

**LIGHTNING-IGNITED FIRES IN THE GRANDFATHER RANGER DISTRICT,  
NORTH CAROLINA**

A Thesis

by

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## ABSTRACT

Fire-dependent plant species persist in the humid North America eastern forests, which is devoid of a wet or dry season. But fire suppression has altered vegetation distributions. Knowledge of the natural fire regime can provide forest managers with the information needed for the conservation of these species. This thesis seeks to understand lightning-ignited fires in the Grandfather Ranger District of Pisgah National Forest in western North Carolina. To this end, I used self-organized maps, an automated synoptic typing procedure, to discern atmospheric circulation patterns. Those atmospheric circulation patterns were then associated with lightning-ignited fires and with lightning strikes to understand the atmospheric configurations that favor these events. I then detailed the surface climatic variables and synoptic classifications associated with each individual lightning-ignition. Finally I used point-pattern analysis to discern the association between lightning-ignitions and mountain golden heather (*Hudsonia montana*), a fire-dependent endemic shrub.

A twenty year period was selected for this study. In Objective 1, 500mb geopotential heights, using North American Regional Reanalysis (NARR) data, were used to create synoptic types via self-organized maps. A 12 type composite was selected for this analysis. Those patterns were then associated with lightning ignited fires using National Interagency Fire Management Integrated Database (NIFMID) data. There were 39 lightning-ignited fire events. Lightning-ignitions occurred more than expected in synoptic types associated with high pressure, and predominantly in June. Objective 2 created a lightning climatology. Lightning strikes occurred most often during summer, peaking in July. Lightning strikes

associated more than expected with synoptic types with high pressure zonal flow with transitional gradients over the study area. Objective 3 detailed the lightning-ignition events. The majority of events experienced high pressure before, with dry cold frontal movement the day before ignition, and high pressure after ignition. Objective 4 used Ripley's K analysis and bivariate analysis to discern the spatial arrangement of lightning-ignitions and *Hudsonia montana*. I found lightning-ignitions to be random at small scales and aggregated at larger scales, and *Hudsonia montana* to be aggregated across the landscape. When compared using bivariate analysis I found lightning-ignition locations and *Hudsonia montana* populations to be random at small scales and aggregated at larger scales. This suggest lightning-ignitions and *Hudsonia montana* populations are not associated with each other by point location, and lightning-ignited fires would need to burn large areas to impact the plant species.

## **DEDICATION**

This thesis is dedicated to my family. They are my source of inspiration and my spark for exploration.

I dedicate this to my parents. I appreciate their constant support. To my mom for keeping my mind open and asking questions. To my dad for always having my back. No matter where I go, I always know y'all are in my corner and rooting for me to succeed. Additionally, I also owe a great deal for the love and support from my "other mom", "other dad", and Aunt Sue.

I dedicate this to my children. Nothing makes me push myself to be better than my girls. My love for them is never ending because their smiles, laughter, and love allow me to carry on regardless the climate and place.

Most importantly, I dedicate this to my wife. She pushed me to take on this challenge. Her tireless support in this endeavor made this all possible. She is my partner in life, anywhere and anytime. I love you beautiful, forever and always.

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# 1. INTRODUCTION

## 1.1 Introduction

Vegetation patterns are an important ecological study that impacts conservation and management. Vegetation is influenced by multiple factors, one being fire (Bond and Keeley 2005). Fire influences vegetation distributions, but these distributions have been altered by fire suppression (Frost 1998). While most fires are anthropogenic in origin, understanding the natural fire regime can provide forest managers with the information needed for conservation of fire associated species potentially affected by fire suppression.

Grandfather Mountain Ranger District is in the Pisgah National Forest of western North Carolina. In this humid environment there is no distinguished wet or dry season (Simon et al. 2005) yet fire-dependent species exist, implying a long history of lightning ignitions (Noss 2013). The Blue Ridge escarpment in northwestern North Carolina has a higher incidence of lightning-initiated fires than some other parts of eastern North America (Lafon and Grissino-Mayer 2007), but no studies have been published that would clarify climatic conditions under which these fires are ignited, or that would show whether the spatial distribution of fire-dependent plants are associated with preferred sites for lightning-ignitions. Such research is needed to understand biogeographic patterns and to manage fire-adapted plants such as *Hudsonia montana*, a rare species endemic to the Grandfather Ranger District.

