areas for landfalling TCs in the USA over the past century include the northern Gulf Coast, south Florida, and the Outer Banks of North Carolina, with tropical cyclone (regardless of intensity) return periods of 3 to 4 years for the northern Gulf Coast, 3 yr for south Florida, and 2 to 3 years for the Outer Banks (Keim, Muller, and Stone 2007). Major hurricanes classified as greater than Category 3 on the Saffir-Simpson scale, are most frequent in south Florida, with return periods of between 13 and 18 years (Keim, Muller, and Stone 2007). Property loss data presents similar findings with the most losses occurring in Florida, followed by North Carolina from 1949 to 2006 (Changnon 2009).

Research into the contemporary hurricane record shows significant spatiotemporal variability. Some regions tend to experience frequent events for a period of time while another region experiences very little activity during the same period (Muller and Stone 2001). For instance, south Florida had many landfalling TCs in the 1920s to the 1940s, but very little activity in the 1960s to 2005 (Muller and Stone 2001; Keim, Muller, and Stone 2007). Unlike south Florida, North Carolina experienced more activity during the 1950s and 90s (Keim, Muller, and Stone 2007; Muller and Stone 2001). Keim, Muller, and Stone (2007) report that region-wide (south Texas to north Maine), the 1920s to 1960s and 1995 to 2005 have been the most active periods over the past century. The ENSO has been linked to spatiotemporal patterns of landfalling TCs (Muller and Stone 2001). Figure 4 depicts the number of TCs making landfall in the Southeast from 1900 to 2008, along with the 10 year moving average.

Relationships between TC activity and large-scale circulation variability are an active area of research. Elsner, Kara, and Owens (1999), in a time series analysis to determine modes of oscillation in hurricane frequency, found a biennial oscillation on the scale of 2.5 years related to the Quasi-Biennial Oscillation (QBO), a semidecadal oscillation on the scale of 5 to 6 years related to the ENSO, and a near decadal oscillation of 7 to 9 years. Earlier research also suggests relationships between the QBO and tropical cyclone activity in the Atlantic (e.g. Gray 1984, Shapiro 1989, Landsea et al. 1998). Likewise, other studies have shown a link between the ENSO and tropical cyclone activity in the Atlantic, including Gray (1984), Shapiro (1987), Landsea et al. (1998), and Emanuel, Sundararajan, and Williams (2008). However, the ENSO and QBO, while important, are not necessarily sufficient to explain tropical cyclone activity as suggested by Lander and Guard (1998). SSTs in the North Atlantic (Goldenberg et al. 2001), the Arctic Oscillation (AO) and western Sahelian precipitation (Gray 1990; Landsea et al. 1992), as well as interactions with other teleconnections like the ENSO (Larson, Zhou, and Higgins 2005), are among other influential factors in tropical cyclone activity impacting the Southeast.

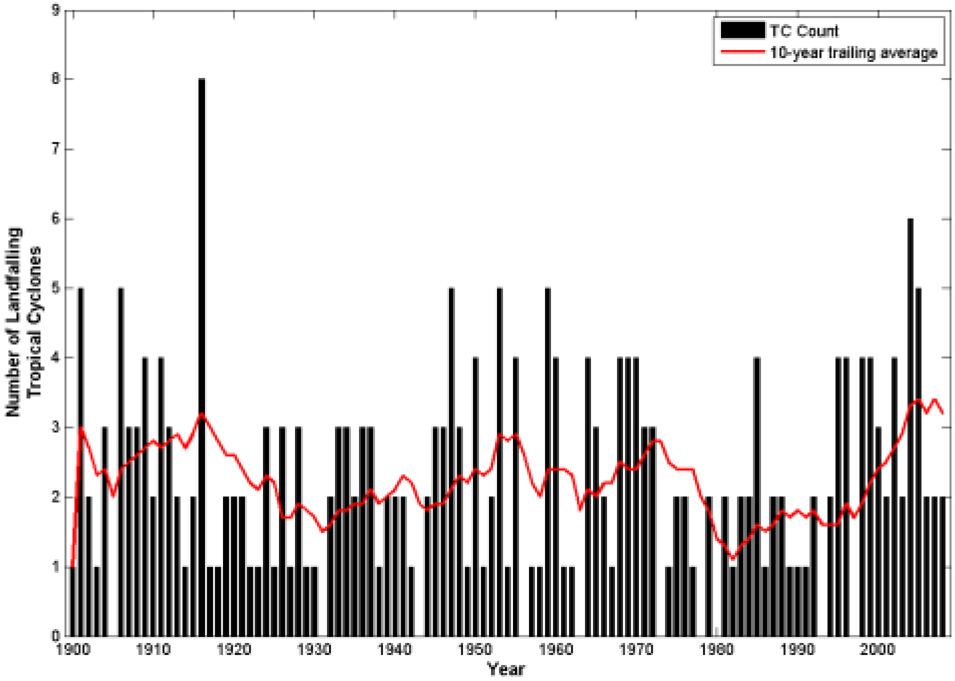


Figure 4. Number of landfalling TCs in the Southeast, 1900-2008. TC counts are derived from the HURDAT dataset and landfalling TCs are determined using the same procedure as Zhu and Quiring (2013). The 10-year average is a trailing average. Prior to 1909, the average is determined based on available years.

Landfalling TCs are known to contribute potentially significant amounts of precipitation to the Southeastern USA. While obviously devastating in terms of losses of life and property, TCs aid in replenishing reservoirs, lakes, groundwater, and streamflow as well. Spatial and temporal patterns of tropical cyclone-induced precipitation in the Southeast have been examined by both Knight and Davis (2007) and Nogueira and Keim (2011). As expected, coastal areas receive the most tropical cyclone-induced precipitation with declining values inland; the Appalachian Mountains acting as a topographic barrier with increased local precipitation along the windward slopes (Knight and Davis 2007; Nogueira and Keim 2011). In an analysis of station data from 1980 to 2004, Knight and Davis (2007) found that precipitation associated with tropical cyclones accounts for as much as 14 to 16% of total hurricane season rainfall in the Carolinas, and between 8 and 14% along the Gulf Coastal Plain and Piedmont. Broadly similar patterns were found by Nogueira and Keim (2011) over the period 1960-2007 with 12 to 14% of total hurricane season precipitation along the Atlantic Coast into Florida, and 8 to 12% along the Coastal Plain and Piedmont, the highest values being in the extreme south of Texas and an isolated portion of coastal North Carolina.

For the Southeast as a whole, TC-precipitation contributes the most to monthly precipitation totals during September, with relatively small contributions made at the beginning and end of the hurricane season in June and November, respectively, due to fewer tropical systems making landfall (Nogueira and Keim 2011; Knight and Davis 2007). In fact, Nogueira and Keim (2011) demonstrate that there is much less TC activity in June and November, and that September experiences the greatest amount of TC activity. This agrees with the findings of Knight and Davis (2007). During June, most TC-associated precipitation is associated with the western and central Gulf Coasts (Knight and Davis 2007). It is not until July and August that significant TC-precipitation is seen along the Atlantic Coast (Knight and Davis 2007). During September, an area stretching from eastern Georgia to southern Virginia receives >24% of its mean monthly precipitation from tropical cyclones (Knight and Davis 2007). Nogueira and Keim (2011) suggested that this peak in September precipitation attributable to TCs may be more limited to North Carolina and Virginia, in addition to an area of south Alabama. By November, TC-precipitation is mostly confined to Florida (Knight and Davis 2007; Nogueira and Keim 2011).

Estimates of TC-induced precipitation have also been obtained using satellite observations. Rodgers, Adler, and Pierce (2001) used passive microwave imagery from the Special Sensor Microwave Imager to estimate TC-induced precipitation in the North Atlantic and found that portions of the Southeast may receive 10% of hurricane season precipitation from tropical cyclones, but as little as 1 to 5% in other areas of the region. Other studies have also used satellite imagery to determine tropical cyclone-induced precipitation (e.g. Cerveny and Newman 2000, Lau and Wu 2007). While the previous studies broadly agree, there are some differences that are likely due to the use of different datasets (e.g. station versus satellite-derived), methodologies (e.g. determining what constitutes TC precipitation), and spatial and temporal scales of analysis. Regardless of the differences, these studies all demonstrate the importance of tropical cyclone-induced precipitation to the sustainability of water resources in the Southeast, and that this contribution varies significantly over time and space.

Trends in TC-induced precipitation explain a significant amount of variation in precipitation in the Southeast. Knight and Davis (2007) found statistically significant increasing trends in TC-induced precipitation along the East Coast and along the Gulf Coast as far as southeastern Louisiana. In contrast, they found only weak trends in non-TC-induced precipitation in the region. In a robust follow-up study using multiple measures and datasets to characterize extreme precipitation attributable to tropical cyclone activity, Knight and Davis (2009) found that positive trends in extreme precipitation were primarily attributable to tropical cyclones. Others have also found similar positive trends in TC-precipitation. From 1994 to 2008, the number of heavy precipitation events attributable to TCs doubled as compared to the long-term average of 1895 to 2008 (Kunkel et al. 2010). This can be partly explained by the increases in landfalling TCs. However, Kunkel et al. (2010) point out that the increase in landfalling TCs is not enough to account for all of the increase in TC-associated heavy precipitation events. Shepherd, Grundstein, and Mote (2007) developed a heavy precipitation metric, termed the millimeter day based on the same concept behind heating degree-days and cooling degree-days. Shepherd, Grundstein, and Mote (2007) found that wet millimeters days (extreme precipitation days) are strongly correlated with major hurricanes (Categories 3-5) in the Southeast over the period 1998-2006. More localized studies have also been performed examining trends in TC-precipitation. For instance, Konrad and Perry (2010) examined TC-precipitation in the Carolinas and found that along the coastal plain and eastern Piedmont, the vast majority of heavy precipitation vents from 1950 to 2004 were associated with TCs.

Landfalling TCs cause extensive injuries, loss of life, and economic damage from storm surge, high winds, inland flooding, and severe weather. Changnon (2009) analyzed hurricanes categorized as catastrophes, those costing >$1 million in insured property, and found that 50 of the 79 hurricanes analyzed from 1949 to 2006 occurred within the boundaries of the Southeast. The Galveston Hurricane of 1900 was responsible for the most deaths in USA history (~8000) followed by the Lake

Okeechobee Hurricane in 1928 (~2500). From an economic loss standpoint, Hurricane Katrina was responsible for the largest economic losses, followed by Hurricane Andrew in 1992 (adjusted for inflation; Blake, Landsea, and Gibney 2011). Inland flooding is the biggest threat to lives and property (Rappaport 2000). For instance, almost 200 deaths were recorded as a result of inland flooding from Hurricane Diane in 1955 (Rappaport 2000).

Despite their destructiveness, tropical cyclones are an important source of precipitation to the region. To underscore the importance of TC-induced precipitation for water resources, Knight and Davis (2007) calculated soil moisture deficits during the hurricane season with TC precipitation removed. Results show significant increases in soil moisture deficits, with a 16 to 32% deficit in much of the region with isolated areas of higher deficits. Tropical cyclones have the ability to alleviate drought conditions. Maxwell et al. (2012)examined the impact of TCs on drought conditions in the Atlantic southeast from 1950 to 2008 and found that ~1 in 5 droughts were ended by TC precipitation (Maxwell et al. 2012). These ‘drought busters’ can end both short-term agricultural droughts and long-term hydrological droughts (Maxwell et al. 2012). Two examples of TCs that have alleviated drought conditions in the Southeast include Tropical Storm Marco in 1990 and more recently Tropical Storm Alberto in 2006, which both provided relief from moderate drought along the Atlantic Coast states in the span of 24 to 48 hr (Maxwell et al. 2012). The link between tropical cyclones and soil moisture deficits/droughts has not been well explored, but represents a critical and unique component in Southeastern hydroclimatology.

I.2.3.5 Conclusions

This study provides an overview of the hydroclimatic characteristics of the Southeastern USA and reviews the primary factors that influence seasonal to interannual variability. The Southeast has a humid climate with an abundance of precipitation. Recent studies however, suggest that the region is characterized by significant precipitation variability marked by heavy, intense precipitation, interspersed with dry periods. Consequently, both floods and drought may become more common in the future.

Major atmospheric controls on Southeast hydroclimatology include phases of ENSO, PNA, and the Bermuda High. Warm El Niño phases lead to positive precipitation anomalies in much of the region, while cold La Niña phases result in negative precipitation anomalies. Positive phases of PNA result in zonal flow, altering tracks of midlatitude cyclones and thereby influencing the precipitation patterns within the region. The Bermuda high influences moisture advection into the region and usually takes place in the Atlantic Coast states giving rise to increased precipitation and at times, heavy precipitation. The Bermuda High, however, can expand and intensify such that troughing is pushed farther west and ridging takes place along the Atlantic Coast and eastern parts of the region leading to drier conditions in the eastern half of the region and wetter conditions along the margins of the western edge of the anticyclone.

Despite their destructive potential, TCs contribute heavily to the Southeast’s annual precipitation and are fundamental to the region’s hydroclimatology. TC-induced precipitation plays a significant role in the spatial and temporal patterns of water resources throughout the region, especially in coastal and near coastal areas. TC-precipitation accounts for a significant proportion of precipitation in many locations in the Southeast, and a lack of it can lead to serious soil moisture deficits and droughts. Consequently, TCs have the potential to alleviate drought conditions. Increasing trends in TC-induced precipitation are present throughout parts of the region.

I.3 Fire History and Climate Interactions

I.3.1 Fire History

Fire has been a component of Southeastern USA landscapes for thousands of years (Lafon 2010; Fowler and Konopik 2007), dating back to Clovis and paleo-Indian populations (Fowler and Konopik 2007). A number of sources have documented Native American burning (Whitney 1994), sometimes widespread, including Denevan (1992), Kay (2007), Mann (2011), and many others. Prior to European settlement, Native Americans altered the eastern USA forests by burning for agriculture, hunting, and gathering among other activities (Denevan 1992; Fowler and Konopik 2007). Anecdotal evidence provides documentation of wildfire in the Southeast. Early explorers recorded in their journals large wildfires along the coastal plain from Virginia to Florida (Pyne 1982). In the same region, search parties sailed from wildfire to wildfire thinking they could be signal fires from Raleigh's lost colonists (Pyne 1982). European settlers to the Southeast evidently learned such intentional burning practices and continued the use of fire in land management practices as it was critical to the success of the Southern agrarian economy (Pyne 1982; Otto and Anderson 1982). With the advent of industrial logging in the late 19th century, more modern industrial forestry fire practices came into conflict with the traditional frequent broadcast burning of the Southern agrarian economy (Pyne 1982). Fires were common as both slash accumulation from industrial logging and arson directed at forestry companies and government agencies became the norm (Lafon 2010). Such widespread burning helped convince federal and state forestry agencies to implement extremely successful suppression policies beginning in the early 20th century (Lafon 2010; Pyne 1982). Ultimately however, fire became and is still becoming recognized for its use as a tool in forest management (Lafon 2010; Pyne 1982)

These fires played an integral role in the creation of vegetation patterns in the region. Frequent fires contributed to the development of oak and pine forests in much of the eastern USA, which are often succeeded by more shade-tolerant species in the absence of fire (Abrams 1992; Nowacki and Abrams 2008; Aldrich et al. 2010; Hoss et al. 2008). Some argue (e.g. Kay 2007) that lightning fires were not in sufficient quantities to alter vegetation composition and therefore anthropogenic ignitions were of critical importance. For instance, Rostlund (1957) argued for the existence of a "crescent-shaped" grassland belt in Alabama and Mississippi maintained by fires often set by Native Americans. Mast and fruit trees, in addition to strawberries, blackberries, raspberries, and blueberries, were cultivated by American Indians in part, through the use of fire (Abrams and Nowacki 2008). Spatial distributions of pre-European settlement Georgia Piedmont vegetation has also been linked with fire (Cowell 1995). Longleaf pine long-dominated the coastal plain of the Southeast from Virginia to Texas and was dependent upon frequent fire for regeneration (Frost 2006; Greene 1931; Chapman 1932).

I.3.2 Fire-Climate Relationships

I.3.2.1 Western United States

Climate-wildfire interactions are studied extensively in the western United States and while there are many unanswered questions still, there are a number of important relationships that have been uncovered. One of the more common relationships is of that between antecedent moisture and wildfire activity. Within the semi-arid to arid West, periods of above average precipitation increase biomass production. If followed by a return to average or even below average precipitation conditions, the new biomass dries out and provides fuels for ignitions and spread (Crimmins and Comrie 2004; Westerling et al. 2003). However, there is spatial and temporal variability within this broad generalization (Westerling et al. 2003; Littell et al. 2009) often driven by vegetation composition and/or fuel type. It has been demonstrated that forested ecosystems are often associated with below normal precipitation, drought, and above average temperature concurrent with fire activity (Westerling et al. 2003; Littell et al. 2009). While grassland ecosystems require antecedent wet conditions as previously noted (Littell et al. 2009; Westerling et al. 2003; Crimmins and Comrie 2004). For instance, fire activity in southern California is influenced by high precipitation amounts the year prior to fire activity (Keeley 2004). However, current environmental conditions can override antecedent climate in the case of the Santa Ana winds in southern California (Keeley 2004). Even within the same montane zone, for instance, fire activity may differ between elevations as evidenced by Sherriff and Veblen (2008) where low elevation fires in the northern Colorado Front Range require antecedent wet conditions for fine fuel accumulation, yet high elevations require current drought for high fire activity. Other studies have also linked drought and antecedent moisture conditions with wildfire activity in Yellowstone National Park (Balling, Meyer, and Wells 1992), the Pacific Coast (Trouet et al. 2006), and South Dakota (Brown 2006) among others.

The intra-annual, inter-annual, and decadal variability in precipitation and drought are often associated with large scale oceanic-atmospheric oscillations. Teleconnections such as ENSO, provide a regional control over precipitation variability on multiple timescales. Swetnam and Betancourt (1990) found that high values of the Southern Oscillation Index led to drier springs and a more active fire season with larger fires in the summer and vice versa throughout the Southwest. Other studies have found similar results (e.g. Brown et al. 2008). In other locations of the western USA, ENSO has different effects. For instance, in the Pacific Northwest, fire activity peaks during El Niño phases as dry conditions dominate and fire activity declines during La Niña phases (Heyerdahl, Brubaker, and Agee 2002).

In addition to ENSO, other teleconnections have proven to be useful in understanding spatial and temporal variability in western US fire activity. Trouet et al. (2006) observed a high pressure ridge, similar to that created by positive phases of the Pacific North American (PNA) pattern and Pacific Decadal Oscillation (PDO), associated with years with large wildfires in national forests of Washington, Oregon, and California. Brown (2006) found regional wildfire activity in the Black Hills National Forest of South Dakota to be strongly associated with cold phases of ENSO, cold phases of the PDO, and warm phases of Atlantic Multidecadal Oscillation (AMO) leading to decreased precipitation and subsequently drier conditions. The importance of concurrent phases of cold ENSO, cold PDO, and warm AMO has also been identified by Sibold and Veblen (2006). La Niña phases were also found to be influential in regional wildfire activity in Utah, often being magnified when cool phases of PDO occurred simultaneously (Brown et al. 2008). Such studies examining interacting teleconnections are an important direction for fire climatology research as they provide detailed insights into the mechanisms of these relationships.

I.3.2.2 Southeastern United States

A general conceptual model proposed by Sauer (1950) and later by Meyn et al. (2007) and Parisien and Moritz (2009) relating climatic moisture gradients and wildfire suggests that intermediate climates are most prone to burning. If these relationships are viewed on a continuum, one side of the continuum is a very dry climate, while the other side is a very wet climate. Areas prone to climatically dry conditions (e.g., the arid southwest USA) do not burn frequently as they lack sufficient fuel and are therefore fuel quantity limited. Areas prone to climatically wet conditions (e.g., tropical rainforests) do not burn frequently either. While possessing adequate fuel, these areas do not experience the dry conditions necessary for ignitions and are therefore fuel moisture limited. Instead, it is the middle of the spectrum or the intermediate climates that are most prone to burning. Such climates possess both adequate precipitation, which leads to abundant fuels, and periodic dry periods, which leads to low fuel moisture necessary for wildfire. This dissertation suggests that the southeastern United States represents an intermediate climate – one that is certainly not too dry to inhibit fuel accumulation and yet still experiences periodic dry conditions necessary for ignitions.

Much like the western USA, droughts, or dry periods in general, are the most commonly identified climatic association with wildfire activity in the southeastern USA. Central Appalachian wildfire activity and PDSI are negatively correlated suggesting that drought conditions lead to increased fire (Lafon, Hoss, and Grissino-Mayer 2005). Positive correlations, however, were not observed (Lafon, Hoss, and Grissino-Mayer 2005), contrasting with the western USA where anomalously wet periods are, in some locations required to accumulate fuel prior to burning in dry years (Westerling et al. 2003; Littell et al. 2009). There is also a spatiotemporal variability component in this relationship. Mitchener and Parker (2005) highlight this relationship between drought and fire activity in the Southeast. While fire season PDSI was a significant predictor of wildfire activity across various sub-regions of the Southeast, relatively warmer and drier areas like the Piedmont and Coastal Plain respond to drought relatively quicker as opposed to the wetter areas like the Appalachian Highlands that may require drought for up to a year before a fire response occurs (Mitchener and Parker 2005).

While the previously discussed conceptual models by Sauer (1950), Meyn et al. (2007), and Parisien and Moritz (2009) use climatic means (such as mean annual precipitation) to define wet and dry climates, precipitation variability can also be included. It is hypothesized that within the humid Southeast, climates with more variable precipitation regimes experience more dry periods and are consequently more prone to burning. Locations in the Southeast with less variable precipitation regimes experience less frequent dry periods and are therefore not as prone to wildfires. As evidence of the value in using precipitation variability to understand spatiotemporal wildfire-climate relationships in the Southeast, fire regimes across the Appalachian Plateau, Ridge and Valley, and Blue Ridge physiographic provinces of the central Appalachian Mountains were examined, and differences in spatial patterns of fire across the three regions are attributed in part to differences in intra-annual precipitation regimes (Lafon and Grissino-Mayer 2007). All three provinces receive approximately equal amounts of annual rainfall, but the Blue Ridge receives more infrequent, heavy rainfall events and high densities of wildfire ignitions suggesting that the Blue Ridge experiences long, frequent dry periods conducive to burning whereas the Appalachian Plateau receives frequent, low intensity rainfall events that inhibit wildfire occurrence (Lafon and Grissino-Mayer 2007). Further evidence comes from the analysis of wildfire activity in 34 federal lands of the eastern USA (Lafon and Quiring 2012). Daily precipitation variability expresses a strong relationship with both mean annual area burned and mean annual fire density (Lafon and Quiring 2012). In particular, the Southeast expressed both high precipitation variability and high wildfire activity suggesting that despite a humid climate, as defined by mean annual precipitation, the Southeast still burns in part due to a variable precipitation regime (Lafon and Quiring 2012).

As demonstrated by these works, wildfire-climatic relationships are not solely a function of mean annual precipitation. Instead, precipitation variability must also be considered. Much of this intra-annual, inter-annual, and decadal climatic variability is explained by shifting phases of large scale teleconnections, which will be discussed below. Lafon and Grissino-Mayer (2007) and Lafon and Quiring (2012) represent two of the only studies in the southeastern United States that identify precipitation variability as a potential climatic driver of spatial and temporal patterns of wildfire activity. Beyond these studies, precipitation variability has not been adequately addressed in the context of wildfire activity and yet studies have suggested that future shifts in climatic variability will have a significant influence on ecosystem processes, including phenology, nutrient cycling, and primary productivity (Fay et al. 2003; Fay et al. 2008; Jentsch and Beierkuhnlein 2008). Chapter II of this dissertation expands upon the work of Lafon and Grissino (2007) and Lafon and Quiring (2012) by examining additional national forests in the Southeast, as well as extending the characterization of precipitation regimes in the Southeast to gridded precipitation data.

The effect of teleconnections on wildfire activity in the Southeast has not been well documented. The one exception to this generalization is the influence of ENSO on wildfire activity in Florida. Inverse correlations between Pacific SSTs and area burned in Florida have been found suggesting that La Niña conditions play a role in driving increased fire activity (Brenner 1991). Further studies have confirmed such findings. Harrison and Meindl (2001) examined synchronous and lagged relationships between ENSO and wildfire activity. While no statistically significant results were uncovered between the two on a synchronous scale, statistically significant results were uncovered on a one year lagged timescale (Harrison and Meindl 2001). This suggests that the occurrence of ENSO may play an important role in conditioning the landscape in Florida to experience burning at some later time (Harrison and Meindl 2001). Beckage et al.

(2003) found that during La Niña periods in the Everglades, below average dry season precipitation was prevalent, lowering surface water levels, and allowing for an increase in the number of fires and area burned. Likewise, the opposite relationship was found between El Niño or warm ENSO phases and decreased wildfire activity (Beckage et al. 2003), a conclusion also supported by Simard, Haines, and Main (1985). Statistical models predicting wildfire activity in the Everglades have also been developed with the use of ENSO (Beckage and Platt 2003). Previous studies have examined contemporary fire occurrence records; however, analyses on longer timescales often require fire-scarred chronologies. Fire scar data from the Florida Keys demonstrates the influence of ENSO as detailed previously (Harley et al. 2014). Interactions between phases of the Interdecadal Pacific Oscillation (IPO) and ENSO suggest that El Niño phases can be aided by positive phases of IPO and PDO (Harley et al. 2014). Such interactions were associated with increased biomass accumulation 3 years prior to fire activity, which is the type of antecedent relationship often seen in the western US (Harley et al. 2014). No relationships were demonstrated between fire activity and AMO or NAO (Harley et al. 2014).

A limited number of studies have examined other teleconnections in addition to ENSO. Relationships were found between ENSO, NAO, PDO, and PNA and wildfire activity in Mississippi (Dixon, Goodrich, and Cooke 2008). In particular, researchers suggested that teleconnection indices, such as ENSO and NAO during the late summer and early fall may provide a lead time in predicting winter wildfires (Dixon, Goodrich, and Cooke 2008). Many of these correlations are statistically weak however and further research is warranted (Dixon, Goodrich, and Cooke 2008). Goodrick and Hanley (2009) confirmed previous analyses exploring the relationship between ENSO and Florida wildfire activity. Correlation analysis with PNA and NAO revealed fewer relationships (Goodrick and Hanley 2009). However, stratifying area burned data by both ENSO and PNA phase show that over a third of the area burned occurs during a cold ENSO and a negative PNA phase (Goodrick and Hanley 2009). Interestingly however, positive phases of PNA showed the greatest variability in area burned and maximum area burned suggesting that both phases of PNA may influence fires in Florida (Goodrick and Hanley 2009). The influence of teleconnections is typically manifested in the frequency of weather and synoptic types, which have also been linked with fire in the region (Heilman 1995; Brotak and Reifsnyder 1977), however these studies are dated as mentioned previously. Despite these studies, the exact mechanisms of teleconnection influence on wildfire activity in the region remains relatively unexplored. Chapter III of this dissertation examines relationships between wildfire weather types, as well as teleconnections. Chapter IV explores the synoptic patterns associated with wildfire activity using a synoptic typing scheme.

I.4 Study Region

This research defines the southeastern United States as the states of Mississippi, Alabama, Georgia, Florida, South Carolina, North Carolina, Tennessee, Kentucky, Virginia, and West Virginia (Figure 5). Because wildfire occurrence data are readily available for national forests and because wildfires are more apt to occur in these areas, all federally-managed national forests are used in the analysis. A total of 25 national forests are used in this dissertation (specific national forests are listed in subsequent chapters).Chapter II uses all 25 national forests whereas Chapters 3 and 4 focus on the national forests located within the central Gulf Coast, a region defined as Mississippi, Alabama, and the panhandle of Florida.

The southeastern United States covers a variety of physiographic provinces, including the Appalachian Mountains (Appalachian Plateau, Ridge and Valley, Blue Ridge), Piedmonts, and Coastal Plain, each with their own unique topography and distribution of vegetation. Low relief and meandering river valleys in the Coastal Plain give way to rolling hills in the Piedmonts and higher elevations and harsher terrain in the Appalachian Mountains. Mixed mesophytic forests span from the northern edge of the study region in West Virginia along the Appalachian Mountains (Delcourt and Delcourt 2000). Beech (*Fagus*), magnolia (*Liriodendron*), maple (*Acer*), chestnut (*Castanea*), and oak (*Quercus*) species exist in the valleys, while a mix of *Quercus* and pine (*Pinus*) species dominate the ridge tops (Delcourt and Delcourt 2000). Western mesophytic forests in the western portion of the study area of Kentucky and Tennessee marks the transition to less diverse forests dominated by *Quercus* and hickory (*Carya*) species (Delcourt and Delcourt 2000). *Quercus-Castanea* forests dominate the eastern Appalachians from Virginia into western North Carolina and eastern Tennessee (Delcourt and Delcourt 2000). Generally following the Piedmonts from eastern Virginia to central Mississippi, an association of *Quercus* and *Pinus* dominate forests (Delcourt and Delcourt 2000). A diverse array of grasslands, savannas, *Pinus* and hardwood forests, and wetland communities inhabit the Coastal Plain (Christensen 2000). The diversity, seen over short horizontal and vertical distances, is attributed to a combination soil characteristics and disturbances, including fire (Christensen 2000).

Figure 5. Southeast United States study region.

CHAPTER II

PRECIPITATION-WILDFIRE RELATIONSHIPS

II.1 Introduction

Spatial variability in climate can influence spatial patterns of disturbance regimes and consequently vegetation patterns on a variety of scales from global-scale (e.g. Bond and Keeley 2005, Bond, Woodward, and Midgley 2005) to landscape-scale (e.g. Harmon, Bratton, and White 1983) and to stand-scale (e.g. Parker, Parker, McCay 2001). Of particular interest in this chapter is how spatial variability in precipitation regimes influence spatial patterns of fire in the southeastern United States. There are a number of factors influencing such a complex phenomena as fire, including vegetation composition and structure, topography, and land management policies (Bond and van Wilgen 1996; Krawchuk et al. 2009; Pyne 1982). However, climate often plays a dominant role (Meyn et al. 2007) dictating spatiotemporal patterns of fire (Krawchuk et al. 2009; Hawbaker et al. 2013). Climate impacts a number of important ignition components (Bond and van Wilgen 1996; Krawchuk et al. 2009). Long-term climate dictates vegetation composition and therefore fuel type and availability. Climate on short to intermediate timescales influence moisture conditions, which in turn influence fuel moisture. Lightning also acts as an important ignition source.

There is currently a need for studies examining how spatial patterns of fire vary over environmental gradients on broad spatial scales (Parisien and Moritz 2009). A conceptual model proposed by Meyn et al. (2007) suggests that climate is a "superordinate" control on the relative influence of fuel moisture and fuel quantity related to large, infrequent fires. On one end of the spectrum, ecosystems that possess abundant vegetation and are always wet (e.g. rainforest) do not burn frequently as they are fuel moisture-limited (Meyn et al. 2007). On the other end of the spectrum are ecosystems that are always dry and lack vegetation (e.g. deserts); these ecosystems rarely burn as they are fuel quantity-limited (Meyn et al. 2007).

Instead, ecosystems that fall between the two extremes are the most prone to fire. There is still, however, significant variability along such a continuum. Meyn et al. (2007) identifies three categories of ecosystems prone to fire. Ecosystems can lack significant vegetation and be seasonally dry or rarely dry making them fuel quantity-limited (fuel moisture-limited as well, in the case of rarely dry ecosystems) (Meyn et al. 2007). Antecedent wet conditions are often required in order to accumulate sufficient biomass for burning (Littell et al. 2009; Crimmins and Comrie 2004). In addition to these two categories, ecosystems can have abundant vegetation and are rarely dry whereby they are fuel moisture limited (Meyn et al. 2007). Drought conditions are often associated with burning in these locations (Lafon, Hoss, and Grissino-Mayer 2005; Mitchener and Parker 2005; Kitzberger, Veblen, and Villalba 1997; Trouet et al. 2006).