Species distributions are often aggregated or hyper dispersed, not random, across spatial scales (Martínez et al. 2010; Wiegand and Moloney 2004). We would expect locations of vegetation species to be located in areas that burn more often due to natural-

ignitions. Therefore spatial aggregation of lightning-ignition and fire dependent species should persist somewhere on the landscape.

This study will investigate the synoptic climate conditions that are optimal for lightning-ignited fires in the Grandfather Ranger District of North Carolina. It will also explore the relationship between the spatial distributions of *Hudsonia montana* and lightning ignitions. Understanding how climate interacts with terrain and vegetation and how that may affect lightning ignitions in this environment will afford broader insights about the ecological and biogeographical role of fire within this humid region. Moreover, it will aid our understanding of vegetation patterns and provide insights for management of endemic fire-dependent species.

## **1.2 Objectives**

There are four primary research objectives:

*Objective 1: Analyze the lightning-ignited fires with respect to synoptic classification*

I will create the synoptic classifications for the study and associate the lightning-ignited fire events with the synoptic types. Lightning-ignited fires will be tabulated from the fire record that is available for the Grandfather Ranger District from 1989-2009.

*Objective 2: Analyze lightning strikes with respect to synoptic classification*

I will analyze the lightning characteristics and associate the synoptic types with the record of lightning strikes from 1989-2003.

*Objective 3: Describe the environmental variables for each lightning-ignited fire event*

I will detail the weather conditions associated with each lightning-ignited fire in the record. This will allow for a clear picture of the climatic variables present during lightning-ignited fires.

*Objective 4: Evaluate whether vegetation patterns are associated with lightning-ignited fires*

*Hudsonia montana* locations will be analyzed with lightning-ignition locations to determine whether the spatial distributions of the plants corresponds with the distribution of lightning-ignited fires.



## 2. LITERATURE REVIEW

### 2.1 Vegetation and fire

Fire is an integral aspect of vegetation patterns. The frequency of fire impacts the types of vegetation patterns present in an area. This feedback loop or ecological memory between patch burning is susceptible to changes in fire frequency (Peterson 2002). The humid eastern United States has fire adapted vegetation species. Fire dependent species in Florida's Everglades depend on spring lightning-ignitions for rejuvenation, and protection from competition of other plants (Beckage et al. 2003). *Hudsonia montana* and pine species exist in the humid environment of Grandfather Ranger District yet require fire to survive. The pristine myth of virgin forests before European settlement has been contested (Denevan 1992; Frost 1998), yet origin and fire adaptability of a species would rely on natural ignition compared to infrequent anthropogenic ignitions (Noss 2013). Endemic fire dependent species in the Grandfather Ranger District imply the requirement of natural ignitions (Noss 2013). Knowledge of the natural ignition cycle is vital in understanding the patterns of fire dependent species in this humid environment.

Mountain golden heather (*Hudsonia montana*) is a shrub endemic to two counties in North Carolina (Radford et al. 1968; Gross et al. 1998). The decline of the shrub has been attributed to fire suppression and trampling from hikers (Gross et al. 1998). Mountain golden heather requires fire as it aids in seed germination (Frost 1990; Gross et al. 1998). The shrub requires open areas as well as occasional wet years (Gross et al. 1998). Trampling from hikers is also a detrimental effect, listed as the third highest factor in elimination of the mountain golden heather (Gross et al. 1998). Gross et al. (1998) found that survival and

population growth could only occur in a trample free environment with a 6-8 year fire cycle. This coincides with the estimated lightning-fire regime of 4-8 years in pine stands, another fire dependent species (Flatley et al. 2013), and an area fire regime of 5-10 years prior to fire suppression (Frantz and Sutter 1987; Gross et al. 1998).