While mean moisture conditions may help explain some of the variability seen in spatial patterns of wildfire, it is important to also consider variability in precipitation regimes. One of the limitations of the model proposed by Meyn et al. (2007) is that it does not consider, among other factors, climatic variability. Lafon and Grissino-Mayer (2007) examined spatial patterns of fire and climate in the central Appalachians and found differences in fire regimes potentially related to differences in precipitation variability. While experiencing similar total annual precipitation amounts, the Appalachian Plateau and Blue Ridge physiographic provinces possess very different fire regimes. In the westernmost Appalachian Plateau, where conditions are cool, moist, and possess less-flammable vegetation, fires are rare. However, in the easternmost Blue Ridge, fires are much more frequent. Authors suggest that this difference in fire regime may be at least in part a product of precipitation variability where the Appalachian Plateau receives frequent, low intensity rain events and the Blue Ridge receives infrequent, high intensity precipitation events creating more frequent dry periods conducive to burning (Lafon and Grissino-Mayer 2007). Precipitation variability has been identified as a critical component in ecosystem processes and may become even more influential under future climate change scenarios (Fay et al. 2003; Fay et al. 2008; Jentsch and Beierkuhnlein 2008).

Lafon and Quiring (2012) investigated the relationship between fire and moisture regimes in the eastern USA. Positive correlations were uncovered between daily precipitation variability and both ignition density and area burned. In fact, daily precipitation variability was found to be more strongly associated with fire activity than mean annual moisture balance suggesting that variability in precipitation regimes, not mean conditions, are more influential in understanding the climatic drivers of spatial patterns of fire.

This chapter also examines the spatial patterns of precipitation regimes and precipitation variability as they relate to wildfire activity. By doing so, this research expands upon the work of Lafon and Quiring (2012) by focusing explicitly on the southeast region of the United States and including national forests and ranger districts not included in the original work. Lafon and Quiring (2012) also use only one station to represent precipitation regimes within a given national forest. This study characterizes precipitation regimes using more than one station to represent each national forest and also uses a gridded precipitation product to better account for the topographic variability of the central and southern Appalachians.

II.2 Data and Methods

II.2.1 Study Region

The southeastern USA is a humid climate. Locations east of the Appalachian Mountains are drier relative to areas in the Gulf Coast states and Florida. Significant snowfall accumulation is limited to areas in the central and southern Appalachians (Soulé 1998). Temperatures are mild to hot most of the year with mean January temperatures dropping below freezing in the Appalachians and northern areas of the region (Soulé 1998). Southeastern national forests are mapped in Figure 6. National forests capture a range in climatic regimes from Florida to the central and southern Appalachian Mountains. A variety of ecosystems are represented in the region as well.

Figure 6. Southeastern United States national forests examined in Chapter I.

II.2.2 Data

II.2.2.1 Wildfire Occurrence Data

Wildfire occurrence data were obtained from the National Interagency Fire Management Integrated Database (NIFMID; USFS 1998). This database contains records for each individual fire occurring on federally managed lands, including ranger district, date of ignition, cause, and area burned. The NIFMID dataset has been employed in previous studies in the Southeast, including Lafon and Grissino-Mayer

(2007), Lafon, Hoss, and Grissino-Mayer (2005), and Lafon and Quiring (2012). A total of 25 national forests were identified for further analysis in Figure 6. Ignition data from 1970-2011 and area burned data from 1986-2011 are extracted from each national forest. Mean annual ignition density (1970-2009) and mean annual area burned (1986-2011) are calculated and reported on a per 400,000 ha basis. Some national forests are subdivided into ranger districts for administrative purposes. A subset of ranger districts were selected based on availability of NIFMID data, identifying stations for precipitation data, and ease in determining the land area needed for reporting fire variables on a per 400,000 ha basis. The same wildfire variables are calculated for a subset of these ranger districts and included in the analysis.

II.2.2.2 Precipitation Data

Global Historical Climatology Network (GHCN) data (Menne et al. 2012) were obtained from the National Climatic Data Center (NCDC; http://www.ncdc.noaa.gov/oa/climate/ghcn-daily/). Both daily and monthly data were downloaded from 1970-2011. Individual stations were assigned to a particular national forest. Stations were selected for their proximity to a national forest (generally within 10 miles of the national forest or within forest boundaries), completeness of record (≤10% missing data) and length of record (1970-2011). Every effort was made to select stations within forest boundaries and around the perimeter of the national forest to represent the precipitation regime within the forest. However, the spatial distribution/availability, record completeness, and record length of stations are highly variable and can be limiting in the more rural areas of the Southeast.

In addition to station data, total monthly precipitation data from the parameter-elevation regression on independent slopes model (PRISM) were downloaded and are available from http://www.prism.oregonstate.edu/. The 4 km gridded precipitation product is developed using a weighted regression model using station data and digital elevation models (DEMs) (Daly et al. 2002; Daly et al. 2008). PRISM takes into account a variety of factors affecting precipitation including topography and proximity to coasts (Daly et al. 2002; Daly et al. 2008). One of the main advantages of using PRISM is that it is designed to represent precipitation in mountainous areas such as the southern and central Appalachian Mountains. Using both station data and gridded data minimizes the limitations of using a single dataset and provides a more robust characterization of precipitation regimes in the Southeast.

II.2.3 Analysis

The precipitation regime of each national forest was determined using the stations assigned to each national forest and the PRISM data. GHCN data were used to calculate the coefficient of variation (CV) of daily precipitation (%) for 1970-2011 and 1986-2011. These data were compared to mean annual ignition density (1970-2011) and mean annual area burned (1986-2011). A subset of PRISM data were extracted for each national forest. The mean annual precipitation (mm) for 1970-2011 and 1986-2011 and the CV (%) of annual precipitation were calculated using the PRISM data. Correlation coefficients were calculated in order to assess the strength of the relationship between fire and precipitation variables (Zar 1984). Correlation between precipitation metrics were assessed, but revealed no statistically significant correlations.

II.3 Results and Discussion

Table 1 shows fire activity and precipitation variables for the national forests used in this study and Table 2 provides the same information for ranger districts. Fire activity in the Southeast occurs across a variety of precipitation regimes as demonstrated in Figures 7-13. Relationships between fire activity and mean annual precipitation are depicted in Figure 7 and 8. Interestingly, there is a positive slope in fire activity and mean annual precipitation, but the relationships are not statistically significant for ignition density (r=0.10, $p>0.05$) or area burned (r=0.09, $p>0.05$) at the national forest scale. There is also no relationship between ranger district fire activity and ignition density (r=0.02, $p>0.05$) and area burned (r=0.02, $p>0.05$).

National Forest	Ignition Density (Fires/400,00ha/yr)	Area Burned (ha/400,000 ha/yr)	CV Daily Precip (%) (1970-2011)	CV of Daily Precip (%) (1986-2011)
Apalachicola	61.9	3,164	292	301
Bankhead	76.6	630	277	278
Bienville	78.6	532	290	293
Chattahoochee	72.1	594	258	265
Cherokee	115.2	1,137	244	247
Conecuh	54.4	564	312	324
Croatan	63.1	3,618	294	303
Daniel Boone	143.5	2,146	250	252
De Soto	171.0	2,854	293	299
Delta	8.5	32	295	303
Francis Marion	191.5	1,843	307	306
George Washington	32.4	831	274	276
Holly Springs	122.8	1,317	282	280
Homochitto	52.4	825	297	296
Jefferson	26.1	126	250	253
Monongahela	7.7	25	228	228
Nantahala	42.7	462	256	260
Ocala	163.3	1,766	281	282
Oconee	53.7	102	297	303
Osceola	97.1	16,565	291	296
Pisgah	47.2	1,184	274	280
Sumter	52.3	180	291	297
Talladega	114.4	1,239	284	283
Tombigbee	73.8	491	287	283
Uwharrie	98.0	437	284	291

Table 1. Southeast USA national forests with wildfire and precipitation metrics.

National Forest	Mean Annual Precip (mm) (1970-2011)	Mean Annual Precip (mm) (1986-2011)	CV of Annual Precip (%) (1970-2011)	CV of Annual Precip (%) (1986-2011)
Apalachicola	1,386	1,356	16.9	17.5
Bankhead	1,441	1,428	17.9	18.9
Bienville	1,451	1,408	17.4	15.5
Chattahoochee	1,595	1,567	17.8	19.9
Cherokee	1,196	1,184	15.1	16.6
Conecuh	1,528	1,452	16.9	16.2
Croatan	1,364	1,343	13.5	14.8
Daniel Boone	1,233	1,221	15.4	15.7
De Soto	1,548	1,498	16.1	15.5
Delta	1,409	1,354	18.9	17.8
Francis Marion	1,249	1,254	14.5	15.2
George Washington	1,026	1,019	17.2	18.9
Holly Springs	1,443	1,435	16.1	16.5
Homochitto	1,460	1,438	15.5	15.0
Jefferson	1,064	1,047	15.1	15.9
Monongahela	1,270	1,262	14.1	15.6
Nantahala	1,508	1,490	17.0	18.9
Ocala	1,273	1,250	14.8	15.3
Oconee	1,204	1,179	16.8	18.1
Osceola	1,245	1,234	15.0	15.7
Pisgah	1,301	1,289	16.1	17.5
Sumter	1,426	1,386	16.9	18.1
Talladega	1,394	1,344	17.3	17.9
Tombigbee	1,438	1,393	19.4	18.5
Uwharrie	1,148	1,112	15.1	16.8

Table 1. Continued.

Ranger District	Ignition Density (Fires/400,00 ha/yr)	Area Burned (ha/400,000 ha/yr)	CV Daily Precip (%) (1970-2011)	CV of Daily Precip (%) (1986-2011)
Andrew Pickens	77.1	295	273	281
Bankhead	76.6	630	277	278
Bienville	78.6	532	290	293
Blue Ridge	32.9	626	251	255
Chattooga	83.3	404	264	273
Chickasawhay	88.4	418	286	292
Clinch	65.6	389	234	231
Conasauga	87.4	610	254	258
Conecuh	54.4	564	312	324
Croatan	63.1	3,618	294	303
De Soto	206.3	3,906	298	304
Delta	8.5	32	295	303
Enoree	44.7	118	291	297
Francis Marion	191.5	1,843	307	306
Holly Springs	122.8	1,317	282	280
Homochitto	52.4	825	297	296
Lee	67.4	853	277	279
Long Cane	45.4	159	294	299
Oakmulgee	62.3	863	289	292
Oconee	53.7	102	297	303
Osceola	97.1	16,565	291	296
Pisgah	35.6	199	274	277
Redbird	200	4,475	237	236
Tombigbee	73.8	491	287	283
Uwharrie	98.0	437	284	291

Table 2. Southeast USA ranger districts with wildfire and precipitation metrics.

Ranger District	Mean Annual Precip (mm) (1970-2011)	Mean Annual Precip (mm) (1986-2011)	CV of Annual Precip (%) (1970-2011)	CV of Annual Precip (%) (1986-2011)
Andrew Pickens	1,958	1,922	18.9	20.6
Bankhead	1,441	1,428	17.9	18.9
Bienville	1,451	1,408	17.4	15.5
Blue Ridge	1,512	1,495	17.7	19.9
Chattooga	1,783	1,733	17.7	19.5
Chickasawhay	1,463	1,420	15.6	14.5
Clinch	1,215	1,152	15.4	16.6
Conasauga	1,410	1,382	18.4	19.9
Conecuh	1,548	1,452	16.1	16.2
Croatan	1,364	1,343	13.5	14.8
De Soto	1,548	1,498	16.1	15.4
Delta	1,409	1,354	18.9	17.8
Enoree	1,166	1,118	15.7	16.2
Francis Marion	1,249	1,254	14.5	15.2
Holly Springs	1,443	1,435	16.1	16.5
Homochitto	1,460	1,438	15.5	15.0
Lee	1,013	993	17.8	19.6
Long Cane	1,155	1,119	16.3	17.5
Oakmulgee	1,446	1,405	15.8	15.6
Oconee	1,204	1,179	16.8	18.1
Osceola	1,245	1,234	15.0	15.7
Pisgah	1,314	1,288	17.7	18.8
Redbird	1,229	1,222	16.0	17.1
Tombigbee	1,438	1,393	19.4	18.5
Uwharrie	1,148	1,112	15.1	16.8

Table 2. Continued.

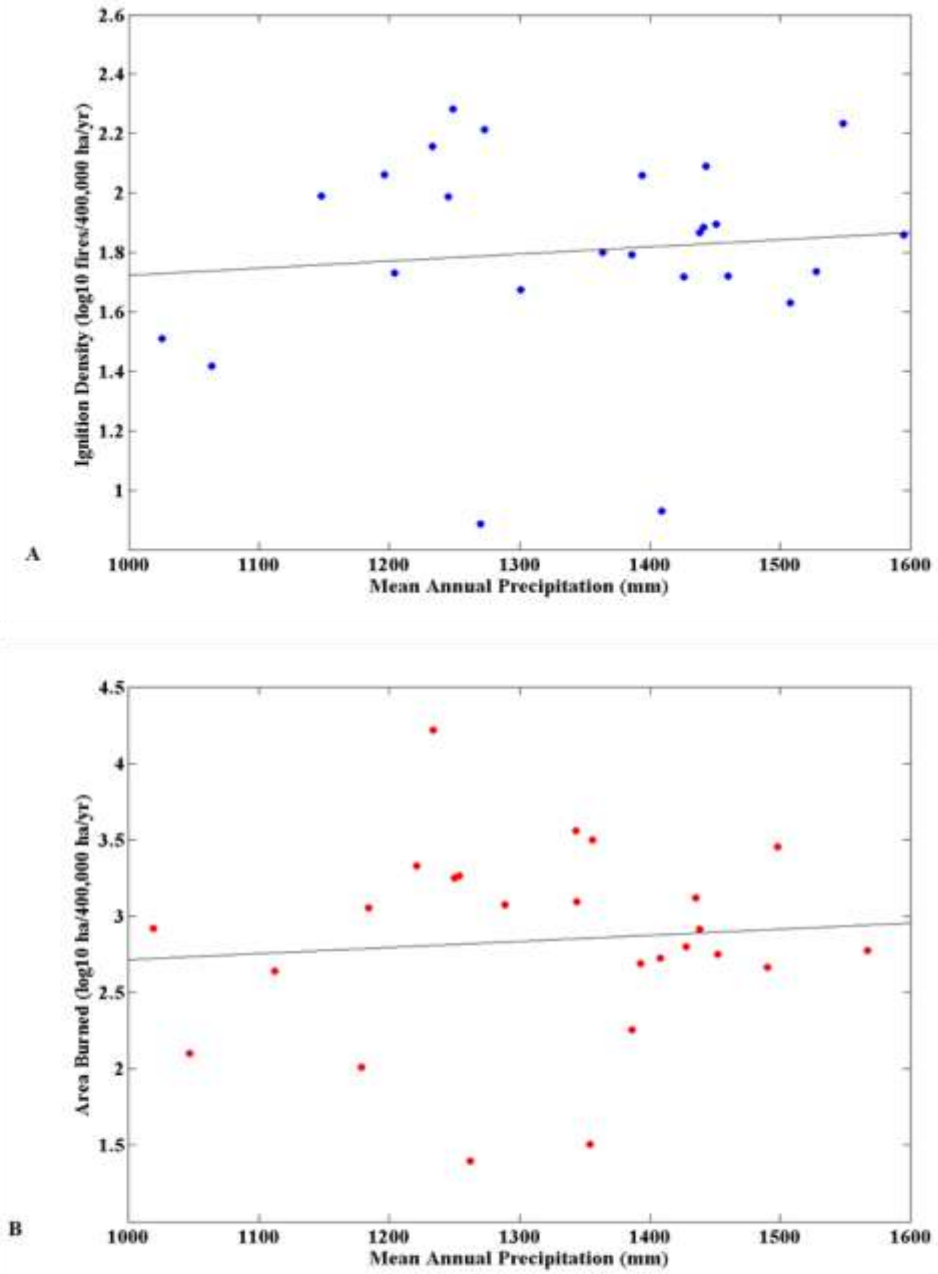


Figure 7. Relationship between mean annual precipitation and national forest (A) ignition density (1970-2011) and (B) area burned (1986-2011).

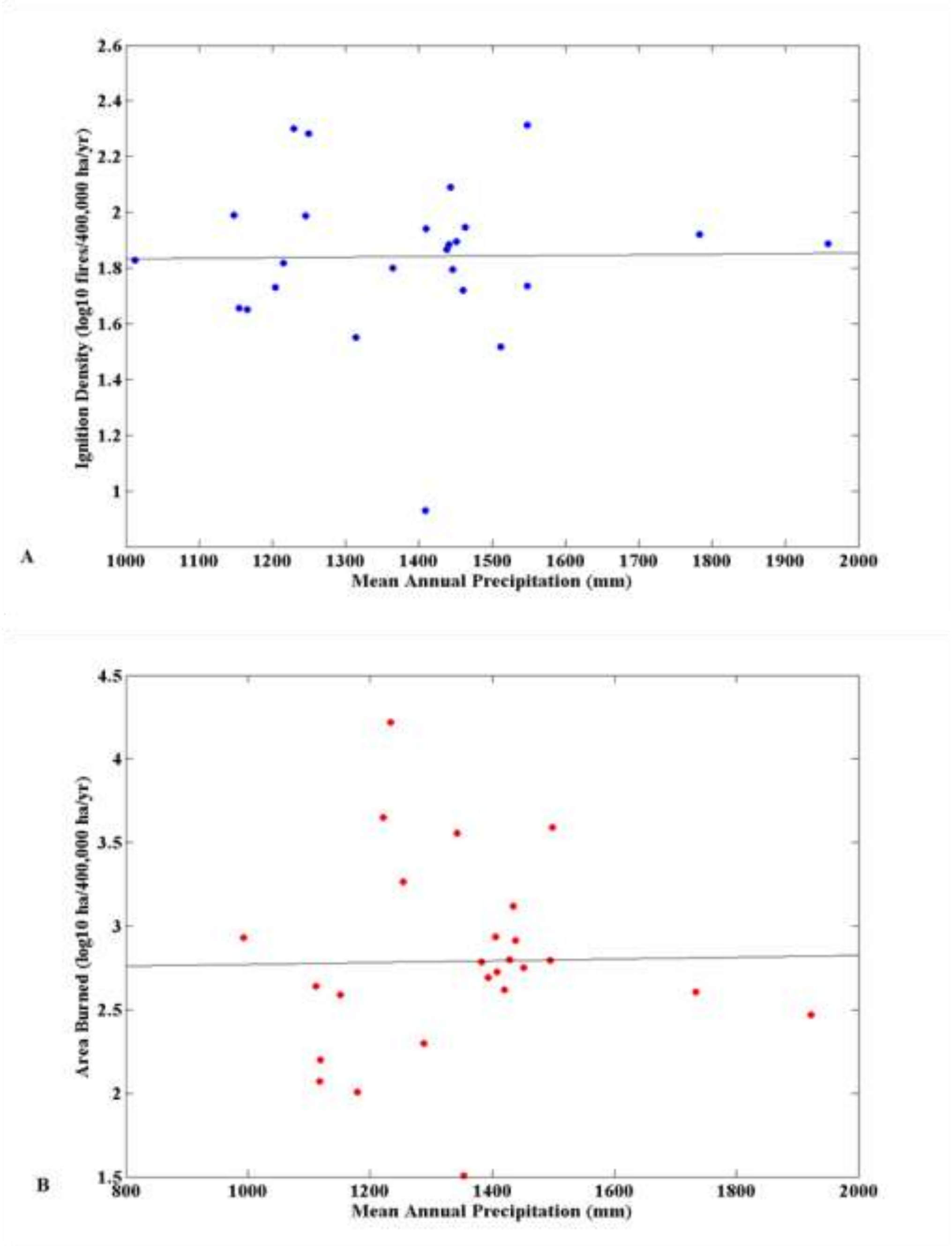


Figure 8. Relationship between mean annual precipitation and ranger district (A) ignition density (1970-2011) and (B) area burned (1986-2011).

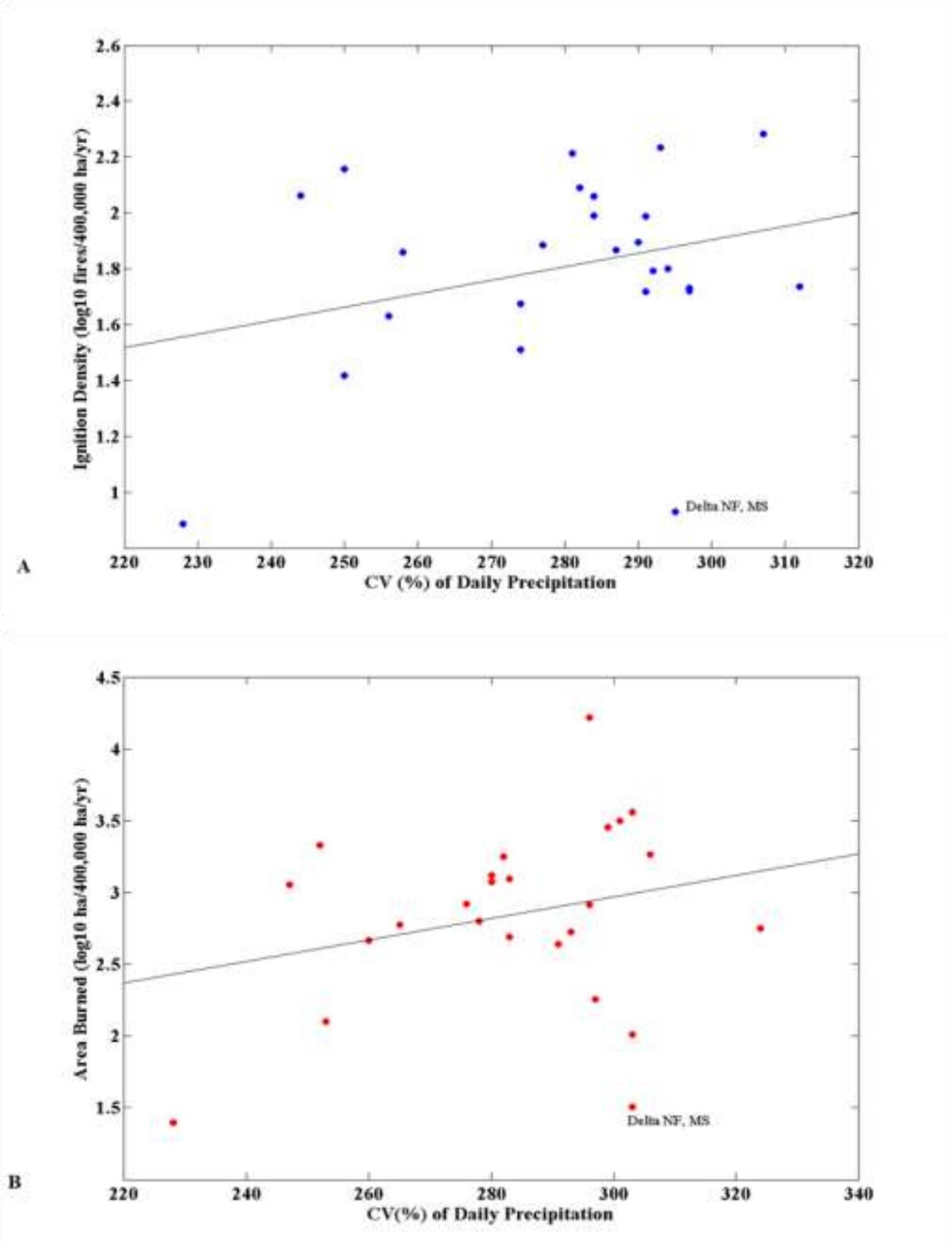


Figure 9. Relationship between CV of daily precipitation and national forest (A) ignition density (1970-2011) and (B) area burned (1986-2011).

Figure 9 depicts the relationship between fire activity and precipitation variability. Ignition density and area burned both demonstrate a general positive relationship with increasing fire activity with increasing precipitation variability. However, a statistically significant correlation is not observed for ignition density (r=0.29, $p>0.05$) or area burned (r=0.26, $p>0.05$).

A visual assessment of the results shows that there is one national forest that seems to deviate from the general trend of increasing fire activity with increasing precipitation variability. Delta National Forest resides in western Mississippi in a flooded bottomland hardwood forest along the Mississippi River. Delta exhibits relatively high precipitation variability (295% from 1970-2011 and 303% from 1986-2011), yet experiences the second lowest ignition density and area burned (8.5 fires/400,000 ha/yr and 32 ha/400,000 ha/yr, respectively). The fire record in Delta demonstrates that fires are exceedingly rare and often do not burn in even the most severe of droughts (e.g. 1986-1988). Because the objective of this chapter is to examine relationships between fire and precipitation regimes, the subjective decision was made to remove Delta National Forest to assess the relationships without this outlier. Figure 10 shows the same information as Figure 9, but with Delta excluded. Statistically significant positive correlations are observed for ignition density (r = 0.43, $p<0.05$), but not for area burned (r = 0.39, $p>0.05$), even though the correlation did increase.

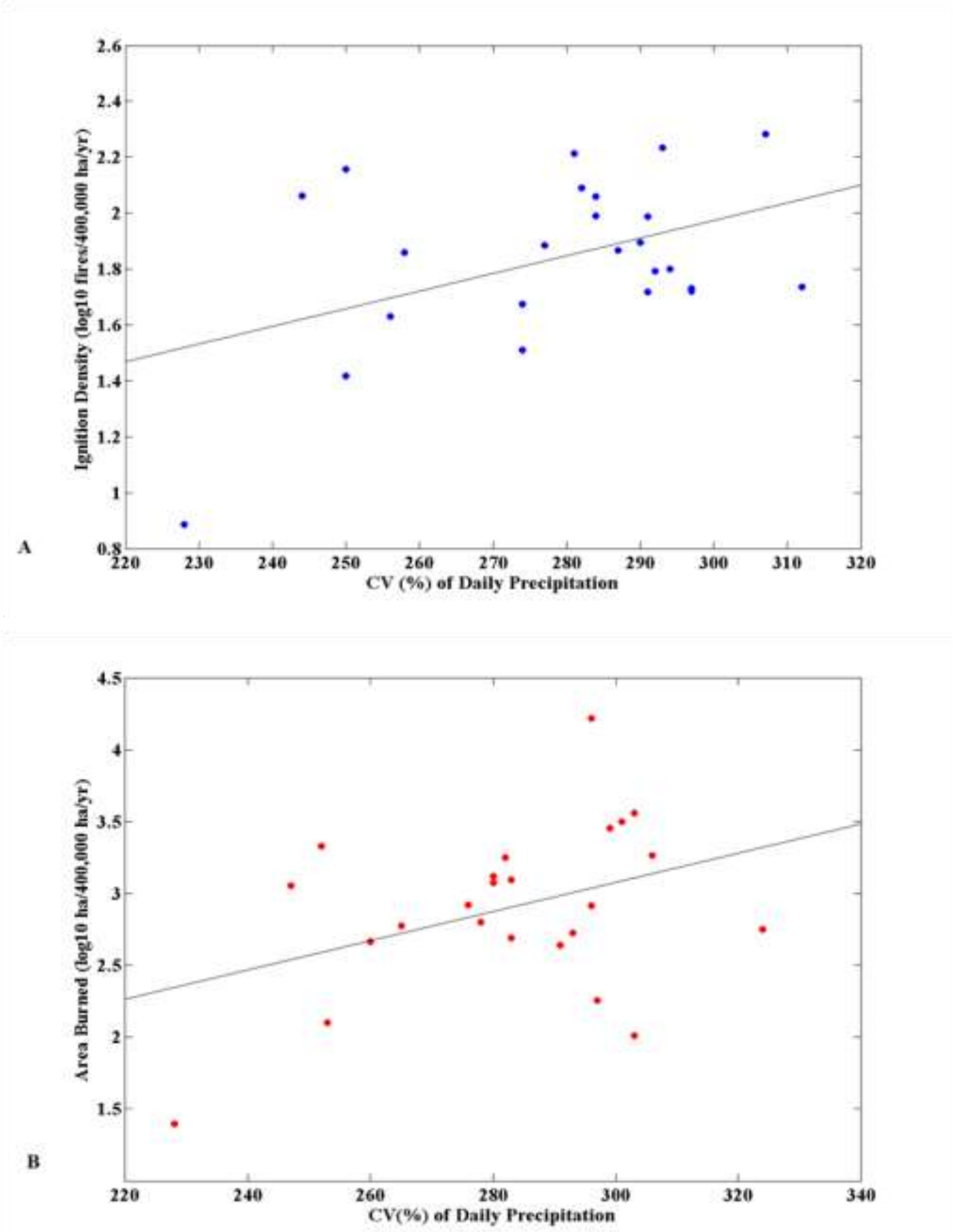


Figure 10. Same as Figure 9 with Delta National Forest excluded.

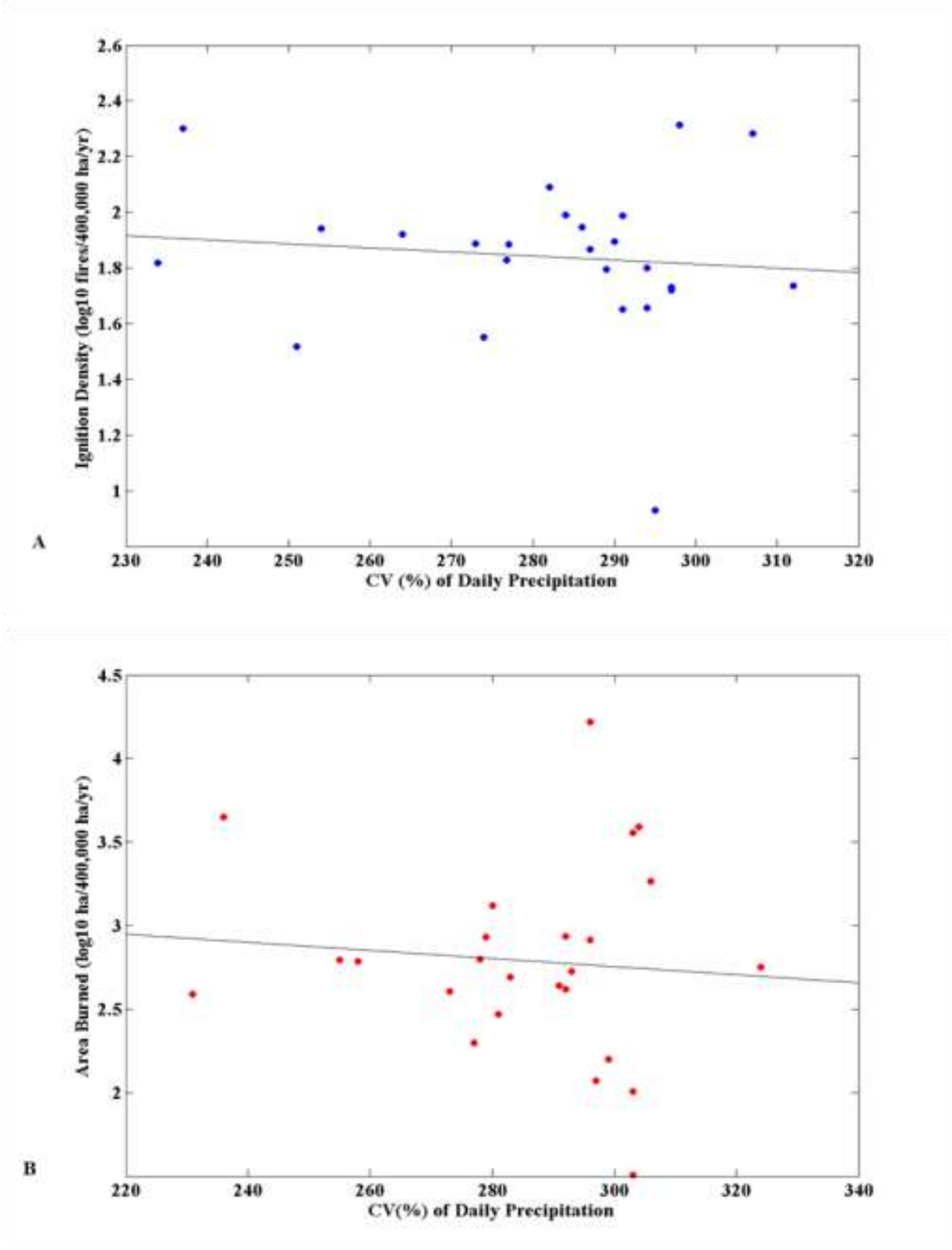


Figure 11. Relationship between CV of daily precipitation and ranger district (A) ignition density (1970-2011) and (B) area burned (1986-2011).

The same analysis of the relationship between fire activity and daily precipitation variability was performed at the ranger district scale (Figure 11). A weak negative relationship was observed between both ignition density and precipitation variability, as well as area burned and precipitation variability. However, no statistically significant correlations were uncovered for ignition density (r = -0.10, $p>0.05$) or for area burned (r = -0.09, $p>0.05$).

Relationships between fire activity and the CV of annual precipitation are shown in Figures 12 and 13. Interestingly, a negative trend is seen at both the national forest scale and ranger district scale, contrary to the results with daily precipitation variability. The correlations for national forest ignition density (r= -0.17, $p>0.05$), national forest area burned (r= -0.28, $p>0.05$), ranger district ignition density (r= -0.37, $p>0.05$), and ranger district area burned (r= -0.37, $p>0.05$) are not statistically significant.

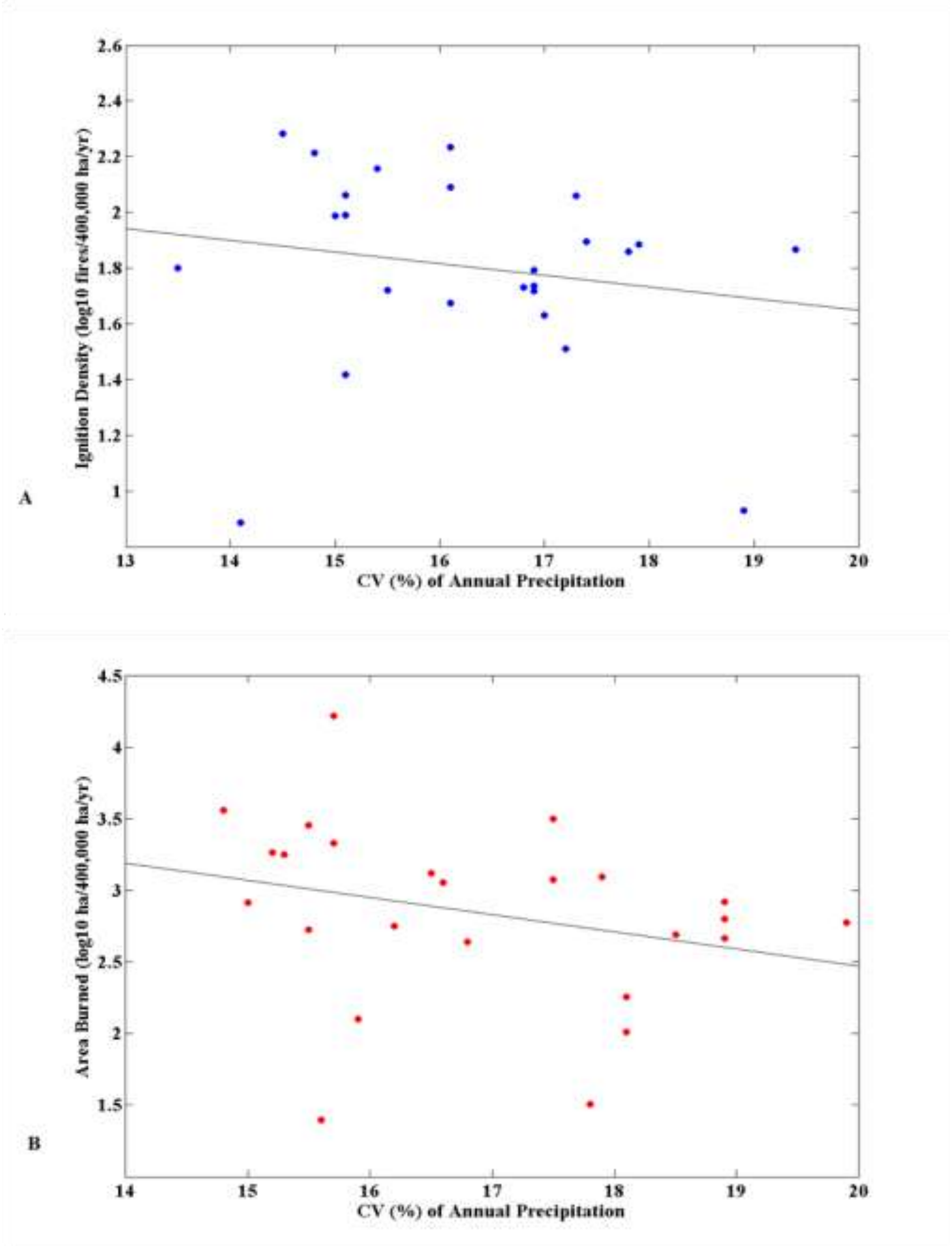


Figure 12. Relationship between CV of annual precipitation and national forest (A) ignition density (1970-2011) and (B) area burned (1986-2011).

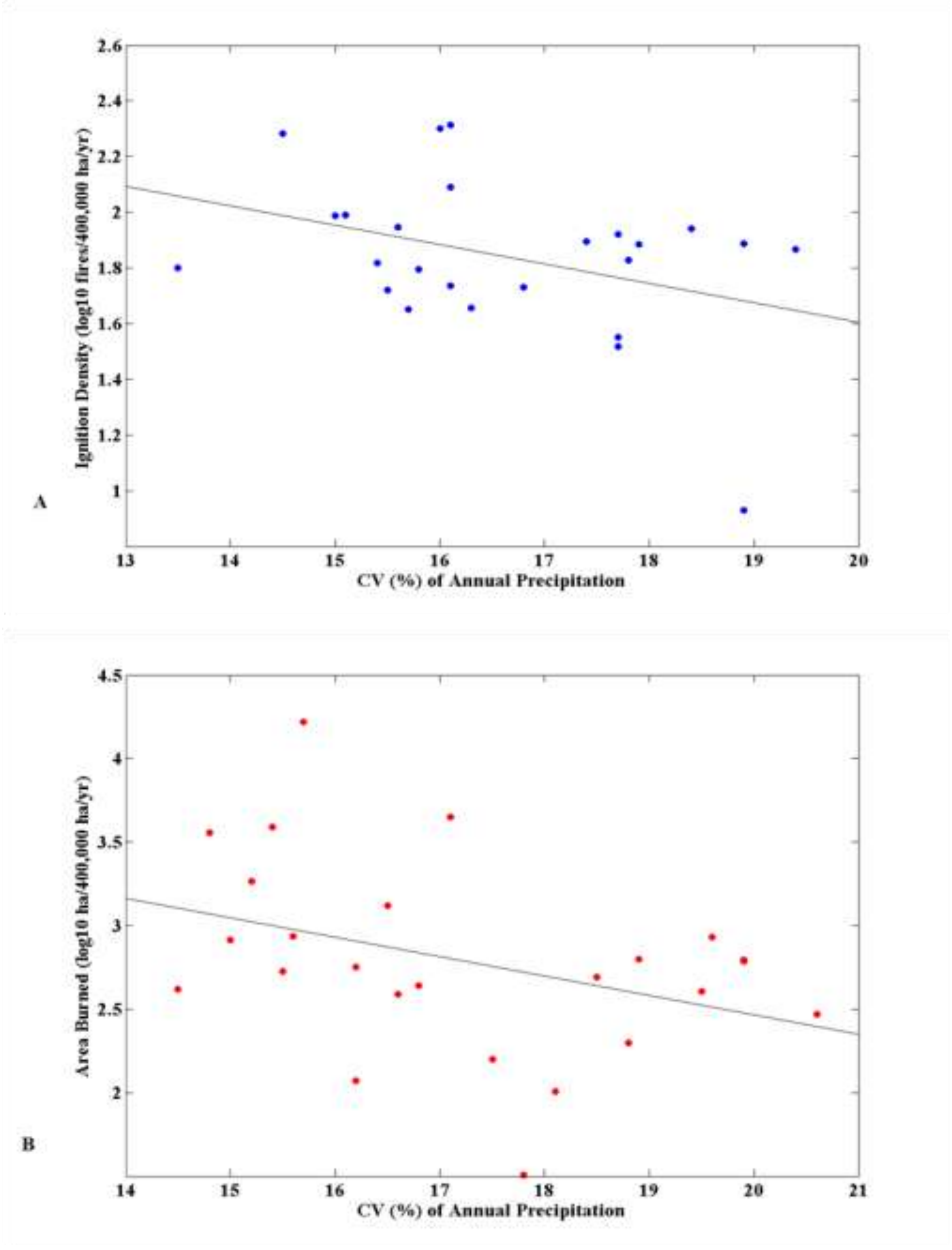


Figure 13. Relationship between CV of annual precipitation and (A) ignition density (1970-2011) and (B) area burned (1986-2011).

Overall, there is a lack of statistically significant relationships between fire activity (ignition density and area burned) and precipitation metrics (mean annual precipitation, CV of daily precipitation, and CV of annual precipitation). There is not a strong relationship between fire activity and mean annual precipitation and the hypothesis laid out in chapter I that drier locations would be more fire prone was not confirmed. It is possible that this is because the Southeast has a humid climate and so even the driest locations in the Southeast are still relatively wet when compared to other locations in the United States.

Daily precipitation variability is a climatic driver of spatial patterns of wildfire in the Southeast. However, this is seen only at the national forest scale and with the exclusion of Delta National Forest from the analysis. This result broadly supports the conclusions of Lafon and Quiring (2012). As hypothesized in chapter I, national forests in the Southeast with high daily precipitation variability experience increased levels of fire activity. Locations that experience a precipitation regime with high intensity precipitation events interspersed with days with no precipitation are more likely to burn, as pointed out by Lafon and Quiring (2012). Precipitation variability on an annual scale produced interesting negative relationships. While these relationships were not statistically significant, this deserves more attention in future work.

There are a number of reasons that may help explain why more significant relationships were not observed. First, the small sample size (n=25 national forests and ranger districts) may not be large enough to establish robust (statistically significant) relationships. Second, many fire records are missing ranger district designation and could not be assigned a ranger district. Consequently, it is uncertain if fire statistics at the scale of ranger districts are reliable. It is also possible that at the ranger district level, local processes (e.g. local management, elevation, topography) may override the larger and coarser-scale climatic processes (Meyn et al. 2007).

This chapter demonstrates the importance of scale in understanding spatial patterns of moisture-wildfire relationships. At the smaller scale of physiographic provinces in the central Appalachians, differences in precipitation variability can explain spatial variations in wildfire activity (Lafon and Quiring 2012; Lafon and Grissino-Mayer 2007). At a sub-continental scale, precipitation variability is also important in explaining spatial patterns of wildfire (Lafon and Quiring 2012). However, this chapter examines relationships at the regional scale. Unlike Lafon and Quiring (2012), which included federal lands from the Southeastern states as well as the Northeast and Great Lakes states, this chapter focused solely on the Southeast. A consequence of this was that the national forests examined represent a relatively small range in mean annual precipitation and precipitation variability. The majority of national forests examined in this study have daily precipitation CV values between 270% and 300%. The national forests that Lafon and Quiring (2012) examined had daily precipitation CV values ranging from 206% to 337%. This clustering of national forests between these two values limited the analysis. This is a primary reason that stronger relationships were not uncovered between precipitation variability and wildfire activity. This may also explain why no relationships were observed between mean annual precipitation and fire activity. The range in mean annual precipitation in this study covered 1,026 mm to 1,595 mm;

also a relatively small range. While previous work has suggested that mean conditions are important (Parisien and Moritz 2009; Meyn et al. 2007; Sauer 1950; Krawchuk et al. 2009), this analysis of the Southeast did not support this finding.

Expanding the analysis presented here to include greater variability in precipitation regimes will likely result in stronger relationships between precipitation variability and wildfire activity, as well as between mean annual precipitation and wildfire activity. Figure 14 demonstrates the potential value in expanding the analysis to include a greater range of precipitation variability values. The analysis pertaining to daily CV originally included a range from 228% to 312% (1970-2011) and 228% to 324% (1986-2011). Expanding the analysis captures a range of daily CV values from 206% to 428% (1970-2011) and 211% to 442% (1986-2011). High daily precipitation variability with high ignition density and area burned are demonstrated with Tonto National Forest in southern Arizona and Black Hills National Forest in western South Dakota. An arid/semi-arid climate should experience very high daily precipitation variability as shown with Tonto and Black Hlls. On the other end of the precipitation variability-fire spectrum are Olympic National Forest and Suislaw National Forest in western Washington and Oregon where mean annual precipitation is also high like the Southeast, but the pattern of precipitation receipt is much different with high frequency, low intensity precipitation events. Statistically significant correlations are observed with ignition density (r = 0.37, $p<0.05$) and area burned (r = 0.52, $p<0.01$). Similar relationships with mean annual precipitation and ignition density (r = -0.25, $p>0.05$) and area burned (r = -0.45, $p<0.05$) are demonstrated in Figure 15.

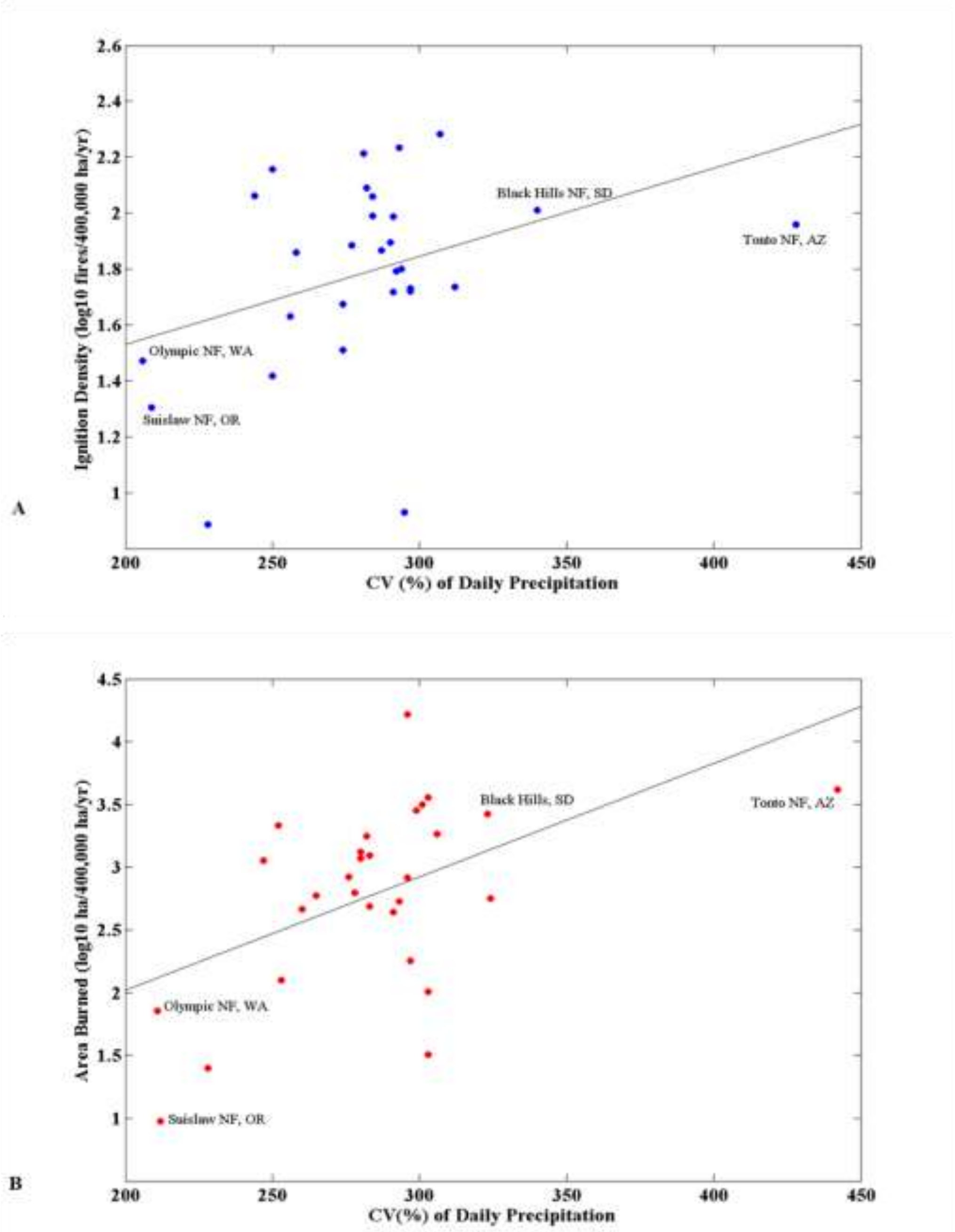


Figure 14. Relationship between CV of daily precipitation and national forest (A) ignition density (1970-2011) and (B) area burned (1986-2011) with the inclusion of national forests in the western USA.

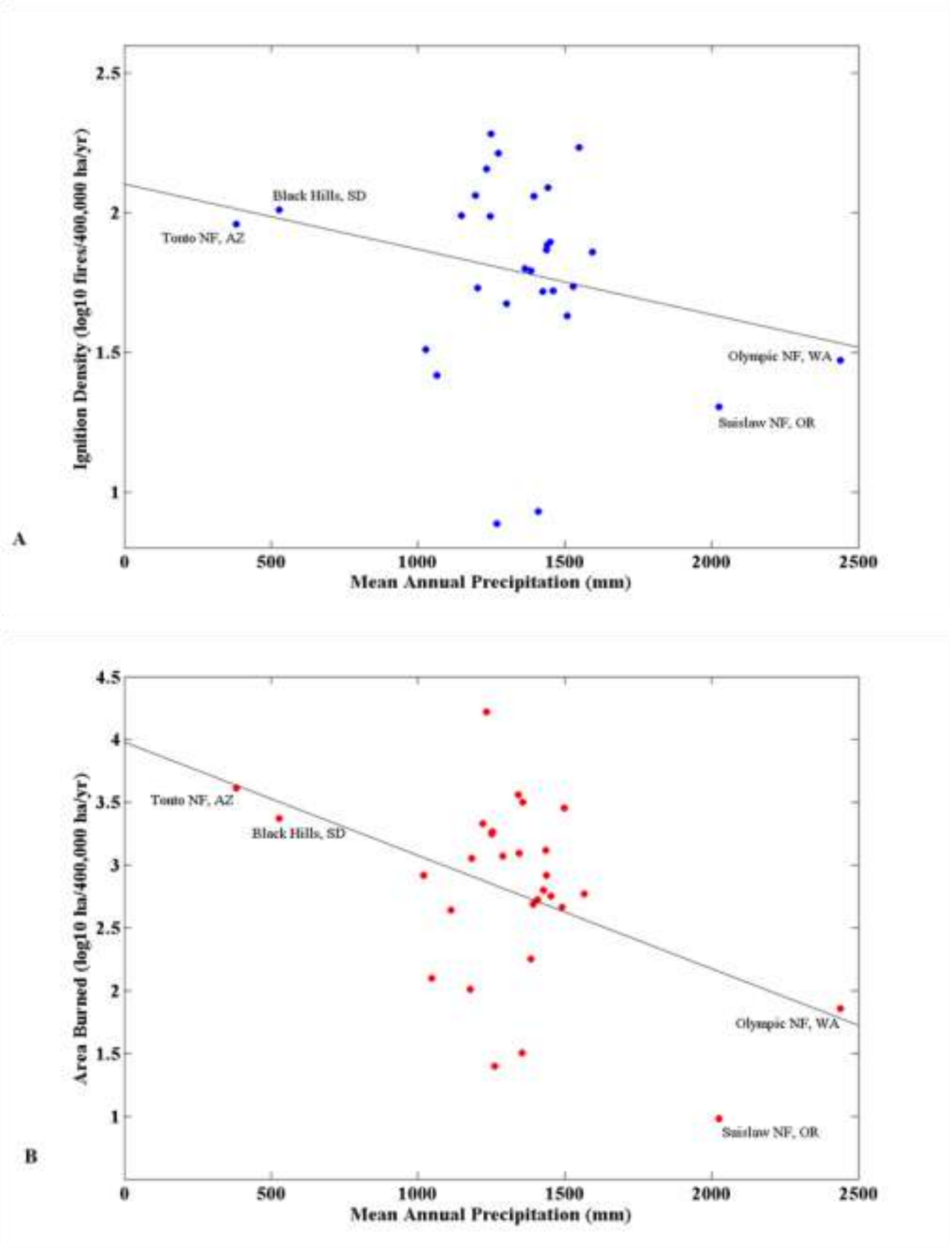


Figure 15. Relationship between mean annual precipitation and national forest (A) ignition density (1970-2011) and (B) area burned (1986-2011) with the inclusion of national forests in the western USA.

Precipitation variability, mean annual precipitation, and climate in general, are not the only factors that influence the spatial patterns of fire. Other climatic variables, such as mean temperature of the warmest month and mean temperature of the wettest month also have an influence (Krawchuk et al. 2009). Vegetation is also an important factor because of its role as a fuel source. Previous work has identified land cover, defined using maximum Normalized Difference Vegetation Index (NDVI), to be associated with fire patterns, particularly in the western USA (Hawbaker et al. 2013). Meyn et al. (2007) hypothesized that fuel characteristics, such as spatial distribution, arrangement and continuity were important. Interactions among disturbances may also be important in some locations (Meyn et al. 2007). In the Southeast, for instance, hurricanes and fire can interact to create patterns not normally observed in other regions (Myers and van Lear 1998). Human activity also influences spatial patterns of fire, especially in the eastern USA. Urbanization, proximity to roads, and distance to major cities have been demonstrated to have an influence on fire patterns (Hawbaker et al. 2013; Maingi and Henry 2007; Syphard et al. 2008; Syphard, Clarke, and Franklin 2007; Grala and Cooke 2010). Ultimately, no single variable can account for the spatial patterns of wildfire activity at any scale. Wildfire is a complex phenomena and the relative importance of any of these factors varies over space.

II.4 Conclusions

The objective of this chapter was to expand upon the work of Lafon and Quiring (2012) in examining spatial relationships between wildfire activity and precipitation regimes in the Southeast USA. Few statistically significant correlations between fire activity and mean annual precipitation or CV of annual precipitation were uncovered. There is evidence of a positive relationship between daily precipitation variability and fire activity. Besides a small sample size, the primary limitation of this work is the scale of analysis. Limiting the analysis to the Southeast region failed to capture a range of precipitation regimes. Evidence shows that expanding the same analysis to the continental scale captures a greater range of precipitation variability and therefore improves the strength of the relationships. While Meyn et al. (2007) and Parisien and Moritz (2009) demonstrate the importance of mean conditions and the propensity of intermediate hydroclimates to be most fire prone, their work covers a much larger spatial extent than this chapter. Certainly intermediate moisture conditions were not observed to be the most fire prone in this study, as again, the region did not capture the full range of precipitation regimes.

Expanding this work to encompass a greater range of precipitation regimes will provide more insight into the how precipitation regimes drive spatial patterns of wildfire activity. In particular locations in the Pacific Northwest, with similarly high mean annual precipitation as the Southeast (and in many cases higher), but with precipitation regimes that generally consist of more frequent, smaller intensity precipitation events will provide an interesting comparison to the Southeast.

Precipitation variability is of key interest in the Southeast. An increase in summer precipitation variability in the Southeast has been detected (Wang et al. 2010) and increases in precipitation are attributable to increases in heavy and extreme precipitation (Karl and Knight 1998; Groisman, Knight, and Karl 2001). Along the same lines, the length of dry periods has been observed to be on the rise in recent decades (Groisman and Knight 2008). As previously mentioned, precipitation variability is known to influence ecological processes (Jentsch and Beierkuhnlein 2008; Fay et al. 2003; Fay et al. 2008) and more attention should be given to how it affects disturbance regimes such as wildfire.

CHAPTER III

WEATHER TYPE CLASSIFICATION OF WILDFIRE

III.1 Introduction

Wildfire is a complex phenomenon, playing multiple roles in the environment and society. Fire is a natural and anthropogenic hazard that threatens ecosystems, wildlife habitat, timber resources, rural communities and sometimes even urban areas causing significant economic impact (Whelan 1995; Butry et al. 2001). Yet fire also plays a necessary role in some biomes (Moritz and Odion 2004; Bond and Keeley 2005; Pyne, Andrews, and Laven 1996). Wildfires influence vegetation structure and composition, maintaining and restoring ecosystems and wildlife habitat (Pyne 1982; Whelan 1995). Current wildfire management policy enables resource managers to use certain wildfires – those ignited during nonhazardous weather conditions – for restoration purposes, for example, to support regeneration of fire-associated plants (Whelan 1995). Because of the multiple roles that wildfire plays, it is particularly important to understand the drivers of wildfire.

Wildfire activity is influenced by various factors, including fuel management and suppression policies, topography, vegetation structure and composition, extreme fire weather, and climate (Pyne 1982; Bond and van Wilgen 1996; Meyn et al. 2007; Krawchuk et al. 2009). Climate affects three necessary ingredients for wildfire: fuel quantity, fuel moisture, and ignition sources (Bond and van Wilgen 1996; Krawchuk et al. 2009). Climate on multi-decal and longer timescales dictates the vegetation composition and structure, which becomes the fuel type and quantity during a fire (Schroeder and Buck 1970). Climatic oscillations also influence precipitation variability, thereby controlling fuel moisture (Krawchuk et al. 2009; Bond and van Wilgen 1996). In addition, climate affects thunderstorms and the potential for lightning as an ignition source (Bond and van Wilgen 1996).

A general conceptual model proposed by Meyn et al. (2007) suggests that wildfire exists along a continuum of relative importance related to limiting factors from fuel quantity on one end of the spectrum to fuel moisture on the other. In ecosystems where vegetation is sparse, fuel quantity is a limiting factor (Meyn et al. 2007). Such ecosystems can be rarely dry (e.g. portions of the Patagonia and northern Colorado high elevation forests), and therefore also limited by fuel moisture or frequently dry (e.g. African dry savanna). Much of the current understanding of wildfire climatology is based on research performed in these ecosystems. However, a third type of ecosystem also exists along this continuum. Ecosystems that possess both abundant vegetation and are rarely dry are certainly not limited by fuel quantity, but by fuel moisture (Meyn et al. 2007). Examples of such ecosystems include the coastal temperate rainforests of the Pacific Northwest USA, rainforests of Indonesia and the Amazon basin, and Florida, USA (Meyn et al. 2007).

In such fuel moisture-limiting ecosystems, below normal precipitation and drought often serve as the primary climatic driver of wildfire (e.g. Gedalof, Peterson, and Mantua 2005). Synoptic circulation patterns leading to prolonged dry conditions and antecedent drought in the Pacific Northwest have been linked to increased fire activity

(Gedalof, Peterson, and Mantua 2005; Trouet et al. 2009). Rainforests in the northern Patagonia and Amazon also experience associations between drought and wildfire activity (Kitzberger, Veblen, and Villalba 1997; Nepstad et al. 1998). Florida Everglades fire activity has been linked to dry conditions often driven by La Niña (Beckage and Platt 2003).

Southeast USA fire-climate studies beyond Florida have found drought to be an important predictor of wildfire activity as well. Lafon, Hoss, and Grissino-Mayer (2005) examined wildfire activity in the central Appalachians and found it associated with monthly Palmer Drought Severity Index (PDSI) values. Mitchener and Parker (2005) found wildfire throughout the Southeast to respond to drought conditions. In wetter regions of the Southeast, antecedent drought became more important in drying fuel loads whereas in drier regions, antecedent drought was not as important as concurrent conditions (Mitchener and Parker 2005).

Air mass patterns, synoptic circulation features, and large scale oceanic-atmospheric teleconnections often control anomalously dry periods and precipitation variability in general in the Southeast and beyond. Cold phases of El Niño-Southern Oscillation (ENSO) have been linked with increased wildfire activity, particularly in Florida, as dry conditions prevail leading to decreased precipitation and lowered surface water levels (Harrison and Meindl 2001; Beckage et al. 2003; Brenner 1991). The North Atlantic Oscillation (NAO), Pacific North American (PNA) patterns, and the Pacific Decadal Oscillation (PDO) have also been explored (Dixon, Goodrich, and Cooke 2008; Goodrick and Hanley 2009). Correlation analyses by Dixon, Goodrich, and Cooke

(2008) revealed relationships between multiple teleconnection indices and wildfire activity in Mississippi. Likewise, Goodrick and Hanley (2009) found relationships between ENSO, PNA, and wildfire activity in Florida.

While American popular media coverage and wildfire research is focused on western USA wildfires, the Southeast leads the nation in regional number of ignitions (Pyne 1982; Andreau and Hermansen-Báez 2008). Wildfire is an influential process in many Southeastern ecosystems (Beckage, Platt, and Panko 2005; Lafon 2010) and has shaped the Southeast for thousands of years (Fowler and Konopik 2007). The longleaf pine (*Pinus palustris*) savanna, for example, is a fire-dependent ecosystem that historically dominated the Coastal Plain before logging and fire suppression (Lafon 2010; Outcalt 2000; Frost 1993).

Relative to western North America, little research regarding wildfire-climate relationships has been done, particularly how weather type or air mass occurrences and teleconnections affect wildfires in the region, an ecosystem with abundant vegetation and which is rarely dry (see Meyn et al. 2007). The purpose of this chapter is to examine the relationship between wildfire activity in the central Gulf Coast national forests and weather type occurrences, according to the Spatial Synoptic Classification (SSC) scheme (Sheridan 2002) in an effort to identify regional patterns of weather type occurrences associated with wildfire activity. This study hypothesizes that because the region possesses abundant vegetation and is rarely dry and therefore, fire activity is limited by fuel moisture (see Meyn et al. 2007), dry weather types should be associated with wildfire activity. An examination of large-scale teleconnections, ENSO and NAO, is provided to investigate what climatic mechanisms may drive weather type occurrences. Synoptic climatology methods provide a useful tool in understanding a variety of environmental phenomena (Yarnal 1993), including wildfire. While other studies have explored the Southeast using PDSI and teleconnections, to the best of my knowledge this is the first study to explore wildfire climatology in the region using a weather type classification scheme derived using modern techniques. Such synoptic weather typing schemes are an ideal way to examine wildfire because relationships between wildfire and single meteorological variables are very difficult to uncover. As pointed out by Schroeder and Buck (1970), wildfires rarely respond solely to high temperatures or low precipitation, but to the collective sum of atmospheric conditions. Therefore, a measure like weather types that incorporates multiple variables may provide results that are more useful.