## **2.2 Climate**

When assessing wildfire at the landscape level it is important to assess the weather, topography, and fuels (DeBano, Neary, and Ffolliott 1998; Pyne, Andrews, and Laven 1996). Weather is noted to be the most variable of the factors for wildfire (DeBano, Neary, and Ffolliott 1998; Pyne, Andrews, and Laven 1996). Certain weather conditions favor ignition. Relative humidity relates to fine and dead fuel moisture content, likewise soil moisture is associated with live fuel moisture content (Pyne, Andrews, and Laven 1996). Wind is also a major driver of wildfire and directly influences fire intensity (Pyne, Andrews, and Laven 1996). Considering the impacts weather holds on fire it is important to understand the general climatic conditions that persisted during past wildfire events. Information on what climatic variables are present during a wildfire provide insight into vegetation management.

Few studies have looked into the relationship of climate and lightning ignited fires. Fuel moisture and fuel architecture have been suggested to be the most important factors in wildfires. Drought and frequency of lightning events have been linked to wildfires (Takle et al. 1994). Although there is literature that has analyzed lightning initiated fires the method and results differ. Not all studies have agreed that climate is the major driver behind lightning ignited fires with fuel type being the more important factor (Krawchuk et al. 2006). High pressure circulation patterns are associated with lightning ignited fires with the time before a

high, during a high, and after a high being the ideal conditions (Nash and Johnson 1996; Takle et al. 1994). Others have instead associated synoptic classifications with hot and dry weather (Crimmins 2006), associating more fires the longer dry weather persists (Labosier et al. 2014).

The scale of persistent dry weather in lightning ignition is debated. Mitchener and Parker (2005) suggested the Appalachians must dry out for a year before lightning ignitions would be consequential. Large temporal scale variability has also been found to influence local lightning-ignitions in Everglades, Florida (Beckage and Platt 2003). Additionally Lafon and Quiring (2012) found a strong relationship between daily variability in precipitation and fire activities, but not between annual variability. They suggested convective storms to be behind frequent fires. Convective storms would bring precipitation and then allow for several days or weeks before the next storm allowing fuels time to dry out and become more susceptible to lightning ignition (Lafon and Quiring 2012). The summer wet season in Florida has been attributed to the majority of lightning-ignited fires, although small (Duncan, Adrian, and Stolen 2010). Convective storms are most associated with high surface temperature and high moisture in the lower troposphere, according to a study in which lightning strikes were proxies for convective storms (Davis and Rogers 1992).

### **2.3 Lightning and fire**

While many studies have looked into synoptic classifications of fires, few have looked into the synoptic classifications of lightning ignited fires. Lightning-ignited fires have been found to increase in both La Niña and El Niño years in different parts of Florida depending on thunderstorm activity (Harrison 2004). Mora et al. (2015) found in their

synoptic classification of lightning weather that higher lightning strikes occurred with dynamic disturbances at medium and high levels, short wave troughs, cyclonic vortexes and lows at 500 mb geopotential height indicating individual thunderstorms.

National Lightning Detection Network (NLDN) data was used to analyze lightning strikes (Mitchener and Parker 2005) but did not analyze the synoptic climatology that is associated with lightning strikes. While not a synoptic classification Miller, Ellis, and Keighton (2015) did inspect the role of surface aspect in its relation to the spatial distribution of single cell thunderstorms using lightning data from the Earth Networks Total Lightning Network. They found convective storms capable of creating lightning formed along east and south facing aspects with steep slopes in the areas including and surrounding Blacksburg, VA (Miller, Ellis, and Keighton 2015). Orographic uplift in the Blue Ridge Mountains occurs along southwest aspects, southern slopes, and higher elevations which are associated with high intensity events (Konrad II 1995). It has been found in Florida that lightning strikes and fire ignition were not statistically significant, although lightning ignitions and precipitation were negatively correlated (Duncan, Adrian, and Stolen 2010). That same study by Duncan, Adrian, and Stolen (2010) found a higher percentage of lightning strikes affected the western portion of their study region. Linville Gorge, a site in the Grandfather Ranger District, is attributed to a higher incidence to lightning ignitions when compared to other parts of the Appalachian Mountains (Flatley et al. 2013; Lafon and Grissino-Mayer 2007; Baker 2009).