III.2 Data and Methods

III.2.1 Study Region

This study explores the relationships between weather type patterns and wildfire activity in the central Gulf Coast, USA. The central Gulf Coast is defined here as the states of Mississippi, Alabama, and the panhandle of Florida as shown in Figure 16. There are nine national forests within the region. Wildfires in Delta National Forest in Mississippi are not analyzed because of the rarity of fires in the flooded bottomland forest. In addition, Tuskegee National Forest in Alabama is not included because data are not available for the entire study period (1970-2011). Vegetation in this region includes xeric sandhill communities with various pine and oak species, more mesic pine communities, and upland hardwood forests (Christensen 2000). Historically, fires were common across the region, supporting a number of fire-adapted communities (Abrams 1992; Lafon 2010; Christensen 2000).

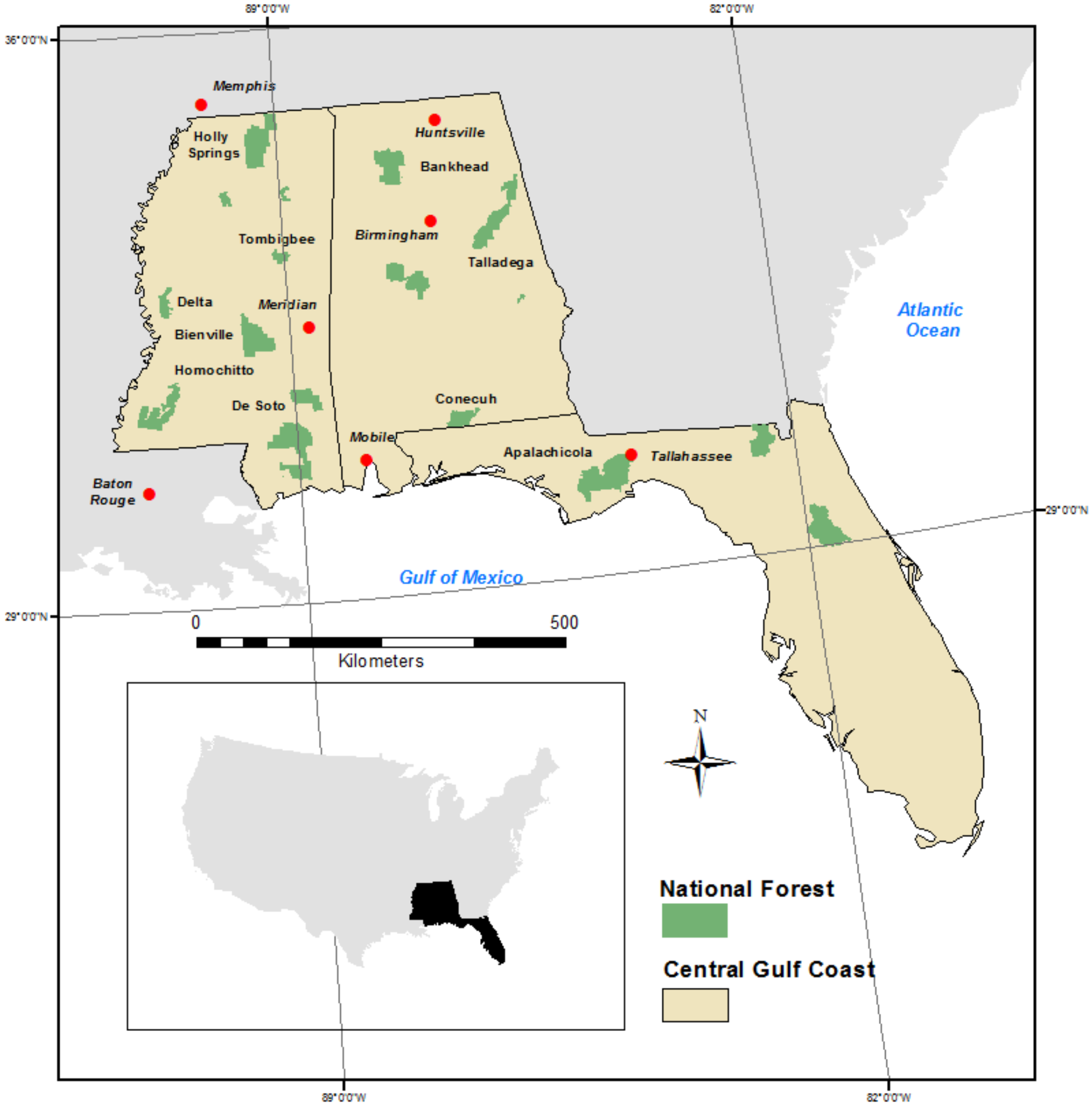


Figure 16. Central Gulf Coast study region.

III.2.2 Data

III.2.2.1Wildfire Occurrence Data

Wildfire occurrence data, obtained from the National Interagency Fire Management Integrated Database (NIFMID; USFS 1998), contain records of wildfires for all federally managed lands in the United States. Information recorded in this database includes dates of ignitions, acres burned, causes, locations, and other data. NIFMID is a commonly used source for contemporary wildfire data and has been used previously in the southeast USA (e.g. Lafon, Hoss, and Grissino-Mayer 2005, Lafon and Grissino-Mayer 2007, Lafon and Quiring 2012). Prescribed fires and fires with a missing ignition date or other relevant data are excluded from this analysis. Reliable ignition data typically begin in 1970, and in 1986 for acres burned (Lafon and Quiring 2012). Due to the longer period available for ignition data, this study focuses on wildfire ignitions.

III.2.2.2 Spatial Synoptic Classification (SSC)

The SSC scheme, developed by Kalkstein et al. (1996) and later updated by Sheridan (2002), is used here to classify daily weather type occurrences in each national forest. The SSC is a hybrid scheme whereby initial weather type categories are determined manually prior to an automated process in which algorithms create hypothetical seed days for each weather type at each location. The hypothetical seed days are then compared to actual days, and each day is classified into one of seven weather types (Sheridan 2002). The SSC is a weather type classification based solely on surface conditions, including minimum and maximum temperatures (°C), dew point (°C), dew point depression (°C), diurnal dew point change (°C), and mean daily cloud cover (tenths). The SSC uses seven discrete classes with nomenclature based on moisture and thermal characteristics, including dry moderate (DM), dry polar (DP), dry tropical (DT), moist moderate (MM), moist polar (MP), moist tropical (MT). The scheme also includes transitional days (T) days, which are comparable to, but not the exact equivalent of, frontal activity (Hondula and Davis 2011).

DM weather types are associated with mild temperatures and dry conditions. These weather types have no particular source region. However, they typically occur in central and eastern North America when zonal flow allows the air mass to push beyond the Rocky Mountains where it subsequently dries and warms adiabatically (Sheridan 2002).

The DP weather type is a cold and dry weather type characterized by clear skies and northerly winds. DP weather develops in Canada and Alaska and migrates into the rest of the continent via cold-core anticyclone (Sheridan 2002).

Hot and dry conditions characterize DT weather types. These weather types originate in the deserts of the southwestern USA and northwestern Mexico but can also develop from downslope winds creating compressed and, consequently, warmer and drier air (Sheridan 2002).

MM weather types are associated with mild temperatures, humid conditions, and cloud cover. Like DM weather types, this category has no explicit source region. MM weather types develop from modified traditional maritime polar (mP) air masses, near warm fronts, or when maritime tropical (MT) air masses are dominant with significant cloud cover and lower temperatures (Sheridan 2002)

The MP weather type is characterized by cold and humid air with cloudy conditions and light precipitation. MP weather types originate over the North Atlantic and North Pacific, but can also develop from frontal overrunning or when the traditional continental polar (cP) air mass moves over a water body, taking on moisture (Sheridan 2002).

Warm and humid conditions characterize the MT weather types, which are advected into North America from the Gulf of Mexico or the tropical portions of the Atlantic and Pacific Oceans. They also develop in the warm portion of a mid-latitude cyclone, or on the western sector of an anticyclone (Sheridan 2002).

The transitional classification represents days in which one weather type gives way to another weather type (Sheridan 2002) and consequently can represent days when frontal activity is present.

Daily SSC data are available from http://sheridan.geog.kent.edu/ssc.html. Data from seven stations in the central Gulf Coast region are used in this study, as shown in Table 3 and Figure 16. Generally, data are available from 1970-2011, matching the wildfire ignition record. Over the study period, less than 1% of the SSC data are missing from any station. The SSC has proven to be a useful tool in a variety of studies including characterizing drought events (Quiring and Goodrich 2008), aiding in identifying sources of pollution (Hondula et al. 2010), and examining urban heat islands (Brazel et al. 2007).

National Forest	SSC Station	Mean Annual Fire Density (fires/400,000 ha)
Apalachicola	Tallahasse, FL	61.9
Bankhead	Huntsville, AL	76.6
Bienville	Meridian, MS	78.6
Conecuh	Mobile, AL	54.4
DeSoto	Meridian, MS	170.8
Homochitto	Baton Rouge, LA	52.4
Holly Springs	Memphis, TN	122.8
Talladega	Birmingham, AL	114.4
Tombigbee	Meridian, MS	73.8

Table 3. Central Gulf Coast national forests with assigned SSC station and mean annual fire density.

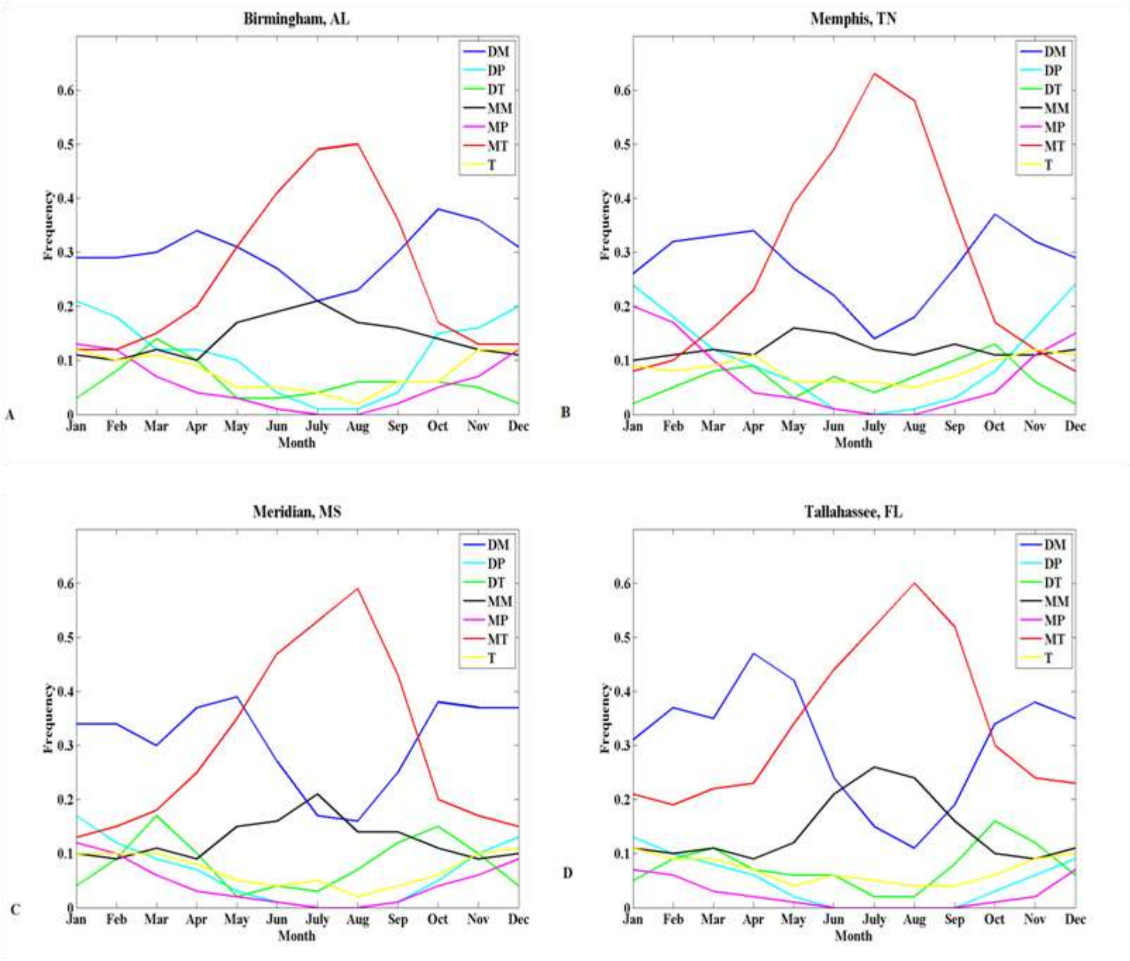


Figure 17. Mean monthly weather type frequencies for SSC stations (A) Birmingham, AL, (B) Memphis, TN, (C) Meridian, MS, and (D) Tallahassee, FL.

MT and MM weather types dominate the central Gulf Coast region during the warm season (Figure 17), as warm, moist air masses are advected in from the Gulf of Mexico and Atlantic Ocean. During winter, spring, and fall, weather type frequencies are more equally distributed, typically with DM weather types being dominant. MP, DP, and T days become more frequent during the winter months as extratropical cyclones traverse the region (Figure 17).

III.2.3 Analysis

III.2.3.1 Changes in Weather Type Occurrences

Due to the meteorological variables required in the classification process, the SSC is generally only available for first-order weather stations often located in urban areas. Consequently, each national forest in the central Gulf Coast was assigned a proximal SSC station as shown in Table 3. Since a typical air mass can exist over hundreds to thousands of square kilometers, the SSC station also serves as the air mass occurrence record for the particular national forest in question. To examine the appropriateness of using an SSC station to represent weather types in national forests, daily maximum temperature (°C) for each SSC station were compared with daily maximum temperatures at a station closer to or within national forest boundaries. January, April, July, and October, representing the mid-season months of the four standard seasons, were assessed for 1970-2011. The correlation coefficient was calculated between the two time series, as well as the mean bias error and mean absolute difference between the two stations.

Using the SSC calendar at each national forest, the mean annual number of days for each weather type over the entire period (1970-2011) was calculated (hereafter referred to as the climatology for each weather type). To determine which weather type(s) was associated with high and low wildfire ignitions, the seven years with the highest and lowest numbers of ignitions were extracted and the mean annual number of days of each weather type during those periods was calculated. In the event that some years were equal in terms of numbers of ignitions, the average of the two years was used as one of the seven years, but this was rare. Chi-square goodness-of-fit tests examined the differences between observed and expected frequencies (McGrew Jr. and Monroe 2009). The Mann-Whitney U test (McGrew Jr. and Monroe 2009; Zar 1984) was used for each weather type to identify if the difference in mean annual counts between high ignition years and low ignition years is statistically significant. Once a particular weather type is identified as being associated with wildfire activity, Spearman's rank correlation is used to test the relationship between annual wildfire ignitions and the annual number of days of a particular weather type. Spearman's rank correlation is a nonparametric alternative to Pearson's correlation and uses ranked measurements (Zar 1984; McGrew Jr. and Monroe 2009).

III.2.3.2 Antecedent Weather Type Occurrences

While analyses at the annual timescale are useful and informative, they do not provide any information about the actual frequency of weather types in the weeks and months leading up to an ignition, which has implications for short-term, seasonal wildfire forecasts. An increase in a particular weather type may occur after an increase in wildfires, in which case, using the annual time scale would erroneously suggest that the increase in fire activity was attributable to a given weather type. Because DT days tend to be associated with higher levels of wildfire activity (results to be shown), an analysis is provided examining the ratio of DT days to the combination of MM and MT days. MM and MT days were chosen for comparison due to their high prevalence. This ratio is calculated for the 1-month, 3-months, and 6-months (30, 90, and 180 days, respectively) prior to each wildfire occurrence in each national forest. The same ratio is also calculated for randomly selected 1-month, 3-month, and 6-month periods using a bootstrapping approach with 10,000 iterations. The median ratio should be statistically greater during the period leading up to a wildfire than for randomly selected periods, and is tested with the Wilcoxon rank sum test at the 95% significance level.

III.2.3.3 Association with NAO and ENSO

The linkages between teleconnections, weather types, and wildfire activity have been explored in previous research and this provides guidance for understanding which teleconnections may be most influential. Sheridan (2003) observed that many weather types are significantly influenced by the phase of both NAO and PNA. These oscillations have also been identified as important drivers of wildfire variability in Mississippi (Dixon, Goodrich, and Cooke 2008). The influence of ENSO has been well-documented in the Florida Everglades. Research by Brenner (1991), Beckage et al. (2003), and Goodrick and Hanley (2009) demonstrate the importance of cold phases of ENSO to increased fire activity. Finally, Schroeder and Buck (1970) suggest that the Bermuda High is influential in wildfire activity in the Southeast.

This chapter therefore examines both NAO and ENSO in relation to weather type variability. Data are obtained from the Climate Prediction Center (http://www.cpc.ncep.noaa.gov/data/indices/). The ratio of DT days to all days is calculated for each month in each national forest from 1970-2011 to correspond with the dates of the wildfire ignition data. The data are subdivided by ENSO and NAO phase where index values ≤-1 represent negative phases and index values ≥+1 constitute positive phases.

III.3 Results and Discussion

III.3.1 Changes in Weather Type Occurrences

Due to the distance between a given SSC station and national forest, it is necessary to assess the validity of using an SSC station to represent the weather type record for a proximal national forest. Figure 18A depicts January maximum temperature (°C) for Bankhead National Forest. Over the period 1970-2011, the correlation coefficient is 0.94, the mean bias error is -0.88°C, and the mean absolute difference is 1.7°C. April, July, and October are shown in Figure 18B-D.

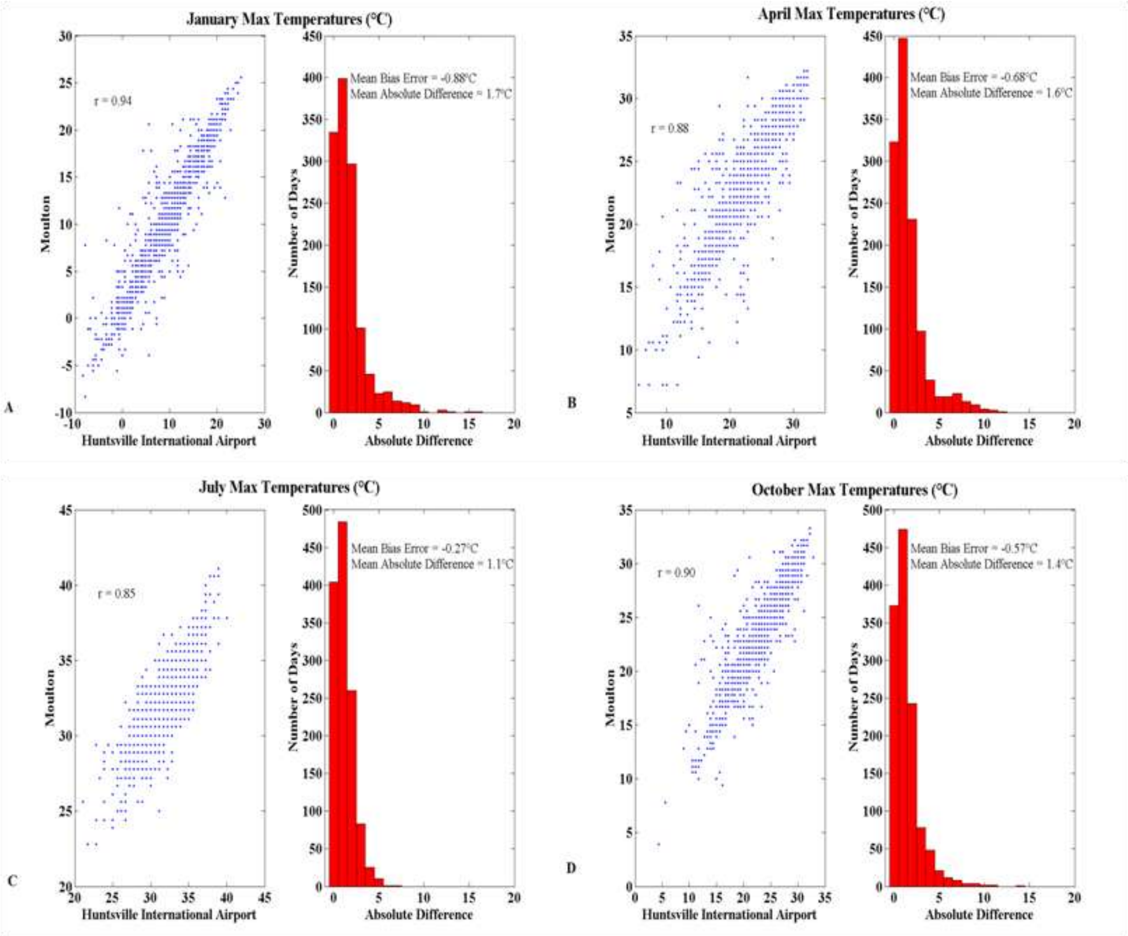


Figure 18. Comparison of daily maximum temperatures (°C) for Bankhead National Forest in (A) January, (B) April, (C) July, and (D) October.

This same procedure was repeated for each national forest with the exception of Apalachicola National Forest, where the first-order SSC station, Tallahassee International Airport, is already immediately adjacent to the northeast boundary of the forest. Overall, results suggest that there is a close association between daily maximum temperatures at an SSC station and a station near or within national forest boundaries throughout the year. Furthermore, absolute differences between the two stations are minimal. While daily maximum temperatures are only one component of the SSC, this is evidence that the use of SSC data is appropriate for representing weather types within national forests. However, some national forests do not possess as strong of a relationship as that presented in Bankhead National Forest. Figure 19 depicts the same analysis for Tombigbee National Forest. The correlation coefficients here are weaker than those for the other national forests. In addition, the mean bias error and mean absolute difference for each of the four months is also relatively larger. Despite the weaker correlations, the assumption is made that the SSC data still reasonably represents a proximal national forest; however, this caveat regarding Tombigbee National Forest should be kept in mind.

Chi-square goodness-of-fit tests revealed no significant differences between observed and expected frequencies ($p<0.05$; results not shown). The climatology of each weather type from 1970-2011 and the mean annual number of days in each weather type category during the seven highest and lowest ignition years in national forests is depicted in Figure 20. For most weather types, the difference between the climatology and high or low ignitions is very small, which explains the lack of statistically significant Chi-square results. Differences between mean annual counts of weather types between years with high and low ignitions is, likewise, also minimal. For example, there is little difference in DP and MP weather types, regardless of ignition level. In Holly Springs National Forest (Fig. 20A), most weather types demonstrate only small differences between the climatology and high or low ignition years, with the primary exception of DT weather types.

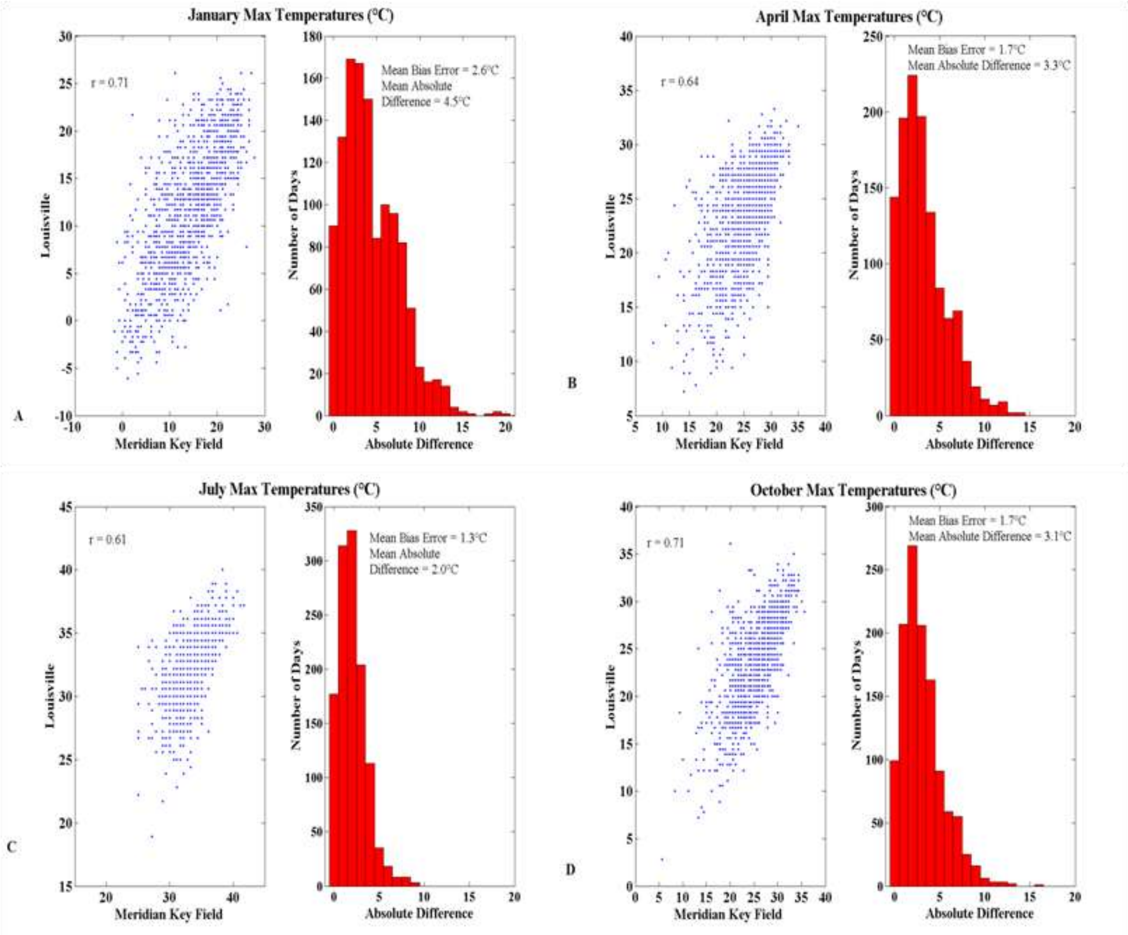


Figure 19. Comparison of daily maximum temperatures (°C) for Tombigbee National Forest in (A) January, (B) April, (C) July, and (D) October.

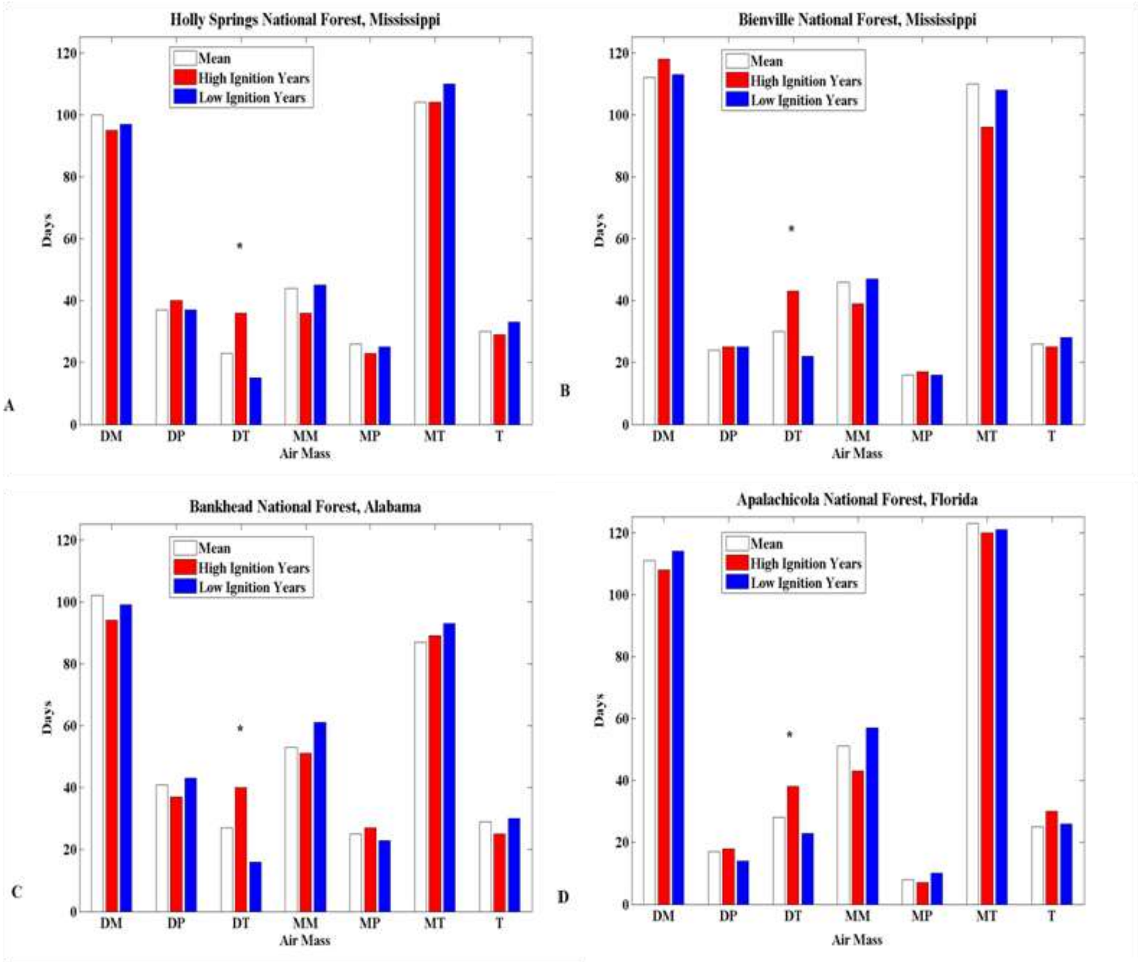


Figure 20. Mean annual weather type counts. The climatology (1970-2011) is depicted in white, years with high ignitions in red, and years with low ignitions in blue for (A) Holly Springs National Forest, (B) Bienville National Forest, (C) Bankhead National Forest, and (D) Apalachicola National Forest. Statistical differences, according to the Mann-Whitney U test, are indicated with an asterisk (*$p<0.05$*).

Table 4 presents the observed differences in mean annual weather type counts between high ignition years and low ignition years, along with Mann-Whitney U test results. Also shown in Table 4 are percentage differences in mean annual weather type counts between high and low ignition years. During high ignition years, Holly Springs experiences 21 more DT days during high ignition periods (Table 4). Similar relationships are found in Bienville National Forest (Figure 20B) with 22 more days (Table 4), Bankhead National Forest (Figure 20C) with 25 more days (Table 4), Apalachicola National Forest (Figure 20D) with 16 more days (Table 4), and Talladega National Forest (Table 4) with 14 more days. Over the 1970-2011 period examined in this study, there were 68% to 140% more DT days during high ignition years than low ignition years. Mann-Whitney U tests reveal that the mean annual number of DT days during high ignition years is statistically different ($p<0.05$) from low ignitions years in five of nine national forests in Figure 20. In addition, MT days are statistically different in Talladega. However, similar patterns with MT days were not uncovered in any other national forest.