## **2.4 Literature review on methods**

### *2.4.1 Self organized maps*

Synoptic climatology allows for the study of atmospheric circulation at different scales (Harman and Winkler 1991). This process allows for linkages between regional and local climate (Harman and Winkler 1991). Synoptic climatology is defined by Yarnal et al. (2001) as the study that, “integrates the simultaneous atmospheric dynamics and coupled response of the surface environment” (p. 1924). This study focuses on the associations between atmospheric conditions and lightning ignited fires, making a synoptic climatology approach ideal.

There are multiple types of synoptic classification schemes. The schemes are either manual or automated and both have been used in assessing fire weather. Manual classification can be time consuming, but allows for total control in its process. The result is subjective however, and not duplicable (Yarnal et al. 2001). Automated approaches allow for replicability, but take some of the control from the author. Self-Organized Maps (SOM) are an automated approach that allows the user to analyze the continuous data present. SOM have the advantage of not relying on an underlying model or specific distribution (Hewitson and Crane 2002). SOM use a clustering algorithm to find points in a measurement space that represent the nearby observations (Crimmins 2006; Hewitson and Crane 2002). Only one project has used SOM in analyzing the synoptic climatology of wildfires to create a daily fire weather index for a three month period over 15 years (Crimmins 2006). Currently, no studies have used SOM to analyze lightning ignited fires.

Many studies that have looked into synoptic climatology associated with wildfires have used a variety of approaches: SSC2 (Labosier et al. 2014), Manual (Nash and Johnson 1996), GCM (Takle et al. 1994), and PCA (Davis and Rogers 1992) to classify climatic conditions. However these approaches assume a specific distribution or an underlying model. Only one has utilized the SOM algorithm (Crimmins 2006) which found increased hazard of fire weather with increasing hot and dry days using the SOM algorithm. Currently no studies have used SOM and NLDN data to classify the hazard of lightning-ignited fires. Due to the continuous data used in this project, lack of weather stations capable of SSC2 data, and replicability of being an automated classification, SOM was chosen for synoptic classification in this project.

Synoptic classification were completed using the SOM methodology first developed by Kohonen (1990). SOM allows its user to analyze non-discrete data without discretely defining the data into particular categories. While synoptic types, nodes, are a classification the defining attributes that make up each classification are not discreet. This can be particularly useful as certain attributes of variables may apply to many variables instead of just one. This method allows for individual observations to be attributed to more than one node. While some have described the SOM as an iterative clustering algorithm (Crimmins 2006) it differs from traditional clustering algorithms in two important ways. First, the SOM algorithm will find nodes in the measurement space that are characteristic of the proximate cloud of observations when taken together represent the multi-dimensional distribution of the data set (Hewitson and Crane 2002). Secondly, the SOM output allows for a more effective visualization of the link between the nodes (Hewitson and Crane 2002).

The SOM algorithm process is best described by Hewitson and Crane (2002). The SOM will define a random distribution of points in the data. Each point, or node, is defined by a weighted reference vector of coefficients (Hewitson and Crane 2002). The coefficients are related to an individual input variable. Thus a 4x3 SOM will have 12 reference nodes or 12 coefficients of each node in the 4x3 grid. When each data record of the coefficients is compared by the SOM with the reference nodes the similarity between the two is measured by Euclidean distance (Hewitson and Crane 2002). The reference vector of the reference node selected as the best match is then modified to reduce the difference between it and the user defined learning rate (Hewitson and Crane 2002). When the best match node is modified to reduce its difference with the input vector all of the surrounding nodes are incrementally adjusted toward the input vector in inverse proportion to their distance to the winning node (Hewitson and Crane 2002). As the best match is updated, the update kernel's size and shape are defined by the user. The first training of SOM uses a broad distribution of nodes while the second training uses the final node vectors from the first training as initial points with a smaller update kernel to clarify the plotting (Hewitson and Crane 2002). The SOM will do this until there is no more changes in the location of the nodes. The final product are nodes clustered in areas of the data space that have high data densities. The node placement is mean position of the nearby samples in the observation cloud (Hewitson and Crane 2002). The advantage of this method is the capability to assess variables in a continuous manner whereas a discrete classification would require classification of variables into unique classes.