National Forest	Air Mass						
	DM	DP	DT	MM	MP	MT	T
Apalachicola	-6 (-5%)	4 (26%)	**16** **(68%)**	-14 (-25%)	-3 (-31%)	0 (0%)	3 (13%)
Bankhead	-5 (-5%)	-6 (-14%)	**25** **(160%)**	-10 (-16%)	4 (17%)	-4 (-4%)	-6 (-18%)
Bienville	4 (4%)	0 (0%)	**22** **(99%)**	-8 (-17%)	1 (3%)	-12 (-11%)	-3 (-11%)
Conecuh	-3 (-2%)	-5 (-21%)	4 (21%)	0 (1%)	1 (4%)	2 (2%)	1 (4%)
De Soto	5 (5%)	-2 (-10%)	16 (59%)	-3 (-6%)	-2 (-15%)	-7 (-6%)	-1 (-3%)
Holly Springs	-2 (-2%)	4 (10%)	**21** **(140%)**	-9 (-20%)	-2 (-8%)	-6 (-5%)	-4 (-12%)
Homochitto	4 (5%)	0 (1%)	13 (75%)	-7 (-13%)	0 (0%)	-8 (-5%)	-5 (-18%)
Talladega	9 (9%)	5 (14%)	**14** **(89%)**	-9 (-16%)	-2 (-9%)	**-15** **(-14%)**	-1 (-5%)
Tombigbee	4 (4%)	8 (39%)	4 (17%)	-1 (-1%)	1 (4%)	-12 (-10%)	-4 (-15%)

Table 4. Observed differences in the mean annual number of days for each weather type between high ignition years and low ignition years (calculated as high minus low). In parentheses are percentage changes. Mann-Whitney U test results are indicated in bold ($p<0.05$). Days are rounded to the nearest whole day.

Five of the nine national forests presenting statistically significant differences in the mean annual number of DT days between high and low ignition years are suggestive of a weak, generalized region-wide pattern with high ignition years experiencing an increase in DT weather types relative to low ignition periods and a decrease in DT days during low ignition years. However, there are exceptions to this general pattern as can be seen in Conecuh, De Soto, Homochitto, and Tombigbee National Forests (Table 4).

Strong positive correlations between the number of DT days occurring in a year and the annual number of wildfire ignitions in six of the nine forests are depicted in Table 5. Spearman's rank correlations were performed between the annual number of ignitions and the annual number of DT days. A relatively consistent pattern emerges (Table 5). Strong positive correlations in Apalachicola, Bankhead, Bienville, De Soto, Holly Springs, and Homochitto suggest that as the number of DT days increases, so does the number of ignitions. No statistically significant relationships were found in either of the two previous analyses for Tombigbee or Conecuh National Forests. It is unclear why these two areas seem to deviate from the general region-wide pattern.

National Forest	**Spearman's rho**
Apalachicola	**0.39**
Bankhead	**0.46**
Bienville	**0.50**
Conecuh	0.08
De Soto	**0.45**
Holly Springs	**0.53**
Homochitto	**0.32**
Talladega	0.25
Tombigbee	-0.02

Table 5. Spearman's rank correlation results between the annual number of wildfire ignitions and annual number of DT days for all national forests in the central Gulf Coast. Significant results are indicated in bold ($p<0.05$).

III.3.2 Antecedent Weather Type Occurrences

Combining the two previous analyses suggests that DT weather types are generally associated with wildfire ignitions in the central Gulf Coast. While relationships between DT air masses and fire ignitions on an annual timescale are useful in identifying general atmospheric conditions associated with years with high fire activity, it does not provide more specific information regarding antecedent conditions leading up to individual fires. Instead, intra-annual timescales should also be examined; in particular, the timing of DT weather types prior to a wildfire occurrence may provide some forecasting ability. If a particular weather type (e.g. DT) is more common in the weeks and months leading up to an ignition, this may provide useful information to future research in improving predictive models of fire risk. As depicted in Figure 21, DT days are more common in the weeks and months leading up to an ignition. Figure 21A compares the ratio of DT days to MM and MT days combined 1-month prior to fire ignitions to the same ratio for randomly selected 1-month periods in Bienville National Forest.

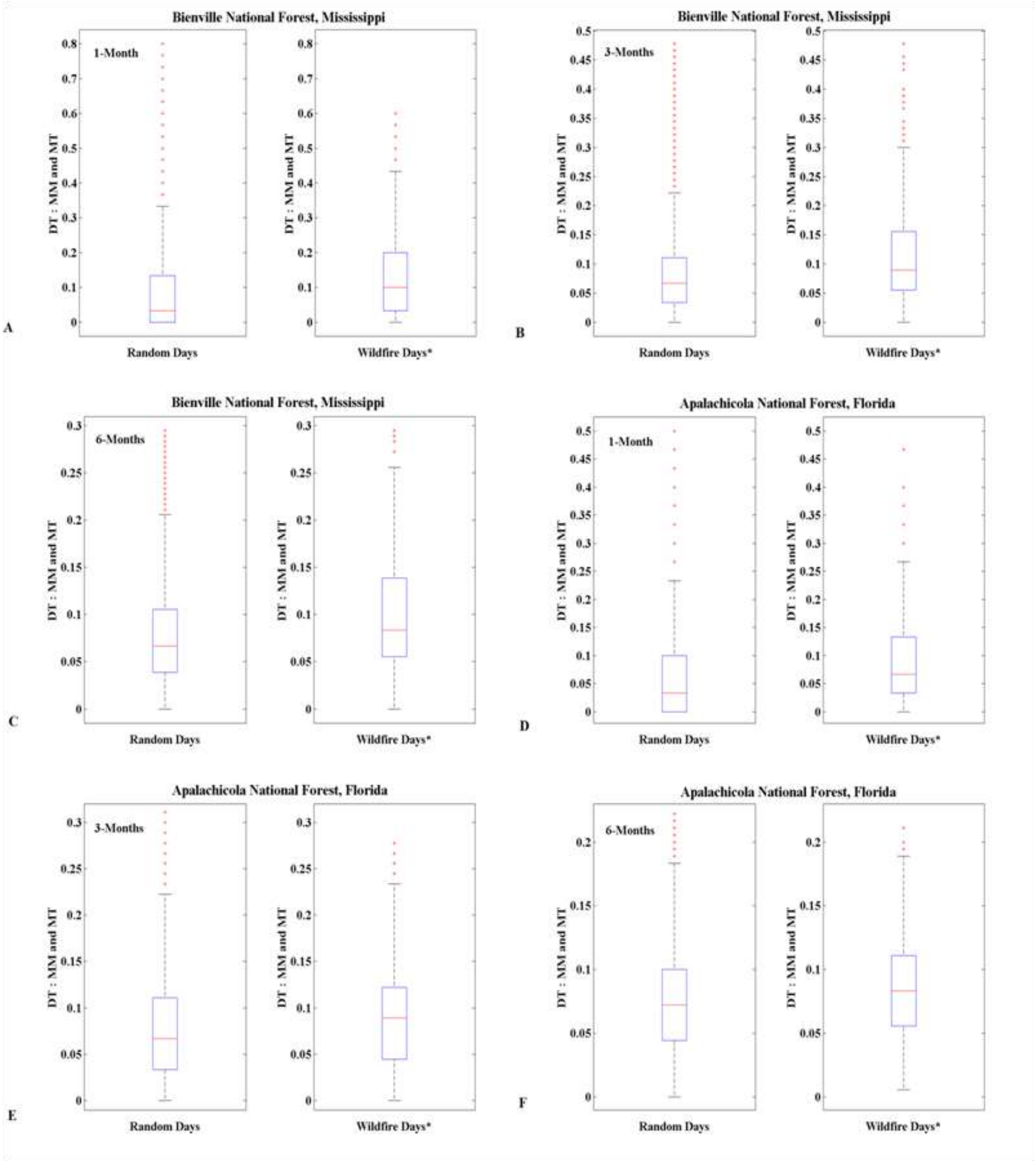


Figure 21. DT days leading up to a fire versus DT days from randomly selected days. Boxplots compare the ratio of the number of DT days to the number of MM and MT days combined for 10,000 randomly selected periods (left plot) and periods prior to a fire ignition (right plot). Results are presented for Bienville National Forest for (A) 1-month, (B) 3-month, (C) 6-month periods and for Apalachicola National Forest for (D) 1-month, (E) 3-month, and (F) 6-month periods. Statistical significance is indicated with an asterisk (*p<0.05*).

According to the Wilcoxon rank sum test, the median ratio of DT days to MM and MT days combined is statistically greater than the median ratio for randomly selected 1-month periods. Similar results are presented for Bienville National Forest 3-months prior to fires (Fig. 21B) and 6-months prior to a fire (Fig. 21C), in addition to 1-month (Fig. 21D), 3-months (Fig. 21E), and 6-months (Fig. 21F) prior to fire ignitions in Apalachicola National Forest. In eight of nine national forests, Conecuh being the exception, similar results are uncovered for the 1-month period prior to fire ignitions. For the 3-month period, all national forests experience a higher median ratio of DT days to MM and MT days leading up to ignitions. At the 6-month period, all national forests with the exception of Tombigbee and Bankhead National Forest experience higher ratios prior to ignitions. It should be noted, however, that because this approach randomly selects 10,000-day periods, it is possible to have results with varying statistical significance. However this is very rare and this is a robust approach for the purposes it is intended for. This suggests that while a strong, consistent, region-wide climate signal (seen in each national forest) is not necessarily detectable when examining weather types or air masses on an annual scale, shorter timescales of weeks to months may uncover more significant relationships in the central Gulf Coast. Schroeder and Buck (1970) suggest that much of the Southeast consists of “flashy fuels”, vegetation that dries quickly and can consequently ignite even during relatively short dry spells. Taken together, this may imply that fire ignitions in this region respond relatively quickly to short-term climate and do not require a lengthy “preconditioning period” as shown in some areas of western North America (Swetnam and Betancourt 1990; Crimmins and Comrie 2004; Littell et al. 2009).

Much of the Southeast possesses a bimodal wildfire season with a primary season the late winter and early spring and a secondary season in the fall (Lafon, Hoss, and Grissino-Mayer 2005; Schroeder and Buck 1970), and the central Gulf Coast is no exception. An examination of the monthly climatology of DT weather types in conjunction with monthly total fire ignitions reveals strong similarities. Figure 22 depicts monthly ignitions for four representative national forests in the region. In addition, the climatology of DT weather types closely follows the monthly pattern of ignitions in each of the national forests in Figure 22. Furthermore, total monthly ignitions and total monthly DT days from 1970-2011 are strongly correlated.

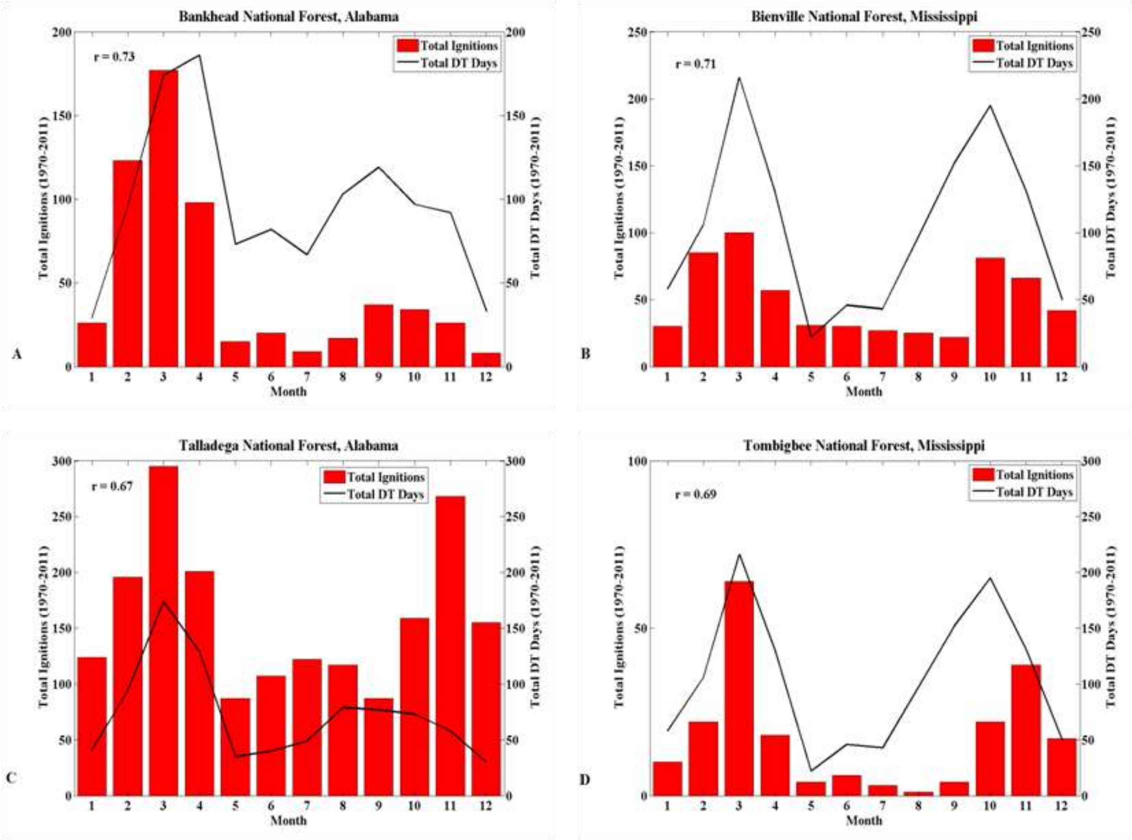


Figure 22. Total monthly ignitions (1970-2011) versus total monthly DT weather types (1970-2011) for (A) Bankhead National Forest, (B) Bienville National Forest, (C) Talladega National Forest, and (D) Tombigbee National Forest. All four exhibit statistically significant correlations (*p<0.05*).

Overall, Figure 22 suggests that the fire season in the Southeast is partly driven by the climatology of weather type occurrences, in particular DT weather types. Anticyclonic flow in January tends to originate in western Canada, tracks through the Midwest and into the Southeast (Zishka and Smith 1980). To make a broad generalization, this anticyclonic flow most likely influences fire ignitions in the Southeast.

In summary, during high ignition years, there tends to be an increase in DT weather types in certain national forests. More specifically, the weeks and months prior to ignitions see elevated number of DT days. As suggested by previous studies detailing relationships between drought conditions and wildfires (Lafon, Hoss, and Grissino-Mayer 2005; Mitchener and Parker 2005), dry, hot weather types should produce conditions more conducive to wildfire ignitions as a lack of moisture and high evapotranspiration dessicates fuels, making them more susceptible to combustion. As expected, a decrease in moist weather types accompanies the increase in DT weather types. Perhaps not as expected, other dry weather types (DM and DP) also decrease. This may suggest that temperature and not solely moisture play a role in creating ideal conditions for wildfire in the region. Doublin and Grundstein (2008) demonstrated that both high temperatures, as well as lack of precipitation control soil moisture deficits in the Southeast. While out of the scope of this research, the climatology of anticyclones in the Southeast may also play a significant role in dictating the timing of ignitions in the central Gulf Coast.

III.3.3 Associations with NAO and ENSO

Due to the presence of a primary wildfire season in the late winter/early spring, discussion of the results of the analysis pertaining to NAO and ENSO will focus on this period. Figure II.8A depicts the ratio of DT weather types to all other weather types divided by NAO phase from 1970-2011 in Bankhead National Forest. It is expected that positive NAO phases result in an increase in the number of DT days as the strength of the westerlies increases, pushing DT weather types farther east into the region, particularly in the late winter and early spring (Sheridan 2003). This time of the year corresponds with the primary peak in wildfire ignitions and DT weather types (see Fig. 22). In Figure 23A, Bankhead National Forest experiences a higher ratio of DT to all other weather types in March and April, corresponding with the peaks in ignitions and DT frequency, as expected. Figure 23B presents similar findings for Bienville National Forest during the months of February through April. Talladega National Forest again experiences similar patterns (Fig. 23C), particularly in March and April. The secondary fall fire season does not seem to be closely related with phases of NAO as the oscillation tends not to be as dominant in the fall. However, October and November may stand out as having DT air masses driven by positive phases of NAO, as demonstrated by Bankhead, Bienville, and Homochitto.

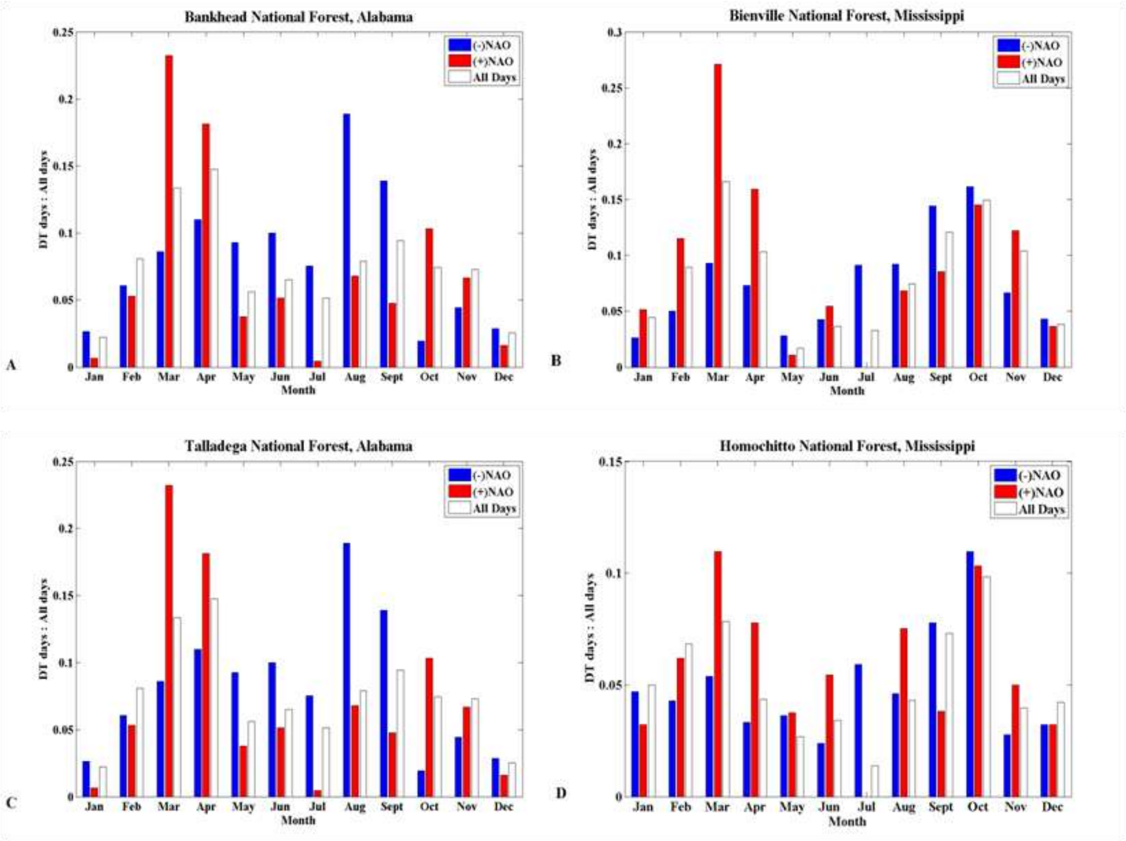


Figure 23. Relationship between ratio of DT days : All days and NAO for (A) Bankhead National Forest, (B) Bienville National Forest, (C) Talladega National Forest, and (D) Homochitto National Forest.

The same analysis was performed for ENSO (Figure 24). As is well known, cold phases of ENSO should result in drier conditions (Douglas and Englehart 1981; Ropelewski and Halpert 1986). It is expected, therefore that La Niña phases would be associated with higher ratios of DT to all other weather types. Results, however, did not prove as conclusive. Locations near the coast tended to show a greater association between the ratio of DT days to all other days during the winter and early spring as demonstrated by De Soto, Homochitto, and Conecuh National Forests in Figure 24.

Apalachicola National Forest (not shown) shares a similar pattern. Because Apalachicola possess a summer fire season, this suggests that a lagged relationship may exist. Further research is warranted to decipher this relationship.

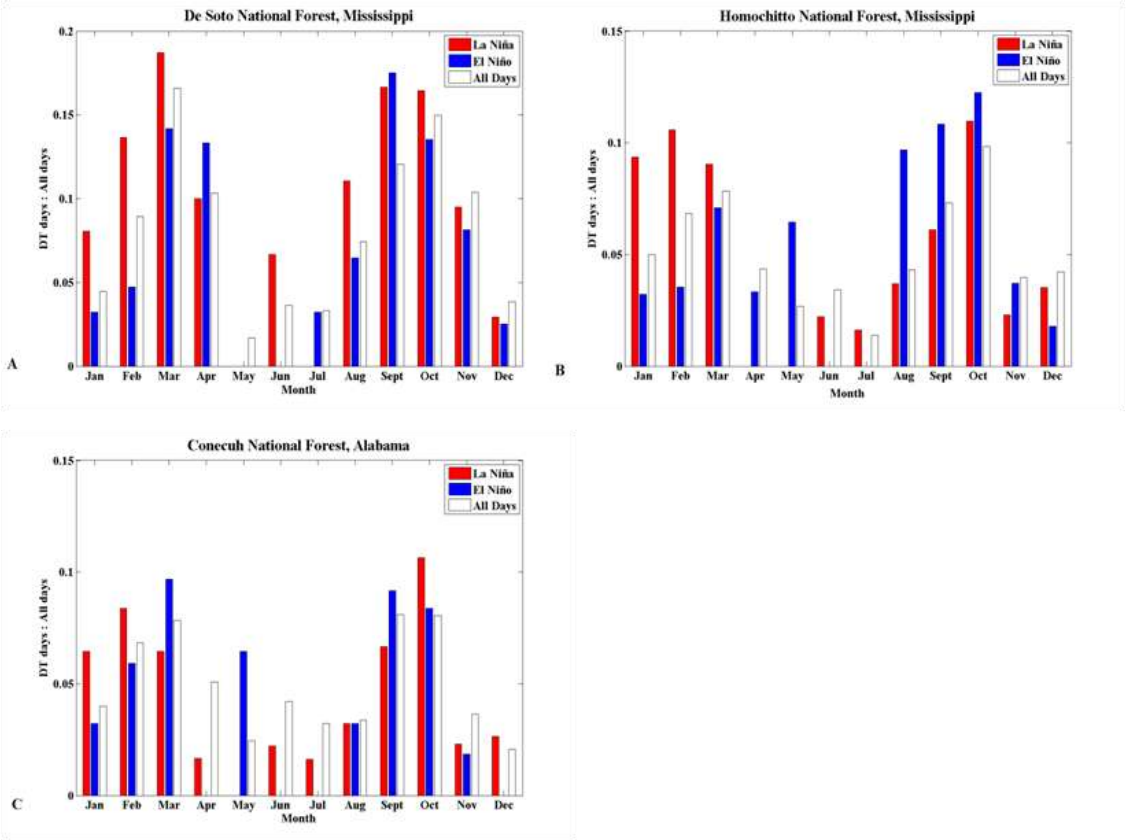


Figure 24. Relationship between ratio of DT days : All days and ENSO for (A) De Soto National Forest, (B) Homochitto National Forest, and (C) Conecuh National Forest.

III.4 Conclusions

This study examined relationships between weather type occurrences and wildfire ignitions in central Gulf Coast national forests to identify regional patterns of weather types associated with wildfire ignitions. The Spatial Synoptic Classification (SSC) scheme (Sheridan, 2002) was used to associate weather types and wildfire ignitions during the period 1970-2011. Chi-square goodness-of-fit tests revealed no statistical differences between weather type frequencies during years with high or low numbers of ignitions. Mann-Whitney U tests did reveal statistically significant differences in mean annual weather type counts between high and low ignition years. In particular, DT weather types tended to be much more frequent during years with high ignitions in certain national forests. Correlations also showed a positive relationship between annual fire counts and annual DT counts in most national forests. Consequently, this study concludes that a weak, generalized pattern is detected in which Dry Tropical weather types occur more frequently during years with high numbers of ignitions.

However, examining the relationship between weather types and fire ignitions on an annual scale does not reveal any information on antecedent conditions leading up to a fire ignition. More specifically, this study investigated the ratio of DT days to MM and MT days combined for the months leading up to fire ignitions. The median ratio of DT days to the combined MM and MT days is statistically greater for periods leading up to a fire than for the median ratio on randomly selected periods. These results are statistically significant for all national forests 1-month prior to fire ignitions, for eight of nine national forests 3-months prior, and for seven of the nine national forests 6-months prior to fire ignitions. Results demonstrate that atmospheric conditions in the preceding months can pre-condition fuels for fire ignitions. Furthermore, an analysis into the large-scale atmospheric drivers of DT weather types reveals that the positive phase of NAO is associated with increased DT weather types, presumably due to the weather type expanding from its source region due to the increase in westerly flow. Relationships with positive NAO are most prevalent during the late winter/spring fire season common in this region. While relationships involving ENSO were similarly explored, such relationships proved difficult to uncover. Cold phases of ENSO may be associated with DT frequencies in national forests near the coast.

This study is the first to examine wildfire using the SSC. The approaches used in this study are easily transmittable to other regions of interest, including western North America, Australia, the Mediterranean, and other locations prone to burning. In addition, this study begins to address the knowledge gap in Southeast USA wildfire climatology and such results may also be applicable to other humid ecosystems where vegetation is abundant and climatic conditions are rarely dry.

CHAPTER IV

SYNOPTIC TYPING OF WILDFIRES

IV.1 Introduction

The categorization of weather patterns, air masses, or circulation features into similar groupings, or synoptic typing, provides an environmental baseline with which to assess a variety of issues (Keim, Meeker, and Slater 2005; Yarnal 1993). Previous studies have used both manual, automated, and hybrid synoptic techniques to examine air pollution (Kalkstein and Corrigan 1986), extreme fire weather (Crimmins 2006), snowfall (Leathers and Ellis 1996), and drought (Quiring and Goodrich 2008), among many others. This chapter takes a circulation-to-environment approach to identify synoptic types in the central Gulf Coast region of the USA. The resultant synoptic types are then associated with wildfire ignitions in nine national forests in the region.

Fire is a critical ecological disturbance in many biomes and its presence, absence, frequency, and magnitude all influence vegetation structure and composition (Pyne 1982; Whelan 1995; Bond and van Wilgen 1996; Pyne, Andrews, and Laven 1996). Fire is a complex phenomena influenced by a number of factors, including topography, land management policies, and vegetation composition among others (Whelan 1995; Pyne 1982; Krawchuk et al. 2009; Meyn et al. 2007; Bond and van Wilgen 1996). One such factor influencing fire is climate. Climate plays a fundamental role in the spatial and temporal patterns of wildfire on the landscape (Hawbaker et al. 2013; Meyn et al. 2007; Krawchuk et al. 2009).

Fire has been a common feature of the southeastern USA landscape for thousands of years (Fowler and Konopik 2007; Lafon 2010) and many fire-adapted communities are found in the Southeast (Lafon 2010). One of the more well known communities is that of the longleaf pine (*Pinus palustris*) once common to the coastal plain (Frost 2006). Despite very successful suppression policies (Pyne 1982), the Southeast continues to lead the nation in fire ignitions (Pyne 1982; Andreau and Hermansen-Báez 2008).

Despite the significant fire activity in the region, studies examining relationships between climate and wildfire in the region are limited. Drought has been the most common climatic feature linked with wildfire in the region (Lafon, Hoss, and Grissino-Mayer 2005; Mitchener and Parker 2005). In turn, variability in drought and therefore, fire are often driven by large-scale oceanic and atmospheric oscillations, including ENSO, NAO, and PNA (Beckage et al. 2003; Goodrick and Hanley 2009; Dixon, Goodrich, and Cooke 2008). Such teleconnections manifest themselves in synoptic circulation patterns.

Earlier works recognized the importance of understanding synoptic conditions associated with fire. One of the earliest studies to examine the relationship between synoptic conditions and wildfire was Schroeder and Buck (1970) who found high pressure systems with dry conditions and strong winds to be important for fires in the central and eastern USA. The passage of cold fronts has also been shown to be important. In an examination of fires in the eastern USA > 5,000 acres, over half the events occurred after a dry cold front passed through an area resulting in strong winds and low humidity (Brotak and Reifsnyder 1977). Another quarter of examined fires occurred prior to cold fronts (Brotak and Reifsnyder 1977). A sequence of high pressure types were found to be associated with fires in West Virginia and the surrounding states (Takle et al. 1994). A pre-high pattern often led to drier conditions and could be replaced by an extended high pressure lasting 2 to 5 days whereby the fire would ignite (Takle et al. 1994). The extended high could then transition into a back-of-high pattern leading to the largest fires in the region (Takle et al. 1994). Finally, Heilman (1995) found three patterns to be strongly associated with fires in the Southeast. A trough over the eastern USA or Atlantic coast resulting in lower geopotential heights, northwesterly flow, and cooler, but drier conditions was determined to be the primary pattern. A ridge over the eastern USA, which Heilman (1995) speculated may shift the Bermuda High westward and consequently block the advection of moisture from the Gulf of Mexico into the region was also found associated with fire. Finally, zonal flow across the region would bring warm, dry air (Heilman 1995). Taken together, it seems that fire activity in the region is associated with various set-ups of high pressure, zonal flow, and interestingly both ridges and troughs. More recent work has examined synoptic patterns and fire outside the region, including Crimmins (2006) in the American southwest, Trouet et al. (2009) along the Pacific Coast, and Skinner et al. (2002) in Canada .

The objectives of this chapter are two-fold. First, synoptic types representing the primary circulation patterns, are identified in the central Gulf Coast. In order to identify synoptic types, the Synoptic Typer Tools (STT) (Smith 2012; Smith, Dahni, and Blair 2013) are used with principal component analysis (PCA). Second, the resultant synoptic types are associated with wildfire ignitions in regional national forests. This is the first study known to employ STT to address wildfire-synoptic circulation relationships and helps address a need for modern synoptic techniques to be used in fire-climate studies in the Southeast. Results from this and future synoptic typing studies of wildfire will address the previously identified knowledge gap. In addition, knowledge of antecedent synoptic circulation patterns will assist in fire risk forecasting.

IV.2 Data and Methods

IV.2.1 Study Region

As defined here, the central Gulf Coast includes the states of Mississippi, Alabama, and the panhandle of Florida as in Figure 25. This region is home to a variety of vegetation communities, including wetlands, grassland savannas, pine and oak, and upland hardwood forests (Christensen 2000). The diversity of vegetation is often attributed to a variety of soils and hydrology, in addition to ecological disturbances, including fire (Christensen 2000). Mean annual precipitation ranges from 1,000 mm to close to 2,000 mm along the coast. Despite the humid conditions, wildfires are prevalent (Pyne 1982; Lafon and Quiring 2012; Andreau and Hermansen-Báez 2008)

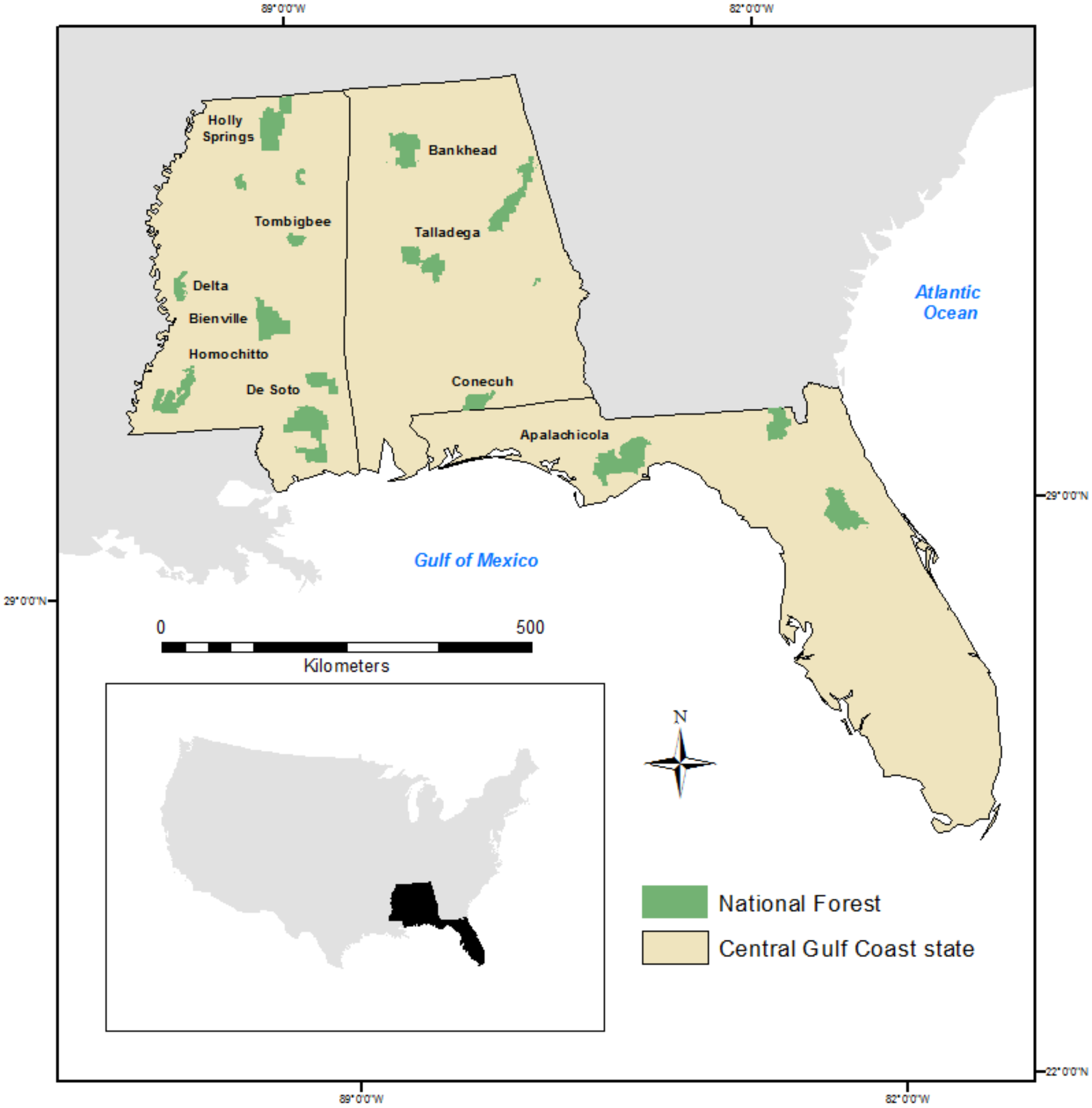


Figure 25. Central Gulf Coast study region and national forests.