Statistical analysis of synoptic types and associations with lightning ignitions is key to understanding any relationships that might exist between the datasets. Bootstrapping

allows for analysis of data that fall outside a normal distribution (Mooney and Duval 1993). The bootstrap process treats the sample of data provided as the total population of data, therefore not assuming a normal distribution like in other parametric analysis (Mooney and Duval 1993). The process involves resampling the data and empirically building a sample mean from the data multiple times. The resampling is done multiple times to obtain the relative frequencies of all the possible variables from the sample population (Mooney and Duval 1993).

#### *2.4.2 Lightning events*

Lightning strikes were analyzed using the National Lightning Detection Network (NLDN) data from 1988 – 2003. Data from the NLDN has been used to analyze lightning ignitions (Mitchener and Parker 2005). However in that study the authors used data from 1989 to 1998. The NLDN underwent upgrades in 1995 that increased its detection efficiency from 70% to 80-90% (Cummins et al. 1998; Orville and Huffines 2001). Distance between sensors affects detection efficiency with the closest sensors being in the Carolinas (Orville and Huffines 2001). There is a noticeable drop in detection efficiency 300 to 400 km from the IMPACT sensors (Cummins et al. 1998). Cummins et al. (1998) states the mean detection error is 0.5 km. It has also been suggested to eliminate discharges with peak currents under 10kA in the post 1995 datasets as the data reflects cloud to cloud flashes (Cummins et al. 1998).



### 2.4.3 Point pattern analysis

Point pattern analysis has both first-order and second-order statistics. First-order analyze the intensity of the spatial point pattern varies across space while second-order analyzes the correlation of spatial point pattern at different scales across space. First-order statistics illustrate the intensity  $\lambda$  of a point pattern and the large scale variation of the intensity  $\lambda$  of those points (Wiegand and Moloney 2004). Intensity  $\lambda$  dictates the amount of population present at a given location. Second-order statistics instead focus on the distribution of distances of pairs of points (Ripley 1981) which describe spatial correlation structure of the point pattern at the small-scale (Wiegand and Moloney 2004). A common second-order statistic is Ripley's K-function. Ripley's K-function characterizes the components of the point pattern over a range of distance scales allowing detection of mixed patterns on the landscape (Wiegand and Moloney 2004). These mixed patterns allow for a population to be identified at different in spatial distributions across different scales, i.e. random at small scales; but clumped at large scale.

The k-function( $r$ ) is the estimated number of points in a circle of radius  $r$  that is centered at an arbitrary point that is divided by the intensity  $\lambda$  of the pattern (Wiegand and Moloney 2004). Alternatively one can replace the circles with rings to compute O-ring statistics. O-ring statistics count the number of points both inside the circle and inside the study region (Wiegand and Moloney 2004). The advantage of O-ring statistics is that it may be more intuitive than k-function statistics; however, O-ring statistic requires multiple points as few points will create jagged plots which are difficult to interpret (Wiegand and Moloney 2004). The U.S. Forest Service has only documented 39 fires to lightning ignition from 1989

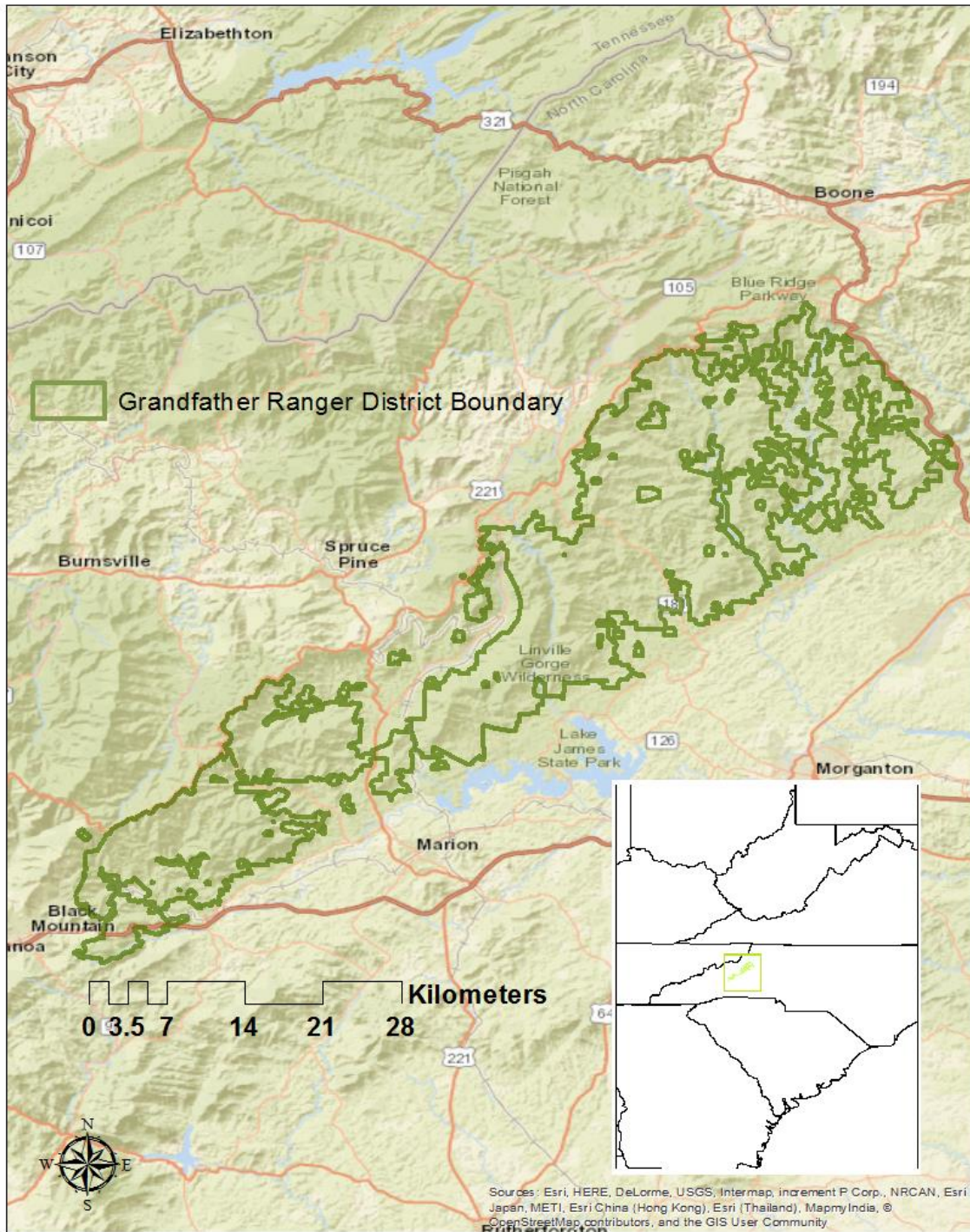
- 2009. Therefore, I used the k-function to determine whether vegetation patterns are associated by lightning-ignitions as it is not as dependent on a robust point source.

### 3. DATA AND METHODS

#### 3.1 Study site

Grandfather Ranger District is located in the Pisgah National Forest in Western North Carolina (Figure 1). The Ranger District lies within the Southern Appalachian Mountains in an escarpment of the Blue Ridge Mountains. Elevation ranges from 326 m to 1,598 m. Relief is characterized as steep with relatively high mountains, and valleys with perennial streams (Simon et al. 2005). The area contains 11 different ecological zones. Acidic Cove, and Xeric Pine-Oak Heath and Oak Heath ecological zones are more abundant while the rest are of roughly the same proportions with the exception of Shortleaf Pine-Oak Heath which is underrepresented (Simon et al. 2005). Mesic Oak-Hickory is found at both the mid and lower elevations that receive more dormant season precipitation (Simon et al. 2005). Acidic Cove exists at low elevations primarily on lower slopes that receive more growing season precipitation and less dormant season precipitation (Simon et al. 2005). Xeric Pine-Oak Heath and Oak Heath are found in upper slopes, on low-base rocks and favor less precipitation in the dormant season (Simon et al. 2005). Fuel flammability is generalized as high flammability with pines, moderate flammability with oaks, and low flammability with mesophytic hardwoods and conifers (Lafon and Grissino-Mayer 2007). The Blue Ridge Escarpment is devoid of pronounced wet or dry seasons as precipitation falls throughout the year with summer precipitation occurring through thunderstorms (Simon et al. 2005). Average annual precipitation from 1989 to 2009 was 2,756 mm on Grandfather Mountain, at 1615.4 m elevation (GHCN Grandfather Mountain weather station). The mean January temperature from 1989 to 2009 was -1.1°C, while the mean July temperature was 17.2°C