IV.2.2 Data

IV.2.2.1 Wildfire Occurrence Data

Wildfire occurrence data for nine national forests in the central Gulf Coast were obtained from the National Interagency Fire Management Integrated Database (NIFMID; USFS 1998) for 1970-2011. NIFMID data contain information, such as ignition source, date, and acres burned, on all fires occurring on federally-managed lands. Prescribed fires, fires with missing ignition source and/or ignition date were excluded from the analysis. In addition, fires burning less than 5 acres were also excluded from the analysis. Table 6 lists the national forests within the study region along with fire statistics.

National Forest	**# of Fire Days (>5 ac burned)**
Apalachicola	396
Bankhead	140
Bienville	168
Conecuh	65
De Soto	1,130
Holly Springs	256
Homochitto	162
Talladega	666
Tombigbee	50

Table 6. Central Gulf Coast national forests with number of fire days analyzed (1970-2011).

IV.2.2.2 Synoptic Typer Tools (STT)

The Synoptic Typer Tools (STT) are an Interactive Data Language (IDL)-based synoptic typing software (Smith 2012; Smith, Dahni, and Blair 2013) available from http://stt.uwinnipeg.ca/STT/HOME.html. STT uses principal component analysis (PCA) to classify geopotential heights and mean sea level pressure from the National Centers for Environmental Prediction/National Center for Environmental Research (NCEP/NCAR) reanalysis data (Kalnay et al. 1996). Data are obtained from the NOAA/OAR/ESRL PSD available at http://www.esri.noaa.gov/psdj. PCA is based on the calculation of eigenvectors where each eigenvector is orthogonal to other eigenvectors (Yarnal 1993). This allows PCA to define unique elements of variation through the principal components (Yarnal 1993). For a more complete review of PCA in the atmospheric sciences, see Preisendorfer, Mobley, and Barnett (1988).

Daily geopotential heights were obtained from the NCEP/NCAR reanalysis data for 1970-2011. Grids of daily (18z) 500 mb geopotential heights were selected for analysis as in Crimmins (2006), Heilman (1995), and Skinner et al. (2002). STT was used in a two-step process. First, data were subjected to PCA through the use of STT using a correlation matrix. Daily grids were subject to varimax orthogonal rotation (Richman 1986) as Skinner et al. (2002) suggests that this provides a more realistic picture of the importance of each component than unrotated components. While Yarnal (1993) suggests that rotation is unnecessary for synoptic typing, it is also not detrimental to the results, therefore the decision to use rotation was made. Second, STT uses K-means clustering to identify synoptic types (Smith 2012; Smith, Dahni, and Blair 2013).

Resulting PCs and synoptic types are discussed. Daily surface weather maps from the National Weather Service (http://www.hpc.ncep.noaa.gov/archives/web_pages/sfc/sfc_archive.php) are displayed to help interpret synoptic types and are displayed where appropriate. In addition, surface weather conditions for each synoptic type are examined using the daily temperature and precipitation data from the Global Historical Climatology Network (Menne et al. 2012).

IV.2.2.3 Synoptic Types – Wildfire Ignitions

Natural resource managers require information about the atmospheric conditions leading up to wildfire activity. To provide an analysis of the antecedent conditions leading up to a fire ignition, the number of days that each synoptic type occurred 180-days prior to an individual fire day were determined. This is then compared to a random 180-day sample. The random sample is determined by a bootstrapping approach that randomly selects 10,000 180-day periods. This is done for each of the nine national forests in the study region. In addition to 180-day periods, this study also examined 90-day periods, 30-day periods, and 5-day periods. While chapter III did not examine 5-day periods, a focus of this chapter is to examine days immediately prior to a fire. Previous literature on synoptic-wildfire relationships (e.g. Takle 1994) also examined antecedent conditions on this time-scale. The bootstrapping procedure is the same procedure used in chapter III of this dissertation. T- tests examined the differences between the medians of the days leading up to an ignition and the randomly selected days. It should be noted here that the process of randomly selecting days can result in selecting a day with an ignition. Also, because the selection process is random, the test statistic and statistical significance can change each time the process is performed. However, by creating 10,000 random samples, the effect of these issues is minimized.

In addition to comparing conditions leading up to fire ignitions with randomly selected days, a similar procedure is used to compare the number of days that each synoptic type occurs prior to a fire with the climatology. For instance, if a fire ignition occurs on February 1, 1987, the number of days that each synoptic type occurs is determined for the 180, 90, 30, and 5 days prior – the same procedure as described above. Instead of comparing these counts to randomly selected periods, the climatology of the 180, 90, 30, and 5 days prior to February 1 is used. A t-test examined the differences between the means of the days leading up to an ignition and the climatology.

Finally, a brief case study is provided documenting the synoptic types and associated weather conditions leading up to a fire. Daily surface weather maps from the National Weather Service are used to provide documentation (http://www.hpc.ncep.noaa.gov/archives/web_pages/sfc/sfc_archive.php).

IV.3 Results and Discussion

IV.3.1 Principal Components

Six principal components (Figure 26) were retained for the creation of synoptic types. There are a number of subjective decisions that must be made when using PCA and there is not a universal rule regarding how many principal components to retain (Yarnal 1993). A visual assessment of the scree plot in Figure 27 suggests a break at 6 principal components. The total variance explained by the 6 principle components retained is 92.6%.

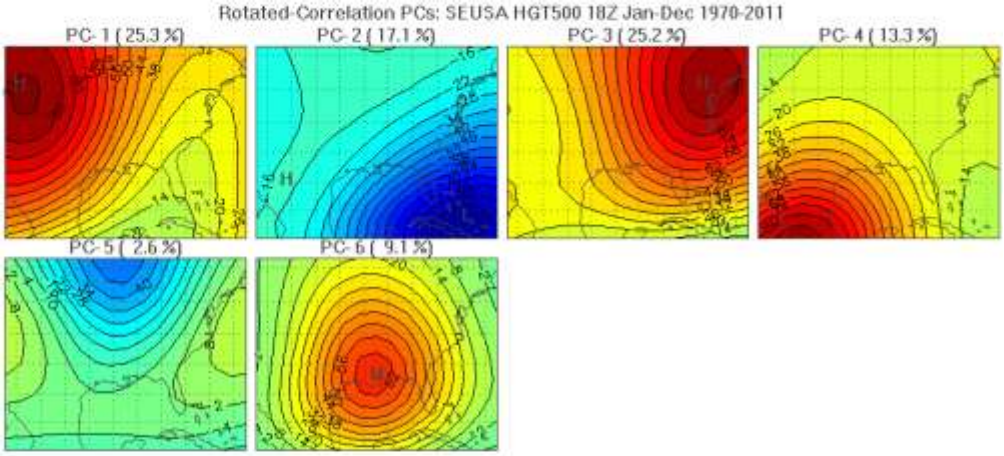


Figure 26. The 6 Principle Components retained for generating synoptic types. The variance explained for each PC is shown in parentheses.

Figure 27. Scree plot with PCs sorted by largest percentage of variance explained (black line) and unsorted variance (red line).

IV.3.2 Synoptic Types

There is little consensus on the optimum method for selecting the correct number of clusters (synoptic types) and this decision is somewhat subjective (Yarnal 1993). Based on previous research, it was determined that between 7 and 12 synoptic types would be appropriate (Muller 1977; Keim, Meeker, and Slater 2005). *A priori* expectations of the number of synoptic types that should result from a classification are common (Yarnal 1993). The STT presents users with plots of between-type and within-type variance (Figure 28). Ideally, the number of types chosen should minimize within-type variability and maximize between-type variability. Using these plots, the number of types was narrowed down to solutions (numbers of types) that minimized within-type variability and maximized between-type variability. Then an expert assessment was used to determine that 11 types was the optimum number. While this is an inherently subjective process, the use of Figure 28 along with *a priori* knowledge of the regional climate and expected number of types (see Yarnal 1993) provides justification of the 11 types retained.

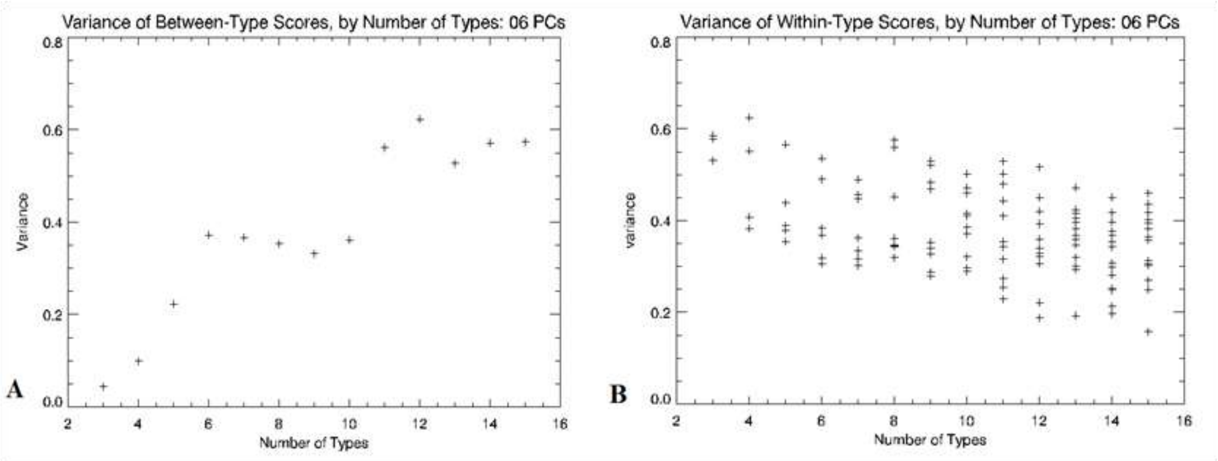


Figure 28. Between-type variance (A) and between-type variance (B) as a function of the number of synoptic types retained.

The resultant synoptic types are depicted in Figure 29. Type 1 occurs most frequently over the duration of the study period at 18.2%, while Types 9, 10, and 11 occur less than 5% of the time. All of the types can occur any time of year, with the exception of Types 10 and 11 which do not occur during July and August. Types 1, 3, and 4 tend to occur most frequently during the summer and are categorized as summer types (Figure 30). Types 5, 6, 9, 10, and 11 occur primarily in the winter (Figure 30). Types 2, 7, and 8 mostly occur during the spring and/or fall (Figure 30). Surface weather conditions are documented in Tables 7-10 (see also Appendix). Multiple stations are used to characterize surface weather conditions. While there is always a certain degree of variability in local weather conditions across a region, similarities can be ascertained.

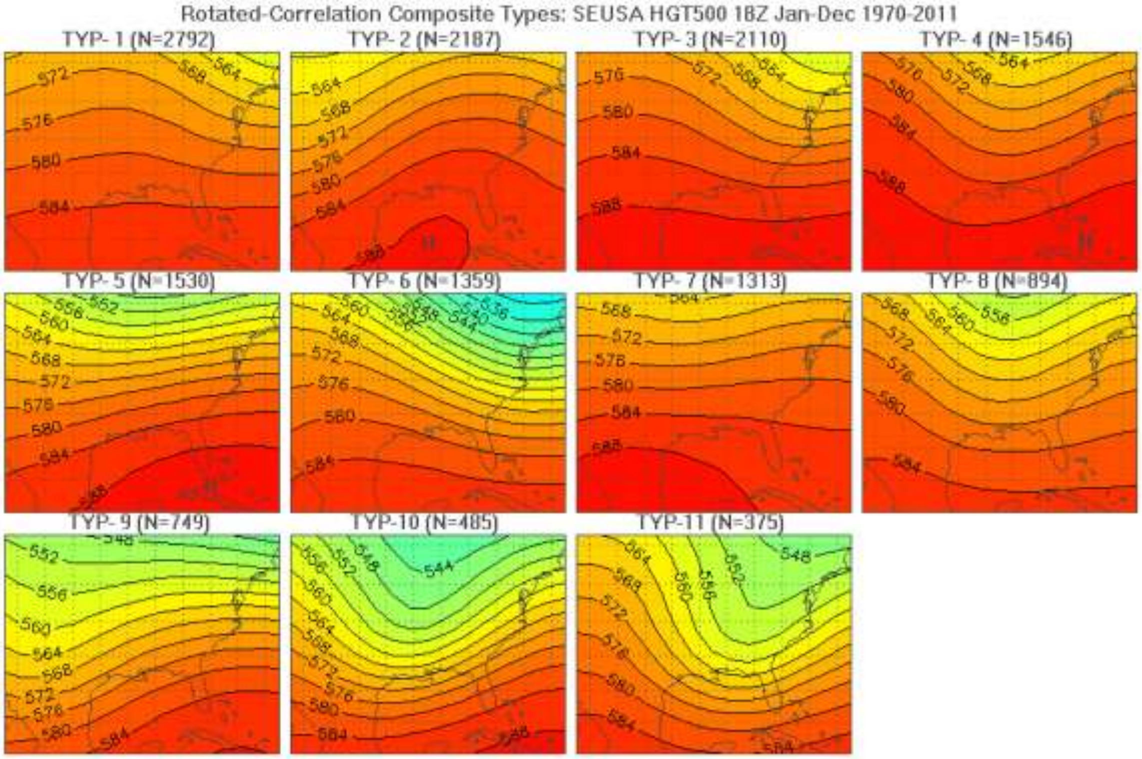


Figure 29. 500 mb geopotential height (decameters) for synoptic types 1-11. The number of days that are classificed in each synoptic type between 1970 and 2011 are shown in brackets.

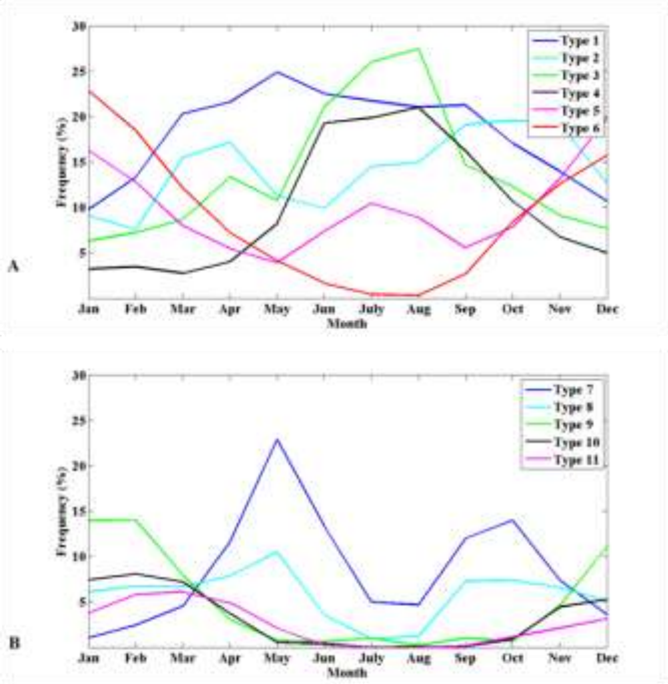


Figure 30. Mean monthly frequency of synoptic types in the central Gulf Coast for Types 1-6 (A) and Types 7-11 (B).

Meridian Key Field: Winter

Types	Precipitation (mm/day)	Mean Maximum Temperature (°C)	Standard Deviation of Mean Max Temp (°C)
1	4.3	15.5	5.9
2	4.6	20.8	4.5
3	1.5	12.6	6.1
4	5.5	14.5	5.8
5	26.4	16.7	6.4
6	0.7	14.6	5.6
7	4.2	18.4	5.1
8	4.4	15.6	5.1
9	8.2	14.8	5.9
10	6.9	11.9	6.0
11	3.2	9.9	5.1

Table 7. Surface weather conditions in Meridian, MS for each synoptic type during winter.

Meridian Key Field: Spring			
Types	**Precipitation (mm/day)**	**Mean Maximum Temperature (°C)**	**Standard Deviation of Mean Max Temp (°C)**
1	3.1	25.4	5.0
2	5.2	27.6	3.6
3	1.8	23.9	5.0
4	6.8	24.8	4.5
5	11.0	25.2	4.9
6	0.9	23.1	5.3
7	4.2	28.3	3.5
8	5.1	24.5	5.3
9	11.2	21.1	4.8
10	7.9	18.7	5.5
11	2.5	18.8	6.3

Table 8. Surface weather conditions in Meridian, MS for each synoptic type during spring.

Meridian Key Field: Summer			
Types	**Precipitation (mm/day)**	**Mean Maximum Temperature (°C)**	**Standard Deviation of Mean Max Temp (°C)**
1	3.1	33.2	2.4
2	1.7	34.3	2.1
3	3.1	33.1	2.6
4	5.5	32.1	2.6
5	5.5	33.7	2.3
6	4.0	34.2	2.6
7	3.4	32.7	2.4
8	4.4	31.3	2.6
9	3.8	32.5	2.0
10	-	-	-
11	-	-	-

Table 9. Surface weather conditions in Meridian, MS for each synoptic type during summer.

Meridian Key Field: Fall			
Types	**Precipitation (mm/day)**	**Mean Maximum Temperature (°C)**	**Standard Deviation of Mean Max Temp (°C)**
1	2.4	26.1	5.9
2	3.2	28.0	4.8
3	0.9	24.5	7.0
4	5.3	25.6	5.6
5	5.5	24.5	6.4
6	0.7	22.6	5.7
7	4.0	27.2	4.7
8	4.3	24.5	5.8
9	6.2	21.6	6.5
10	9.2	15.8	4.9
11	4.5	16.9	5.0

Table 10. Surface weather conditions in Meridian, MS for each synoptic type during fall.

Type 1 is the most common of the 11 synoptic types and is present throughout the year. It occurs most frequently in May (24.9%) and least frequently in January (9.7%). However, it is dominant during the warm season from March through September. This synoptic type is characterized by upper level zonal flow with high geopotential heights. Often, a high pressure cell is present over the region or near the region in either the Atlantic Ocean, Gulf of Mexico, or to the west. Surface conditions are generally dry with moderate temperatures throughout the year. During the summer, wetter conditions characterize Type 1 in Tallahassee.

Type 2 is also a common type and exists throughout the year, particularly in April and September through November. High geopotential heights and frequent high pressure cells in the Gulf of Mexico and Atlantic Ocean characterize this type. The

Bermuda High influences Type 2 as seen in the surface observation from an example Type 2 day (Figure 31A). Type 2 is similar to the Gulf High type described in Muller (1977). Continental tropical or maritime tropical air is advected into the region depending on the position of the Bermuda High and the season (Muller 1977). A ridge sometimes develops along with the high pressure cell. Some days are also more characteristic of Coastal Return (Muller 1977) with winds out of the east, northeast, or southeast . Precipitation patterns vary spatially. In western locations, Type 2 is dry to moderate in the spring and fall. In Tallahassee however, conditions are drier. Mean maximum temperatures are generally warm.

Type 3 is most common during the summer, but is present throughout the year. Type 3 occurs most frequently in June, July, and August. Like Type 1 and 2, Type 3 is associated with a high pressure cell in the Gulf of Mexico, Atlantic Ocean, to the west of the region, or directly over the region (Figure 31B). Type 3 is dry throughout the year.

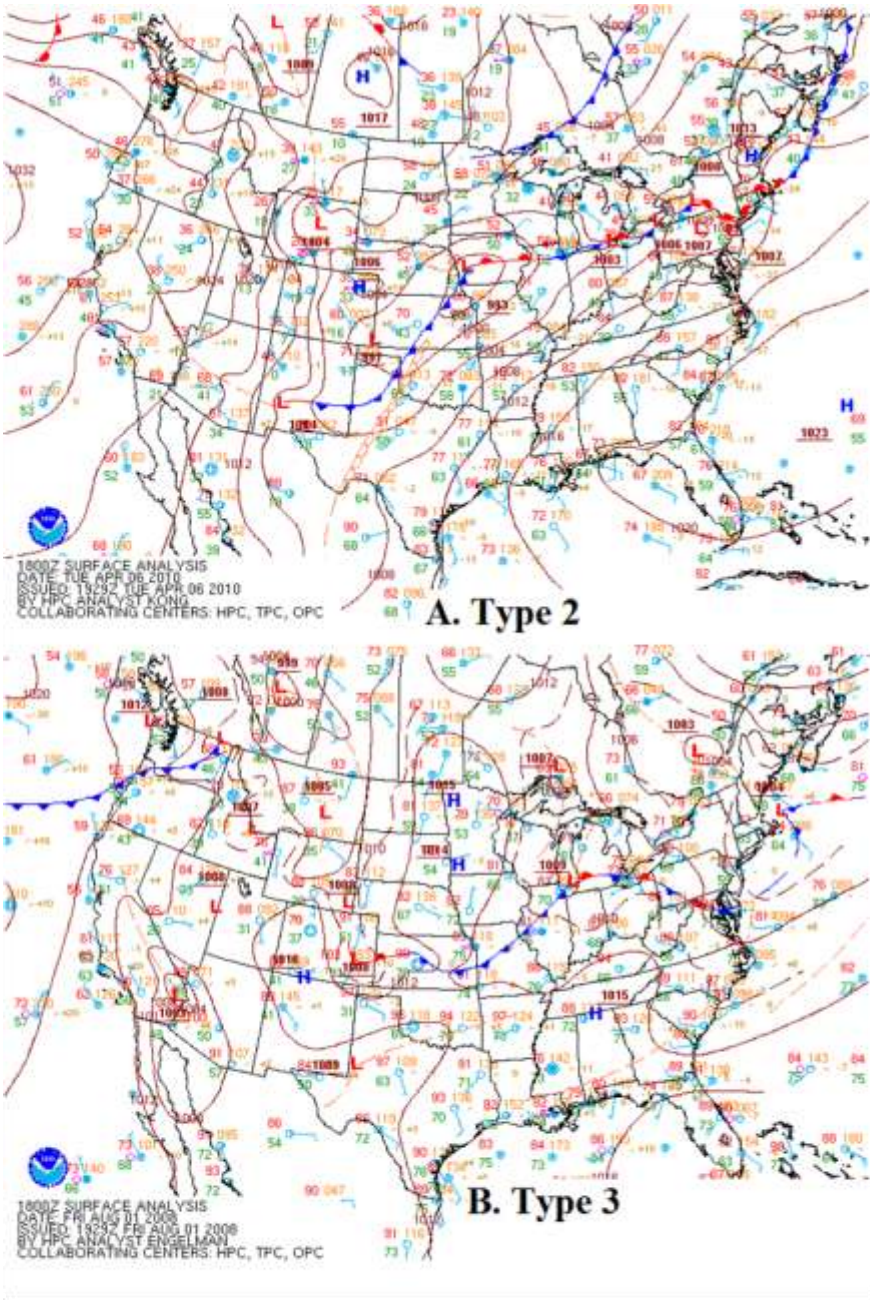
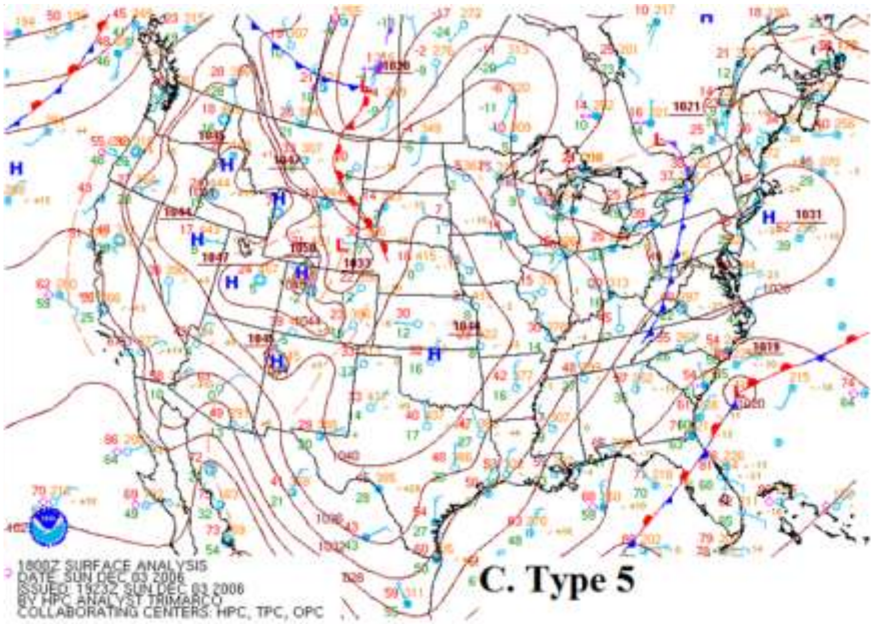
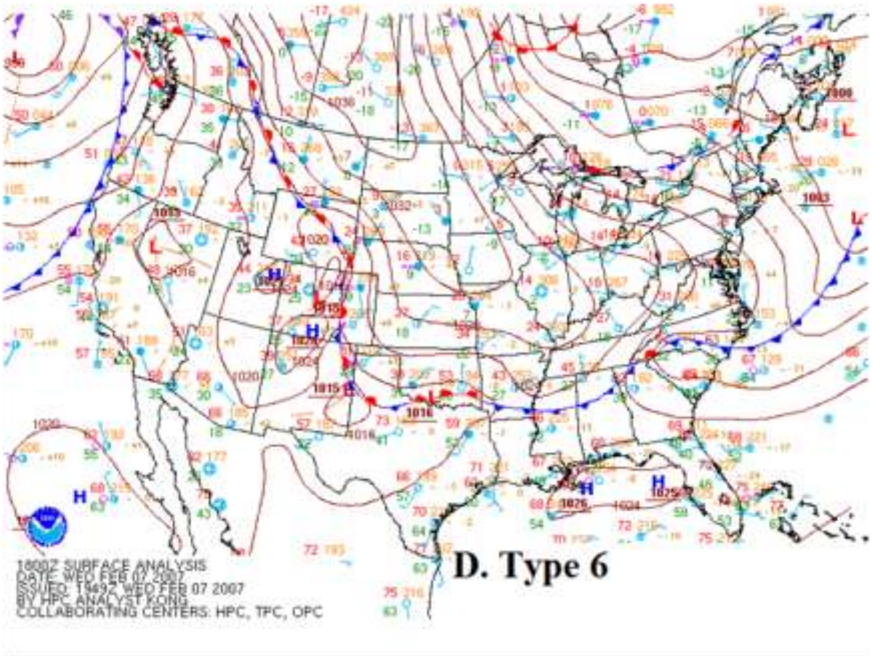


Figure 31. Surface weather maps for a representative day for the following synoptic types: (A) Type 2, (B) Type 3, (C) Type 5, (D) Type 6, (E) Type 10, and (F) Type 11 Maps obtained from the National Weather Service (http://www.hpc.ncep.noaa.gov/archives/web_pages/sfc/sfc_archive.php).

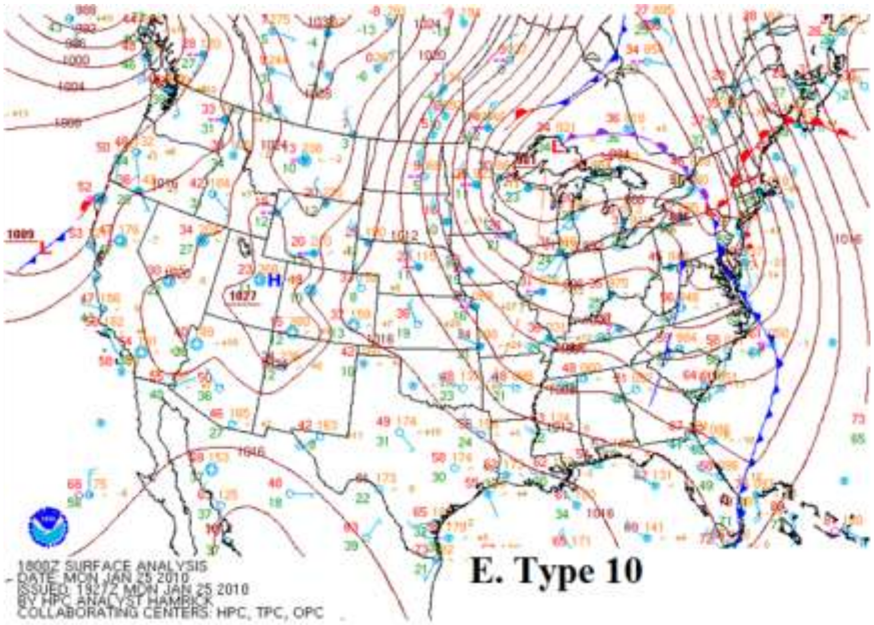


C. Type 5

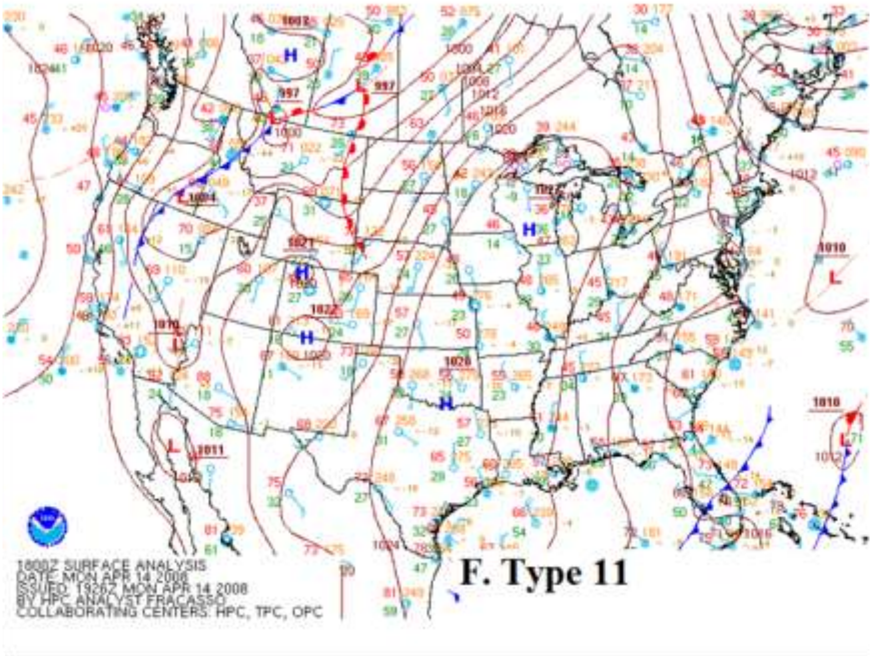


D. Type 6

Figure 31. Continued.



E. Type 10



F. Type 11

Figure 31. Continued.

Type 4 is also a dominant summer type with peak frequencies in June through August into September and October. Type 4 is associated with high geopotential heights, upper-level flow from the northwest and a high located to the south of the study region. Type 4 is relatively wet during the summer and fall.

Type 5 occurs throughout the year, but it is most frequent in the late fall and winter. Interestingly, there is a small peak in frequency in July. There is no known reason why any particular synoptic type in this region would peak in both winter and July. It is noted that many of the summer versions of type 5 differ from the winter versions. Consequently, this discussion focuses on the more dominant winter types. It is possible with all synoptic typing procedures that some days will be classified into categories where they do not necessarily fit and hence, the higher within-type variability. Composites show upper-level zonal flow with a strong gradient in geopotential heights. Type 5 is associated with high pressure over the western USA or the north Pacific and can also occur after a frontal passage, as shown in Figure 31C. Type 5 is associated with wet conditions particularly in the winter. In Meridian, Type 5 is the wettest winter type.

Type 6 peaks in January, but it is prevalent from November through March. Type 6 rarely occurs during the summer months. Type 6 is associated with a trough to the east and a ridge over the Midwest or West. This creates upper-level northwesterly flow into the central Gulf Coast. Cold, dry air is advected into the region, especially after the passage of a cold front, as shown in Figure 31D. Type 6 is associated with moderate to high geopotential heights over the study region. Type 6 is consistently dry across the region.

Type 7 occurs most frequently in spring/early summer and fall. It is characterized by upper-level zonal flow with a high located to the south/southwest. Precipitation conditions are highly variable, ranging from dry to wet depending upon the location. Temperatures are moderate to warm with spring temperatures in Holly Springs (Appendix) the hottest (25.8°C).

Type 8 has an interesting pattern of occurrence. Type 8 is seen throughout the year, but peaks in May. However, it occurs only rarely in June through August. Type 8 is associated with a weak trough over the eastern USA with low to moderate geopotential heights in the region and westerly or northwesterly upper-level flow. Some days classified as Type 8 suggest that the trough over the eastern USA may be associated with frontal passage in the region. Moderately wet conditions characterize Type 8.

Type 9 peaks in February and it is also present in the months of December and January. Type 9 rarely occurs during the summer. Upper-level southwesterly flow is common feature of Type 9. At times, a ridge develops over the East Coast with a trough over the Midwest. Type 9 is generally wet with moderate mean maximum temperatures during the winter. In Meridian, Type 9 is the second wettest winter and fall type and the wettest spring type.

Type 10 occurs January through March and it is absent during the summer. Type 10 represents a trough directly over the region or to the immediate west. An intense low is sometimes seen to the north of the study area. Cold fronts may be traversing the region or have recently passed through and upper-level flow is from the northwest (Figure

31E). Surface conditions are very wet during the fall, winter, and spring. Mean maximum temperatures are cold throughout the region.

Type 11 is very similar to Type 10 because it is associated with a trough directly over the region and low geopotential heights to the north. The main difference between Type 10 and 11 is that the distribution of Type 11 is shifted into the early spring, March being the most common month, rather than the late winter (February) as in Type 10. Type 11 is associated with cold front passage (Figure 31F), whereas Type 10 is the pre- and post- frontal days. Types 11 is comparable to Muller’s (1977) Continental High classification following a cold front passage originating in Canada and bring cold, dry air behind it. Surface conditions are dry and cold.

IV.3.3 Synoptic Types – Wildfire Ignitions

The number of days that each synoptic type occurs prior to an ignition is compared to a random sample of days for each national forest. This analysis is performed for 180 day, 90 day, 30 day, and 5 day periods prior to ignition. An example of this analysis for Apalachicola and De Soto National Forests is presented in Figure 32. There is often a large degree of variability in the synoptic types associated with the days leading up to a fire and the randomly selected days. There are instances where a synoptic type persists for several days, but there are also cases where there is little persistence. Results of the t-tests comparing the mean number of days prior to a fire with randomly selected days for each synoptic type are in Tables 11-14.

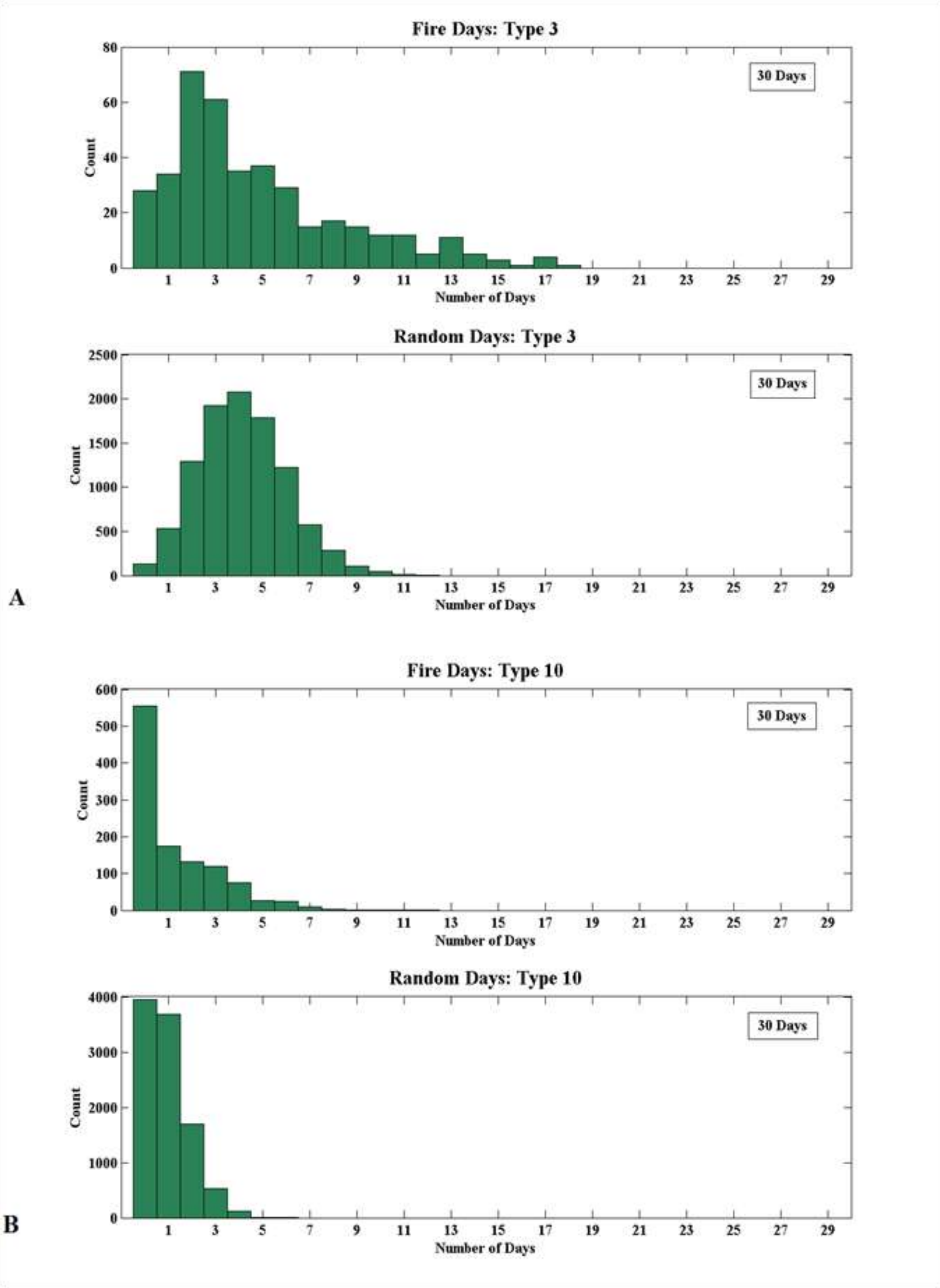


Figure 32. Histograms comparing the number of days leading up to a fire ignition versus the number of randomly selected days for (A) Type 3 in Apalachicola National Forest and (B) Type 10 in De Soto National Forest.

National Forest	180 days Higher	 Lower
Apalachicola	5, 6, 9, 10, 11	1, 4, 7, 8
Bankhead	5, 6, 9, 10	1, 2, 3, 4, 7
Bienville	5, 6, 8	1, 4
Conecuh	2, 9, 10, 11	1, 3, 4, 7
De Soto	5, 6, 8, 9, 10, 11	1, 2, 3, 4, 7
Holly Springs	5, 6, 9, 10, 11	1, 2, 3, 4, 7
Homochitto	3, 6, 9, 10, 11	1, 2
Talladega	3, 5, 6, 9, 11	1, 4, 7
Tombigbee	5, 6, 9, 11	1, 2, 3, 4, 7

Table 11. Synoptic types demonstrating statistically higher (lower) mean number of days 180 days prior to a fire ignition than randomly selected days. Statistical significance assessed with a t-test ($p<0.05$).

National Forest	90 days Higher	 Lower
Apalachicola	1, 3, 7, 8, 11	4, 5, 9, 10
Bankhead	5, 6, 9, 10, 11	1, 2, 3, 4, 7
Bienville	5, 6, 8, 9, 10	1, 2, 3, 4, 7
Conecuh	5, 6, 9, 10	3, 4
De Soto	5, 6, 8, 9, 10, 11	1, 2, 3, 4, 7
Holly Springs	5, 9, 10, 11	1, 2, 3, 4, 7
Homochitto	5, 6, 9, 10, 11	1, 2, 4, 7
Talladega	3, 5, 6, 9, 10, 11	1, 2, 4, 7
Tombigbee	5, 6, 9, 10, 11	1, 2, 3, 4, 7

Table 12. Same as Table 8 for 90 days.

National Forest	30 days Higher	Lower
Apalachicola	3, 4, 7	5, 6, 9, 10
Bankhead	6, 8, 9, 10, 11	1, 2, 3, 4, 5, 7
Bienville	6, 8, 9, 10, 11	2, 3, 4, 5, 7
Conecuh	5, 6, 9, 10, 11	2, 4
De Soto	6, 8, 9, 10, 11	1, 2, 3, 4, 7
Holly Springs	6, 8, 9, 10, 11	2, 3, 4, 5, 7
Homochitto	6, 8, 9, 10, 11	1, 2, 4, 5, 7
Talladega	3, 6, 10, 11	1, 2, 4, 5, 7
Tombigbee	6, 8, 9, 10, 11	2, 3, 4, 5, 7

Table 13. Same as Table 8 for 30 days.

National Forest	5 days Higher	Lower
Apalachicola	1, 3, 7	4, 9, 10
Bankhead	6, 11	4, 5
Bienville	6, 8, 11	5, 9, 10
Conecuh	10, 11	1, 2
De Soto	6, 8, 10, 11	1, 2, 3, 4, 5, 9
Holly Springs	6, 8, 11	2, 4, 5, 7
Homochitto	6, 10, 11	2, 5, 9
Talladega	1, 6, 8, 11	4, 5, 7, 9
Tombigbee	6, 9, 10	4, 5, 7

Table 14. Same as Table 8 for 5 days.

Overall, results from comparisons between antecedent synoptic conditions prior to ignitions and randomly selected time periods do not provide coherent, meaningful patterns. For instance, at the 180-day time period (Table 11), a mix of dissimilar synoptic types exhibit statistically higher and lower mean number of days prior to ignitions. Types 6 and 11, both characterized by dry conditions area associated with increased occurrence prior to fires. However, Types 5, 9, and 10 also demonstrate statistically higher means prior to fires. However, these are wet synoptic types. The reverse is also true when examining statistically lower mean counts. For instance, Type 1, a characteristically dry type is associated with lower occurrence prior to fires. For reasons that are not entirely clear, this does not seem to be an appropriate method for identifying synoptic types associated with the days, weeks, and months leading up to fire activity in the central Gulf Coast.

Results from the t-tests between antecedent synoptic types prior to fire ignitions and the climatology provide somewhat more meaningful results and are depicted in Tables 15-18. The objective of this chapter is to find region-wide patterns of antecedent synoptic circulation types associated with wildfire. For that reason, the arbitrary decision is made to declare a region-wide pattern as one in which similar results are detected in the majority of the national forests examined (i.e. five of the nine national forests).

At 180 days prior to a fire, no relationships are detected in the majority of national forests (Table 15). Type 3 has a statistically higher mean count prior to fire events than the climatology in four of the nine national forests. Type 3 is a predominantly summer type, but can also occur in the spring and fall. High geopotential heights and dry conditions characterize Type 3. High pressure cells are often located over or proximal to the region. Type 11 also occurs more often in two of the national forests. Type 11 is characterized by dry air advected into the region from the west or northwest and is indicative of post cold front passage.

National Forest	**180 days**	
	Higher	**Lower**
Apalachicola	3	
Bankhead	11	
Bienville		
Conecuh		
De Soto	3	
Holly Springs		2
Homochitto	3, 11	2
Talladega	3	1
Tombigbee		

Table 15. Synoptic types demonstrating statistically higher (lower) mean number of days 180 days prior to a fire ignition than the climatology. Blanks indicate that no synoptic type was associated statistically associated with wildfire during the time period examined. Statistical significance assessed with a t-test ($p<0.05$).

At 90 days prior to a fire events, no statistically significant relationships are uncovered in the majority of national forests (Table 16). Like the 180 day period, Type 3 demonstrates a statistically higher mean count in a third of the national forests. Statistically lower mean counts are observed in three national forests (all in Mississippi) for Type 2. This type was previously characterized as a dry and warm synoptic type and it is unclear why this particular would be associated with fewer fire ignitions. Type 2 may have associations with the Bermuda High and depending upon its exact position, may actually bring increased moisture into the western portions of the study region. Further analysis is warranted to clarify this situation.

National Forest	90 days	
	Higher	**Lower**
Apalachicola		9
Bankhead		
Bienville	8	
Conecuh		
De Soto	3	1, 2
Holly Springs		2
Homochitto	3	2
Talladega	3	1
Tombigbee		

Table 16. Same as Table 8 for 90 days prior to a fire ignition.

There is more variability in key synoptic types 30 days prior to an ignition (Table 17). Type 3 is again associated with fire ignitions in four national forests. Type 8 occurs with statistically higher mean counts prior to fires in a third of the national forests. A number of other synoptic types are also observed to have statistically higher mean counts prior to fire events, however, they each only occur in one national forest and therefore a region-wide pattern is not observed. Types 2, 11, and 6 are all characterized as dry types. Type 4 is a wet type and it is unclear why this pattern is observed. Interestingly, Type 2 also occurs with statistically lower mean counts in four of the nine national forests. It is likely that there is a degree of spatial variability in terms of the local surface conditions created by a given synoptic type and this may be the case with Type 2. Type 5 also demonstrates lower mean counts as it is characterized as a wet synoptic type.

	30 days	
National Forest	**Higher**	**Lower**
Apalachicola	2	9
Bankhead	11	
Bienville	8	
Conecuh		
De Soto	3, 4, 6, 8	1, 2, 5, 9
Holly Springs	3	2
Homochitto	3	2, 5
Talladega	3	5
Tombigbee	8	2, 5

Table 17. Same as Table 8 for 30 days prior to a fire ignition.

Finally, 5 days prior to a fire shows no statistically significant higher mean counts in the majority of national forests (Table 18). Type 6, with dry conditions and upper level northwesterly flow, occurs more often in four of the nine national forests. Other important types include Type 8 and Type 11. However, statistically significant lower mean counts were observed in the majority of national forests for Type 5 (two-thirds of national forests) and Type 9 (seven of nine national forests). Both types are characterized as wet synoptic types.

National Forest	5 days Higher	 Lower
Apalachicola	6	9, 10
Bankhead	11	5, 9
Bienville		5, 9, 10
Conecuh		1
De Soto	6, 7, 8, 11	1, 2, 9
Holly Springs	3, 6, 8	2, 5, 9, 10
Homochitto		2, 5, 9
Talladega	6	5, 9
Tombigbee		2, 5, 7

Table 18. Same as Table 8 for 5 days prior to a fire ignition.

Based on the analysis comparing synoptic type counts leading up to fire events with the climatology, limited region-wide patterns were observed. The only timescale with a statistically significant results in the majority of national forests was the 5 day time period. Types 5 and 9 are both characterized as wet types and demonstrated lower mean counts in the 5 days leading up to a wildfire. Type 5 occurs in late fall into winter is associated with zonal flow and on some days, may be associated with cold front passage. Type 9 also occurs during the winter with upper level southwesterly flow bringing moisture from the Gulf of Mexico into the region.

IV.3.4 Case Study

A case study is used to illustrate how the synoptic types described above are related to wildfire on February 15, 2011 – February 17, 2011 in Talladega National Forest. While finding statistical relationships is certainly important, any individual event may deviate from the statistical relationships as will be shown here.

The case study comes from Talladega National Forest in central Alabama and is documented in Figure 33 and Table 19. Fifteen consecutive precipitation-free days began on February 10, 2011. On February 13, 2011, a low pressure system moved through north of the region within the last day bringing dry air and high pressure into the region (Figure 33A). With the passage of a dry cold front, the day is categorized as Type 6. By the following day (Type 6), another cold front is approaching the region (Figure 33B). Over the next few hours, the cold front continues to develop and push through the region and by February 15, 2011 the front is replaced by high pressure (Figure 33C). On February 15, 2011 fires ignited burning a total of 44 acres in Talladega National Forest. On February 16, 2011, high pressure remains in place, but another cold front approaches from the north (Figure 33D). On this day, a fire ignites burning 26 acres. Finally, by the next day, the cold front has passed (Figure 33E), and another fire ignites burning 154 acres.

This example shows the interaction between fronts and high pressure. Two consecutive Type 6 days associated with cold front passage give way to high pressure types and dry conditions (Types 1 and 2) under which the ignitions occur. It also seems that these cold fronts were largely dry cold fronts and temperatures remained unseasonably warm. By February 17, for instance, the maximum temperature was 22.2°C. It is worth noting the limitation of synoptic typing. Despite 2/16/2011 and 2/17/2011 being classified as Types 1 and 2, respectively, a cold front did move through the region during this time. Based on the work done here, cold front passage is not typically associated with these two types.

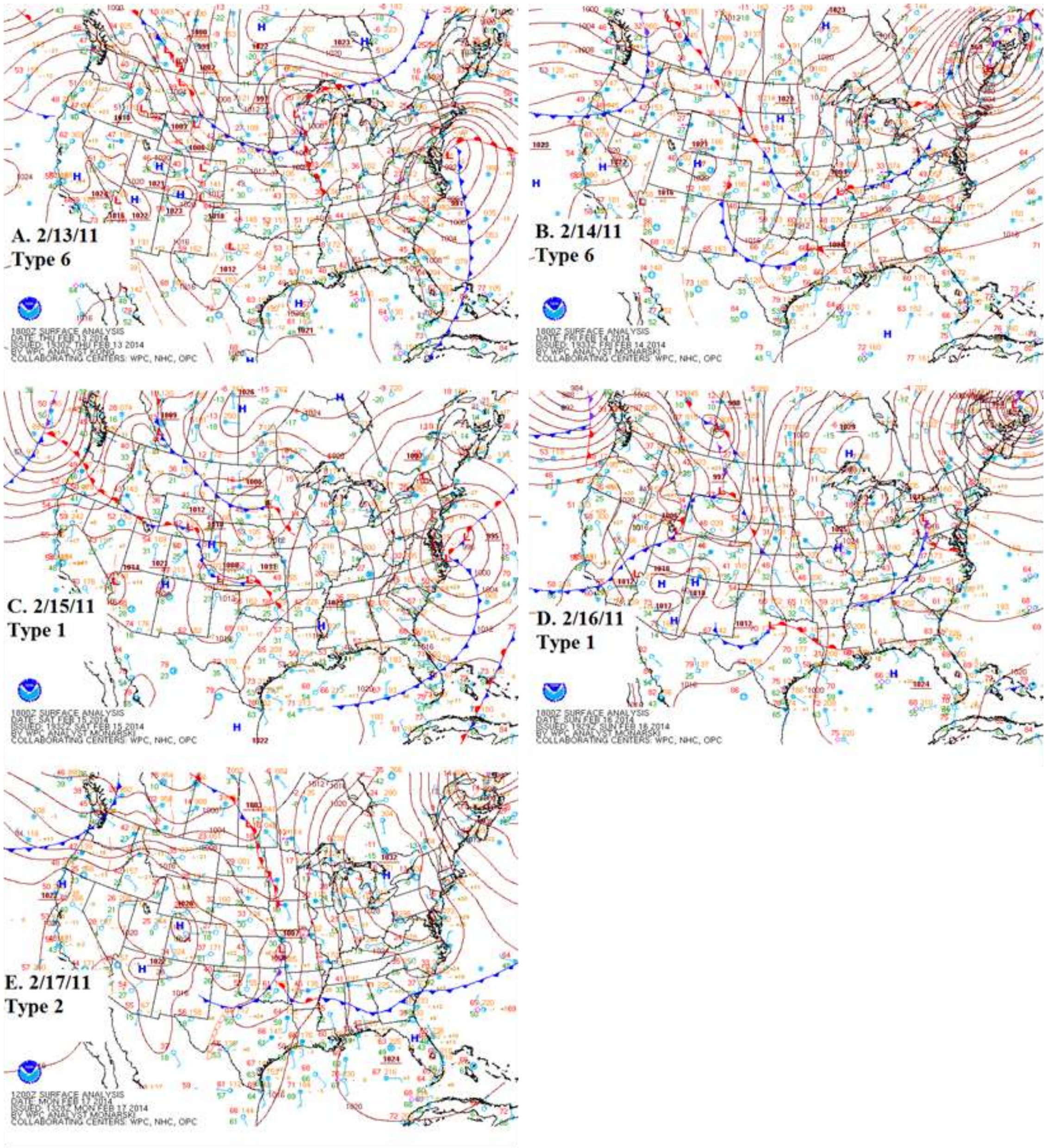


Figure 33. Talladega National Forest case study. Daily surface weather maps obtained from the National Weather Service (http://www.hpc.ncep.noaa.gov/archives/web_pages/sfc/sfc_archive.php).

Talladega National Forest - February 2011			
Date	**Fire Ignition**	**Synoptic Type**	**Weather Pattern in central AL**
2/13/2011		6	Cold front has passed
2/14/2011		6	Another cold front approaches the region from the north
2/15/2011	3 - 44 acres	1	Cold front has passed, Replaced by high pressure
2/16/2011	1 - 26 acres	1	High pressure remains in place, but another cold front approaches
2/17/2011	1 - 154 acres	2	Cold front passes, High pressure to the NE

Table 19. Talladega National Forest case study documentation of weather patterns and synoptic types prior to fire ignitions.

IV.4 Conclusions

The objective of this chapter was to identify synoptic types in the central Gulf Coast using 500 mb geopotential height from NCEP/NCAR reanalysis data. Eleven synoptic types were created using STT (Smith, Dahni, and Blair 2013; Smith 2012), which employs PCA and K-means cluster analysis. After a description of the eleven types, the objective was also to identify relationships between the synoptic types and antecedent conditions leading up to wildfire ignitions in national forests of the central Gulf Coast.

The mean number of days of each synoptic type prior to a fire in each national forest was compared with randomly selected days. This analysis was performed for 180-days, 90-days, 30-days, and 5-days prior to a fire. This analysis did not provide meaningful results. Instead, the mean number of days of each synoptic type prior to a fire was compared with the climatology of each time period. This analysis resulted in more useful results.

Overall, only the 5 day timescale resulted in statistically significant relationships in the majority of national forests. Types 5 and 9 both demonstrated lower mean counts in the 5 days leading up to a fire ignition. Both types generally occur in the winter and are associated with moderate to significant precipitation. For instance, in Meridian, Type 5 is the wettest type during the winter months and Type 9 is the second wettest during the winter. While not occurring in the majority of national forests, other types of interest include Types 3, 6, and 11 – all dry types occurring more often prior to fire ignitions. Previous literature suggests that such circulation patterns are associated with wildfire activity (Heilman 1995; Takle et al. 1994; Brotak and Reifsnyder 1977). However, there are still unexplained deviations that warrant further research, including the commonly observed Type 2, a generally dry type, occurring less often prior to fire ignitions. Type 2 may be associated with the Bermuda High. The position of the Bermuda High in the Southeast can have a significant influence on spatial patterns of precipitation in the region (Coleman 1988; Keim 1997). Synoptic typing with the STT would not necessarily take this into account and therefore may explain the pattern.

The challenge in studying wildfire-climate relationships using fire occurrence data is that conditions may be ideal for fire to take place (i.e. several rainless days prior, low relative humidity, high temperatures, strong winds, flammable vegetation, etc.) and yet, an ignition does not happen. A corollary to this is the many other types of hazards, like tornadoes and hurricanes that occur very infrequently, yet with a high magnitude.

When synoptic or any other environmental conditions are appropriate for fire, and a fire does not take place, this is inherently going to bias the results. At the same time, there are instances when environmental conditions are less than ideal and an ignition still takes place.

A potential solution to this intractable problem is to employ fire danger ratings rather than depend on fire occurrence data. Fire danger ratings use a variety of variables from temperature, precipitation, atmospheric stability, and fuel moisture, among many others to provide a measure of fire risk or fire probability. Fire danger ratings are not subject to many of the issues discussed with using fire occurrence data. Extreme fire risk, for example, should only happen when the variables that the index accounts for truly exceed some particular threshold. Employing such data would help alleviate the issue of having ideal conditions for an event without experiencing the event itself.

Future work will continue to explore the issue of antecedent synoptic conditions. Along the same line of thinking, knowledge of the synoptic conditions that lead to rapid fire spread or large fire outbreaks where multiple large fires across multiple states occur would also prove beneficial. From a climatological standpoint, understanding the large-scale drivers of synoptic type variability would also provide useful information. For instance, the Bermuda High has not been well studied for its links with wildfire activity in the central Gulf Coast or the larger Southeast. Yet, the Bermuda High has been linked to drought and consequently, may play a role in synoptic type variability and wildfire activity. It would also prove beneficial to examine surface weather conditions for each type. Such an analysis would benefit interpretation of both the individual types, but the relationships with fire as well.

CHAPTER V

SUMMARY, FUTURE RESEARCH, AND CONCLUSION

V.1 Summary

Wildfire plays an important role in vegetation composition and structure (Bond and van Wilgen 1996; Pyne 1982; Whelan 1995). Wildfire is a complex process influenced by a variety of factors, including topography, fuel type, elevation, and land management policies (Bond and van Wilgen 1996; Krawchuk et al. 2009; Pyne 1982). Climate, however, often plays a dominant role (Meyn et al. 2007; Krawchuk et al. 2009). The overarching goal of this dissertation was to examine how spatiotemporal climatic variability influences wildfire activity in the southeastern United States. Three objectives guided this dissertation, including 1) quantify the relationships between fire activity and precipitation regimes, 2) identify weather types associated with fire activity in the central Gulf Coast, and 3) identify synoptic types associated with fire activity in the central Gulf Coast. Despite the frequent fires in the Southeast (Pyne 1982; Lafon 2010; Andreau and Hermansen-Báez 2008), the focus of fire climatology research has been in the western USA. This dissertation begins to address the knowledge gap in Southeast fire climatology by examining spatial patterns in precipitation regimes for relationships with wildfire activity and using modern synoptic techniques to explore links with wildfire.

Chapter II examined how gradients in precipitation regimes influence spatial patterns of fire in the southeastern United States. Results did not show statistically significant relationships between mean annual precipitation and ignition density or area burned. Instead, a weak positive relationship was observed between daily precipitation variability and fire activity supporting previous research (i.e. Lafon and Quiring 2012) . As demonstrated in chapter II, two national forests can have similar mean annual precipitation, but very different patterns of precipitation delivery (number, intensity and magnitude of precipitation events) to arrive at that value. Locations in the humid Southeast with more variable precipitation regimes are those whose precipitation regime is characterized by infrequent, high intensity precipitation events interspersed with dry days. The national forests with variable precipitation regimes experienced increased ignition densities, while forests with less variable regimes experienced decreased ignition densities. No significant relationships were uncovered between daily precipitation variability and area burned.

Lack of statistically significant relationships between precipitation metrics and fire activity is partly attributable to a failure to capture a full range of precipitation regimes. A brief, preliminary analysis employing national forests from the western USA demonstrated the presence of both higher and lower values of the CV of daily precipitation, as well as mean annual precipitation. This analysis demonstrated statistically significant positive correlations between daily precipitation variability and ignition density and area burned, as well as mean annual precipitation and area burned. Such work provides the motivation for an expansion of this work to include other regions.

Chapter II begins to address the need highlighted by both Parisien and Moritz (2009) and Meyn et al. (2007) for studies examining spatial patterns of wildfire as a function of environmental gradients. Such studies assist in understanding the major controls of wildfire patterns both now and under future climate change (Parisien and Moritz 2009). Concerning precipitation variability, this is particularly important as the Southeast may become a region with more variable precipitation regimes (Wang et al. 2010; Groisman and Knight 2008; Karl and Knight 1998).

Chapter III identified weather types according to the Spatial Synoptic Classification (SSC) scheme (Kalkstein et al. 1996; Sheridan 2002) associated with wildfire ignitions in the Central Gulf Coast. Dry Tropical (DT) weather types occurred more frequently during years with high numbers of wildfire ignitions in over half of the national forests examined, suggesting a general, but weak, region-wide pattern.

While analysis at the annual scale is warranted in furthering the field of Southeast fire climatology, it is more useful from an application or operational standpoint to understand what weather types occur prior to a wildfire. Results were much more consistent when employing a bootstrapping approach to compare ratios of DT days to MM and MT days prior to fire day and prior to randomly selected days. The ratio of DT days to MM and MT days was statistically higher for most national forests 30, 90, and 180-days prior to a fire than for the randomly selected days. This suggests that dry and hot conditions occur more often prior to a fire ignition and may pre-condition the landscape for burning.

The monthly climatology of DT days was also positively correlated with monthly ignitions in a number of national forests. Peak fire seasons of spring and fall frequently match the peak occurrence of DT days. Finally, a basic analysis of the influence of NAO and ENSO on DT variability suggested that positive phases of NAO influence the westerly expansion of DT air masses during the dominant spring fire season. Results with ENSO were inconclusive and further research is required to address weather type-fire-teleconnection interactions.

Chapter IV employed the Synoptic Typer Tools (STT) to develop synoptic types for the central Gulf Coast. Eleven synoptic types were identified and linkages between the synoptic types and wildfire ignitions in the central Gulf Coast national forests were assessed. As detailed in chapter II, the most useful information for applied purposes is to identify what synoptic types occur in advance of days with fire ignitions. A similar bootstrapping approach was employed to compare the synoptic types 180, 90, 30, and 5-days prior to a day with a fire ignition with the climatology of each day. Results demonstrated limited statistically significant results across the majority of national forests. Generally speaking, synoptic types associated with moderate to high precipitation amounts were observed to occur less often in the preceding 5 days prior to a fire ignitions. Other types of interest include types associated with cold front passage as in Brotak and Reifsnyder (1977), high pressure as in Takle et al. (1994), and troughs over the eastern U.S. as in Heilman (1995).

A case study from Talladega National Forest demonstrated how synoptic types lead to particular surface weather conditions and consequently to conditions conducive to burning. Unseasonably warm temperatures and multiple consecutive dry days because of dry cold fronts and high pressure over the region lead to three ignitions burning several hundred acres.

V.2 Future Research

V.2.1 Spatial Patterns in Precipitation-Wildfire Relationships

Spatial patterns in moisture-wildfire relationships were observed in Chapter II. A small sample size and analysis at the regional-scale limited the statistical robustness. While the relationship was weak, statistically significant positive correlations were observed between precipitation variability and ignition density.

In order to address the limitations of sample size and scale, future work will include an examination of national forests in the Northeast, Midwest, and Western United States. By examining the continental-scale, this work broadens the range of precipitation regimes captured in the analysis. Preliminary results suggest that the expanded range (and increased sample size) will lead to statistically significant positive correlations between precipitation variability, mean annual precipitation, and wildfire activity. While no relationships were found between wildfire activity and other measures of precipitation regimes, these measures will continue to be assessed in a similar context. Longer-term work will also assess this relationship on a global scale, identifying fire activity and precipitation regimes around the world.

There are also other physical and human factors that can be assessed to help explain spatial patterns in wildfire activity at the continental scale. Vegetation and fuel type are key explanatory variables of spatial patterns of fire. Prevalence of pine species, for instance, helped explain patterns in Mississippi (Grala and Cooke 2010). Land cover and NDVI were identified as especially important in the western USA (Hawbaker et al. 2013). In Kentucky, Mississippi, and southern California, proximity to roads and populated areas demonstrate a relationship with fire activity (Maingi and Henry 2007; Syphard et al. 2008; Grala and Cooke 2010). However, Syphard et al. (2008) points out that while ignitions may be related to human settlement, these fires are also often suppressed and occur in areas of fragmented vegetation. Therefore, fires near urban areas do not burn as many acres as those occurring in more rural locations with less suppression and more continuous vegetation. The importance of moderate levels of human activity has also been demonstrated, where low and high levels are not associated with wildfire (Syphard, Clarke, and Franklin 2007). Size of the national forest may also prove to be an explanatory variable, related to human settlement patterns. Large national forests are often located in very remote and rural areas. Consequently, it is hypothesized that fires in larger forests are not suppressed as quickly as in smaller forests, which may be more proximal to human settlements. Management policies regarding fire also play a key role in this relationship. Along with precipitation variability and mean annual precipitation, vegetative and/or human settlement variables may provide a more robust explanation of large-scale spatial patterns of wildfire.

V.2.2 Weather Type-Wildfire Relationships

Chapter III detailed the importance of DT weather types in annual wildfire variability and in the months and weeks leading up to wildfire ignitions. However, it is still not clear where DT days originate from in the days leading up to an ignition and if the source region differs during periods when fire is not present. Preliminary results from a climatology of back trajectories of DT weather types in Birmingham, Alabama suggests that DT weather types originate from a west/northwesterly direction, particularly during the primary fire season months of February, March, and April. However, this analysis does not discriminate between fire occurrences and no fire occurrences. Results from a continuation of this analysis will provide insight into whether the source region for DT weather types influence fire or whether it is solely the frequency of DT weather types that matters.

It is also unknown whether the environmental conditions differ between DT days associated with fire and those not associated with fire. Subdividing DT days by association with fire and calculating meteorological variables, such as temperature and dew point depression for each group, will provide insight into the actual meteorological conditions associated with DT-fire days. This will assist in determining if DT days associated with fire are drier and/or warmer or if the frequency of DT days is the sole driver.

A preliminary analysis of the connections between DT weather types and teleconnections (NAO and ENSO) was provided in chapter III. However, a more robust analysis is warranted as the analysis was entirely observational. Furthermore, other teleconnections may be of interest, including the Bermuda High and Pacific North American (PNA) pattern. Future work will address this limitation and continue to address the Southeast fire climatology knowledge gap.

V.2.3 Synoptic Typing of Wildfire

Chapter IV used the Synoptic Typer Tools (STT) to create eleven synoptic types based on 500 mb geopotential height. Future work will include a more in-depth characterization of the individual types using surface weather observations. Including temperature and precipitation characteristics for each type will provide a more adequate and useful understanding of the types, but will also aid in the interpretation of the links between synoptic circulation patterns and wildfire activity.

Synoptic typing provides useful tools and information, which can be applied to a variety of disciplines and issues. This dissertation examined two different synoptic typing methods and applied each to understanding relationships with wildfire activity in the central Gulf Coast, USA. A comparison of the two methods is appropriate and provides a summary of the advantages and disadvantages of each method applied to wildfire activity. A preliminary summary comparison is provided here (Table 20), but future work can include a more in-depth qualitative and quantitative analysis.

Criteria	Spatial Synoptic Classification (SSC)	Synoptic Typer Tools (STT)
Subjective Decisions	X	
Ease of Understanding	X	
Customizeable		X
Peer-Reviewed	X	

Table 20. Qualitative assessment of SSC and STT.

The SSC is a hybrid classification, blending both manual and automated techniques (Sheridan 2002), while the STT is an automated approach (Smith 2012). A key issue in synoptic techniques is the number of subjective decisions that the user has to make (Yarnal 1993). There is a stark difference in the number of subjective decisions between the two approaches. Because the SSC is complete in the sense that the method has already been applied and weather type calendars are readily available for hundreds of stations around the world, there are essentially no subjective decisions that the end-user must make. However, this is not to say that in its creation, there were no subjective decisions made. As a semi-manual technique, the creation of the SSC had many subjective decisions. For a full discussion of these decisions, see Kalkstein et al. (1996) and Sheridan (2002). The STT, on the other hand, required many subjective decisions. For instance, whether to perform unrotated PCA or rotated PCA, whether to use a correlation matrix or covariance matrix, and the number of PCs to retain (Yarnal 1993; Smith 2012). Perhaps the biggest issue, at least encountered in chapter IV of this dissertation, is the selection of the number of types, which is often arbitray (Yarnal 1993). Ultimately, the SSC has the advantage in terms of fewest subjective decisions required by the end-user.

It is also important to be able to understand and communicate the results of any synoptic typing study. The classes of the SSC are inherently self-explanatory. With six weather types named after the thermal and moisture characteristics of a given weather type, the SSC is easy to understand and communicate. For the STT, it is up to the end-user to be able to explain each synoptic type, which may or may not be a simple task. Understanding the process behind the development of each is just as important. The SSC is a relatively straightforward, hybrid technique laid out in multiple publications (Sheridan 2002; Kalkstein et al. 1996). On the other hand, PCA is a complex technique and often difficult to understand. For these reasons, the SSC also has the advantage in terms of ease of understanding.

The main advantage of the STT is its ability to be customized. While the number of subjective decisions required can be a disadvantage, this also allows it to be customizable. The STT is available for the vast majority of the world and can be applied to varying spatial areas (Smith, Dahni, and Blair 2013). Varying levels of geopotential heights or sea level pressure can be used, as well as customizing the number of resulting types (Smith, Dahni, and Blair 2013). The SSC, however, is not truly customizable. As a finished synoptic typing approach, the weather type calendar for any particular location is complete and should remain unchanged.

Peer-reviewed techniques have the advantage of being assessed by multiple scientists in a variety of different disciplines for a variety of different applications. While chapter III of this dissertation is the first study to examine the SSC in the context of wildfire, the technique has been used many times for a variety of applications, including health (Hondula, Vanos, and Gosling 2014; Vanos and Cakmak 2014), drought (Quiring and Goodrich 2008), and air pollution (Kelly et al. 2013) just to name a few. The STT, on the other hand, has not been published. Again, the SSC has the advantage. Based on this brief and preliminary summary comparison, the SSC is the better synoptic typing approach. However, the objectives of the study should always be considered and there are certainly times when the STT is a better option.

There are also factors that are neither advantages, nor disadvantages. The SSC is based solely on surface meteorological conditions, while the STT can be based on either surface conditions or upper atmosphere conditions. Again, the STT is customizable. The choice of which is better is entirely dependent upon the objectives of the study and one is not necessarily better than the other is. A potential useful technique is to use them in conjunction with one another.

V.2.4 Fire Danger Rating Database

NIFMID and any other contemporary wildfire occurrence data can be problematic in detailing wildfire-climate relationships. First, an individual wildfire ignition and subsequent size and intensity is the summation of a variety of factors, including fuel type, fuel quantity, fuel moisture, topography, elevation, aspect, land management policies, meteorological factors, and proximity to urban areas (Bond and van Wilgen 1996; Whelan 1995; Pyne 1982; Pyne, Andrews, and Laven 1996; Krawchuk et al. 2009). Consequently, exploring relationships with climate using wildfire occurrence data only accounts for a subset of the factors contributing to that particular wildfire. In addition, wildfire, like other anthropogenic and natural hazards, is a rare event that has a great impact. Environmental conditions may be ideal for the event to take place, and yet the event does not occur. For instance, SSTs in the Gulf of Mexico may be especially warm and wind shear may be low, but a tropical cyclone may not develop. This certainly does not mean that SSTs and wind shear have no physical relationship with tropical cyclogensis. In the case of wildfires, there may be ample fuel quantity, low fuel moisture, high temperatures, low relative humidity, and strong winds, yet again, a wildfire may not ignite.

A potential solution to the limitation of wildfire occurrence data in examining relationships with climate is to employ fire danger ratings. Fire danger ratings are indices that integrate for various key variables, depending on the particular rating, which provides a measure of fire danger or fire risk (Hardy and Hardy 2007). Many of the factors influencing actual occurrence data do not affect these indices. The use of fire danger ratings may provide for a more robust climate signal as many of these indices incorporate or use solely meteorological variables.

Prior to using fire danger ratings in such studies, a performance evaluation of these fire danger ratings will provide a much needed assessment of how well these fire danger ratings measure fire risk. Logistic regression and percentile analysis (Andrews, Loftsgaarden, and Bradshaw 2003), in addition to a qualitative assessment (Quiring 2009; Keyantash and Dracup 2002) provides a robust evaluation of fire danger ratings currently lacking in the Southeast. The Keetch-Byram Drought Index (KBDI; Keetch and Byram 1968), Energy Release Component (ERC) of the National Fire Danger Rating System (NFDRS), and Haines Index (Haines 1988) will all be assessed using the aforementioned analyses.

Development of a fire danger rating database will provide a number of future research directions. Subsequent analyses include using the SSC and STT to examine how weather types and upper atmospheric synoptic types are associated with extreme fire danger. In addition, teleconnections (e.g. ENSO, NAO, PNA, BHI) will be examined as potential climatic drivers of extreme fire danger. Previous work has used fire danger ratings in the exploration of wildfire-climate relationships, including Trouet et al.

(2009), Winkler et al. (2007), and Crimmins (2006) among others. These studies primarily examine relationships in western North America, so studies pertaining to the Southeast will help fill a knowledge gap in the Southeast in regards to extreme fire risk and climate relationships.

V.2.5 Wildfire Trends in the Southeast USA

One question not addressed in this dissertation is that of trends in regional wildfire occurrence. Like many wildfire studies, there is significant research being done in the western USA. Large fires (>405 ha) were observed to be on the rise since 1984, particularly in southern and mountain ecoregions (Dennison et al. 2014). This increase in large wildfires is attributable to increased drought severity (Dennison et al. 2014). Trends have also been observed in extreme fire weather. Collins (2014) observed increasing trends in the northern Sierra Nevada Mountains, which could make control efforts more difficult.

In addition to current trends, the question of how climate change will impact the frequency, severity, size, and timing of wildfires is also important. Liu, Goodrick, and Stanturf (2013) observed higher fire danger in multiple regions of the USA, including the Southeast under future climate change scenarios. This is an interesting question in the Southeast as studies suggest a slightly wetter, but more variable precipitation regime in the region’s future (Wang et al. 2010; Groisman and Knight 2008; Karl and Knight 1998). The potential impacts on vegetation and primary productivity of changing precipitation variability have also been raised (Jentsch and Beierkuhnlein 2008; Fay et al. 2003; Fay et al. 2008; Knapp et al. 2008). This quickly becomes a complex issue when considering how a changing climate can alter both forested ecosystems and disturbance regimes separately to possibly create new interactions between ecosystems and disturbances. Nowacki and Abrams (2008) report on the "mesophication" of eastern USA forests. Authors argue that changes in fire regimes have replaced many fire-tolerant species with those that are less-tolerant to fire (Nowacki and Abrams 2008). Future work will require integrating climate change, ecosystem structure and composition, and fire regimes. The fire danger rating database discussed previously will provide useful data in determining the frequency, timing, duration, and magnitude of extreme fire weather under different climate change scenarios. Results from such studies will inform forest management efforts and allocation of resources (Liu, Goodrick, and Stanturf 2013).

V.3 Conclusion

This dissertation identified a knowledge gap in southeast USA fire climatology. First and foremost, the region is often overlooked in terms of wildfire, despite the abundance of burning that occurs here (Andreau and Hermansen-Báez 2008; Pyne 1982). It is hoped that this dissertation and publications resulting from this dissertation will encourage or renew an interest in the field. Secondly, few studies have employed modern synoptic climatology methods to address wildfire-climate interactions.

These knowledge gaps were addressed and the discipline advanced with this dissertation. Gradients in precipitation variability were examined for relationships with wildfire and addressed a need identified by Meyn et al. (2007) and Parisien and Moritz (2009). While robust results were not observed, future work will continue to address this issue. Two synoptic typing methods were used to assess wildfire in the central Gulf

Coast. These studies add to not only the fire climatology literature, but also to the dated literature pertaining to synoptic circulation and wildfire activity in the Southeast, including Brotak and Reifsnyder (1977) and Heilman (1995).

Wildfires pose a serious threat to homes, business, timber, and lives (Butry et al. 2001), yet they are also a natural and required process in many ecosystems (Bond and van Wilgen 1996; Pyne 1982; Pyne, Andrews, and Laven 1996) and prescribed fires are often used as a tool for restoration and maintenance (Beckage, Platt, and Panko 2005). Balancing the hazard component of fire with the ecological process can prove difficult (Hawbaker et al. 2013). Continuing to study wildfire-climate interactions will help restoration efforts (Beckage, Platt, and Panko 2005) and making climate information useful for fire managers will aid in fire risk forecasts (Roncoli et al. 2012), ultimately aiding in balancing the tradeoffs between protecting communities from severe fire and employing fire and/or allowing fire on the landscape as a natural ecological process.

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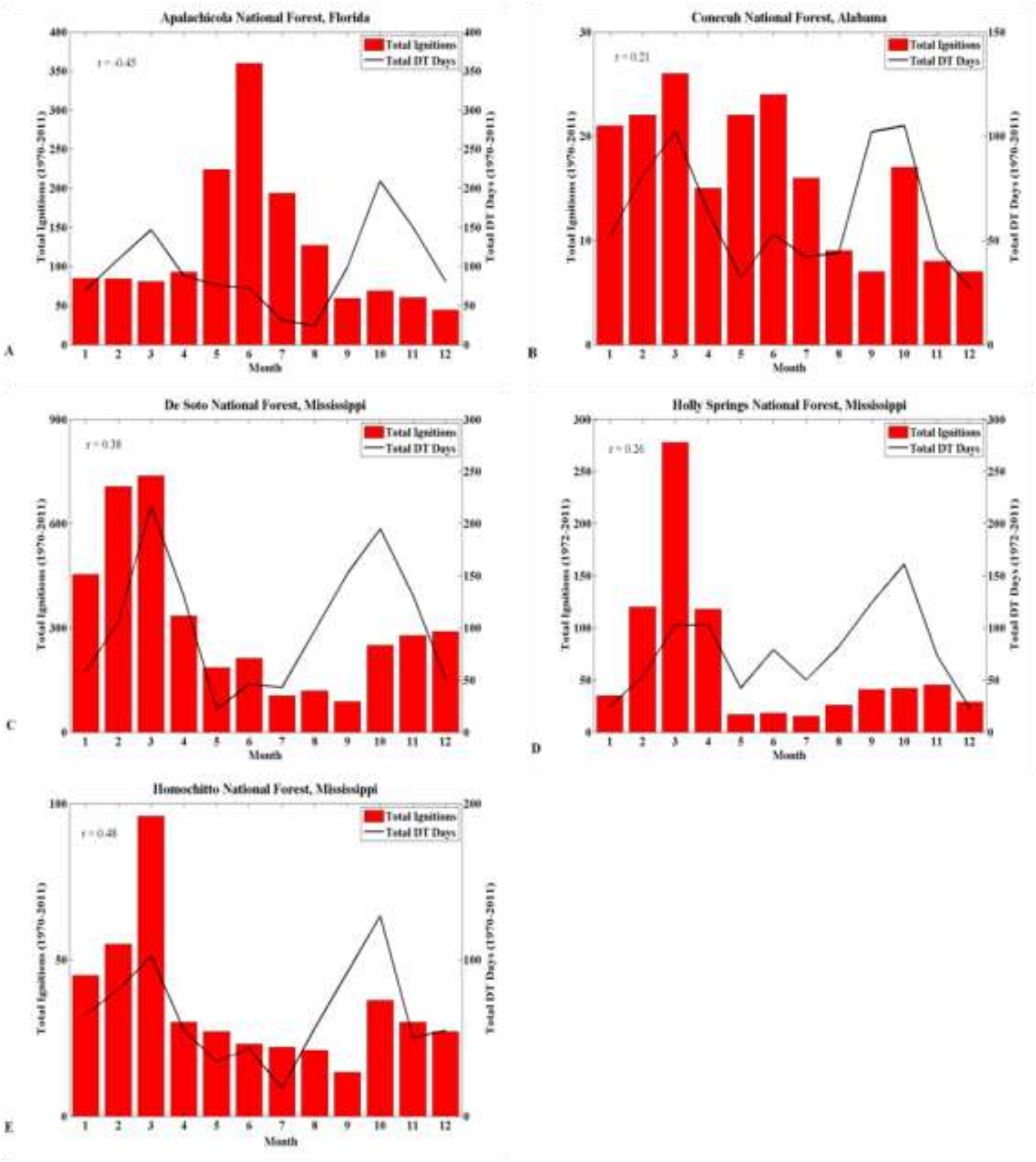

Figure 34. Total monthly ignitions (1970-2011) versus total monthly DT weather types (1970-2011) for (A) Apalachicola, (B) Conecuh, (C) De Soto, (D) Holly Springs, and (E) Homochitto. See Figure 22 in Chapter III for more information.

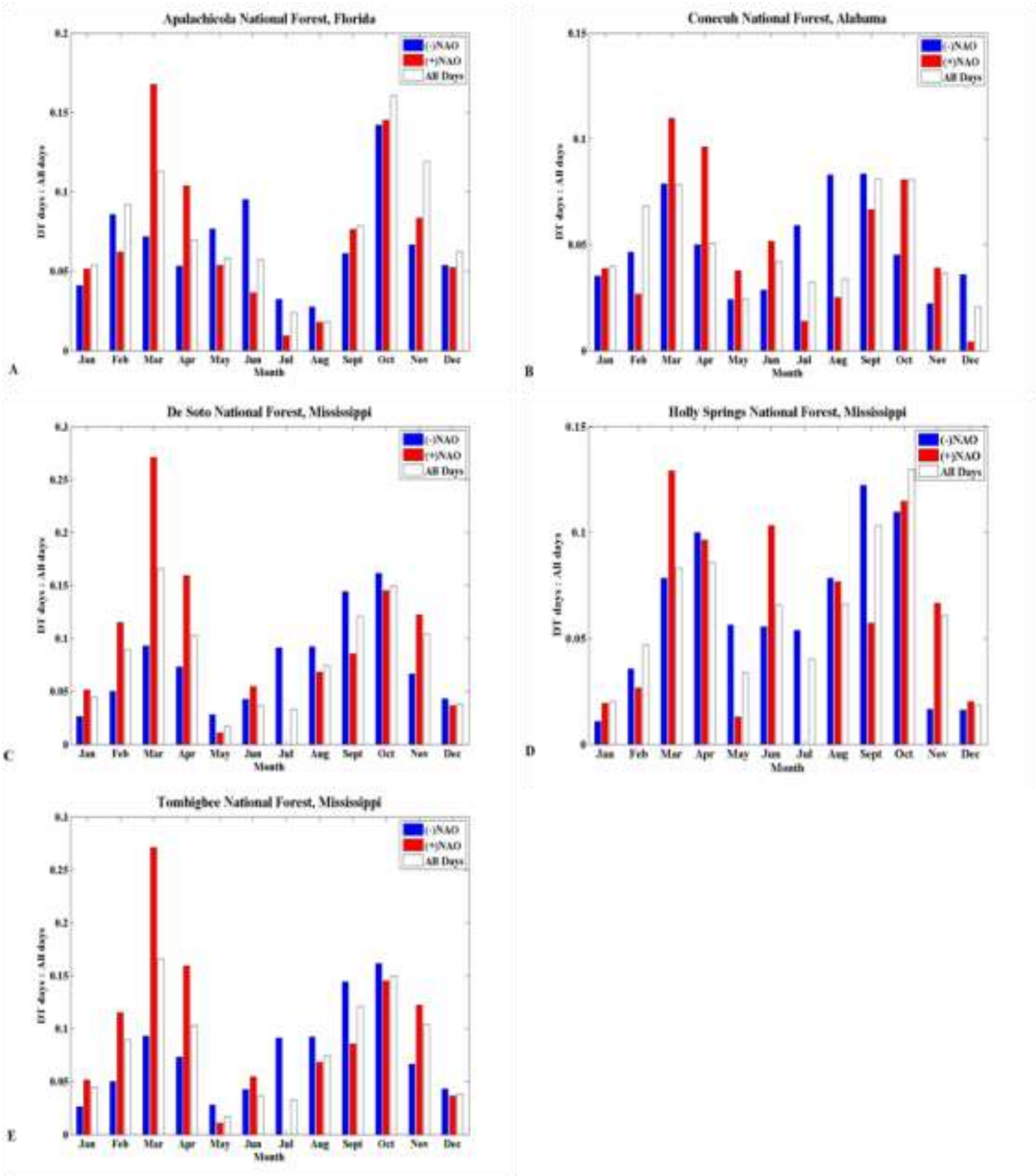

Figure 35. Relationship between DT weather types and NAO for (A) Apalachicola, (B) Conecuh, (C) De Soto, (D) Holly Springs, and (E) Tombigbee. See Figure 23 in Chapter III for more information.

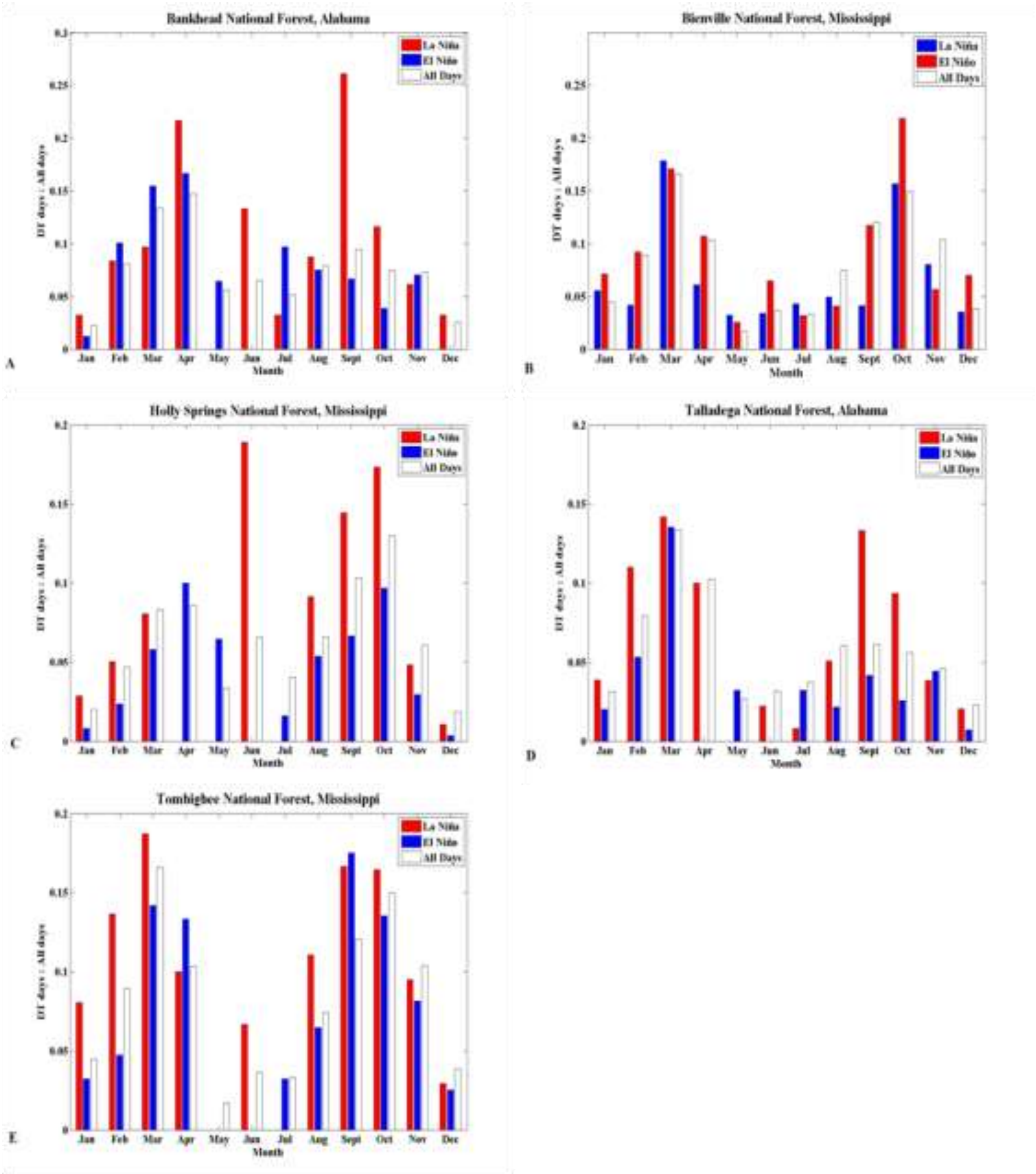

Figure 36. Relationship between DT weather types and ENSO for (A) Bankhead, (B) Bienville, (C) Holly Springs, (D) Talladega, and (E) Tombigbee. See Figure 24 in Chapter III for more information.

Holly Springs: Winter			
Types	Precipitation (mm/day)	Mean Maximum Temperature (°C)	Standard Deviation of Mean Max Temp (°C)
1	1.8	10.5	6.8
2	3.2	16.1	5.6
3	1.8	7.8	6.6
4	9.0	10.5	6.8
5	7.5	11.3	7.3
6	0.7	9.0	6.7
7	4.2	13.5	6.6
8	4.6	11.8	6.4
9	4.7	10.3	6.5
10	9.3	9.2	6.5
11	2.6	7.4	6.6

Table 21. Surface weather conditions in Holly Springs, MS for each synoptic type during winter. See Chapter IV for more information.

Holly Springs: Spring			
Types	Precipitation (mm/day)	Mean Maximum Temperature (°C)	Standard Deviation of Mean Max Temp (°C)
1	2.5	22.1	6.4
2	4.5	24.7	4.8
3	2.9	19.7	6.3
4	9.1	22.7	5.2
5	9.9	21.7	6.2
6	1.5	18.7	7.1
7	6.0	25.8	4.6
8	5.3	22.7	6.3
9	6.7	17.8	5.9
10	11.2	16.7	6.0
11	3.4	16.3	7.3

Table 22. Surface weather conditions in Holly Springs, MS for each synoptic type during spring. See Chapter IV for more information.

Holly Springs: Summer			
Types	Precipitation (mm/day)	Mean Maximum Temperature (°C)	Standard Deviation of Mean Max Temp (°C)
1	2.2	31.7	2.9
2	1.9	32.7	2.7
3	3.4	31.7	3.1
4	5.3	30.7	2.9
5	2.8	32.5	2.8
6	2.0	32.7	3.5
7	3.8	30.7	3.2
8	4.0	29.4	3.6
9	4.2	31.8	2.1
10	-	-	-
11	-	-	-

Table 23. Surface weather conditions in Holly Springs, MS for each synoptic type during summer. See Chapter IV for more information.

Holly Springs: Fall			
Types	Precipitation (mm/day)	Mean Maximum Temperature (°C)	Standard Deviation of Mean Max Temp (°C)
1	1.9	23.9	7.0
2	3.6	25.1	5.7
3	1.3	21.7	7.9
4	5.2	24.2	6.4
5	5.8	21.5	7.7
6	1.5	19.5	6.9
7	4.6	24.8	5.5
8	6.0	23.0	6.3
9	4.4	17.6	7.5
10	13.4	13.9	5.6
11	4.3	15.7	5.4

Table 24. Surface weather conditions in Holly Springs, MS for each synoptic type during fall. See Chapter IV for more information.

Tallahassee: Winter			
Types	**Precipitation (mm/day)**	**Mean Maximum Temperature (°C)**	**Standard Deviation of Mean Max Temp (°C)**
1	1.4	18.0	5.0
2	0.7	22.5	3.6
3	2.0	16.1	5.5
4	6.6	18.4	5.0
5	3.7	21.0	4.8
6	0.8	17.1	4.8
7	3.1	20.0	4.0
8	4.3	18.4	4.3
9	6.3	18.7	4.8
10	15.8	17.3	5.2
11	4.4	13.5	5.1

Table 25. Surface weather conditions in Tallahassee, FL for each synoptic type during winter. See Chapter IV for more information.

Tallahassee: Spring			
Types	**Precipitation (mm/day)**	**Mean Maximum Temperature (°C)**	**Standard Deviation of Mean Max Temp (°C)**
1	2.7	27.0	4.5
2	1.3	28.7	3.3
3	2.7	26.2	4.8
4	8.4	27.4	3.8
5	3.8	27.7	3.7
6	0.5	25.2	5.2
7	2.7	29.5	3.2
8	4.6	26.8	4.5
9	9.7	24.2	3.9
10	18.8	22.7	4.5
11	5.9	21.5	5.5

Table 26. Surface weather conditions in Tallahassee, FL for each synoptic type during spring. See Chapter IV for more information.

Tallahassee: Summer			
Types	Precipitation (mm/day)	Mean Maximum Temperature (°C)	Standard Deviation of Mean Max Temp (°C)
1	5.9	32.9	2.4
2	4.2	34.2	1.9
3	5.6	33.2	2.4
4	9.7	32.3	2.5
5	4.7	33.8	2.1
6	2.1	34.3	2.2
7	5.5	33.0	2.3
8	5.8	31.1	2.8
9	7.4	32.4	2.5
10	-	-	-
11	-	-	-

Table 27. Surface weather conditions in Tallahassee, FL for each synoptic type during summer. See Chapter IV for more information.

Tallahassee: Fall			
Types	Precipitation (mm/day)	Mean Maximum Temperature (°C)	Standard Deviation of Mean Max Temp (°C)
1	2.7	27.3	4.9
2	1.2	29.1	3.8
3	1.5	26.3	6.1
4	6.6	27.7	4.5
5	5.0	27.2	5.0
6	0.8	24.5	5.5
7	2.2	28.7	3.9
8	4.1	26.8	4.7
9	5.9	24.2	4.7
10	18.4	21.6	3.6
11	8.5	20.8	4.6

Table 28. Surface weather conditions in Tallahassee, FL for each synoptic type during fall. See Chapter IV for more information.