(GHCN Grandfather Mountain weather station). Fire has been shown to favor south or west-facing slopes, ridgetops, upper slopes and lower elevations in the neighboring Great Smoky Mountains National Park (Flatley, Lafon, and Grissino-Mayer 2010). Lightning ignitions in the region are strongly associated with slope and aspect position patterns (Flatley, Lafon, and Grissino-Mayer 2010), with lightning ignitions peaking in May (Frost 1998). Pre-suppression fire frequency has been generalized at a 7-12 year interval (Frost 1998), current fire regimes are longer intervals, and occurring primarily in the spring or fall (Baker 2009; Barden 1974; Flatley et al. 2013).



**Figure 1. Map of Grandfather Ranger District showing elevation (m)**

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### **3.2 Analyze lightning-ignited fires with respect to synoptic classification**

#### **(Objective 1)**

The size of the spatial grid used in the SOM depends on the need of the study. The precedent set by the literature is for researchers to do multiple iterations of different spatial grids before analysis to pick the size that best fits their study (Crimmins 2006; Hewitson and Crane 2002; Michaelides, Tymvios, and Charalambous 2010). Prior to analysis classifications were produced with a 4x3 SOM, and 5x5 SOM. The results of each were then analyzed and the spatial grid that best fit the synoptic classification need was chosen. The SOM was run for 2,000 iterations, the literature varies between 2,000 (Michaelides, Tymvios, and Charalambous 2010) and 5,000 (Zurita-Milla et al. 2013).

Synoptic classifications from the SOM were done using 500mb-geopotential heights. The geo-potential height is gravity adjusted height or based off the mean seal level of the Earth instead of the elevation allowing for approximation of pressure surfaces above mean sea level. This pressure at a given height varies with the density of the air, with warm air being less dense and higher altitude while cold air is denser and will have a lower altitude. The 500 mb-geopotential heights represent the troposphere near the level of non-divergence, and was found to illustrate mid-tropospheric buoyance which is important in generating lightning activity (Mora et al. 2015). Higher geopotential heights move further away from the surface and closer to the jet stream; while lower geopotential heights are closer to the surface and are better suited for low elevations. Previous climatology studies that have analyzed lightning have done so using 500 mb-geopotential heights (Nash and Johnson 1996; Mora et al. 2015). North American Regional Reanalysis (NARR) reanalysis data was used for 500

mb-geopotential heights. The spatial resolution of the NARR data is 32 km. The NARR reanalysis data is also closer to observed temperatures throughout the troposphere compared to the National Centers of Environmental Prediction-National Center of Atmospheric Research (NCEP-NCAR) data (Mesinger et al. 2006).

Synoptic classification was completed with the SOM algorithm (Kohonen 1990) using 500mb geopotential heights from NARR data. Daily geopotential heights were selected because preliminary work showed that using 3 hour NARR data were too specific for the ignition timing provided by fire data. SOM analysis was completed for both the 4x3 and 5x5 SOM. The distributions were similar to those created during preliminary work when an additional SOM was created using 6x6 nodes. Preliminary results suggested only two different SOM's need to be created using daily data. Final selection for which SOM would be used was based on the lowest variance for between group and within group variance of the nodes.

Lightning ignited fire data were obtained from the National Interagency Fire Management Integrated Database (NIFMID). Fires are listed by specific cause. Ignitions attributed to lightning were tabulated for 1993-2009 and were compared to the two different SOMs. Although the NARR data included dates from 1989 to 2009, there were no fires in the study area that were attributed to lightning-ignition from 1988-1992.

SOM's were then examined by each node. Seasonality of each node was recorded. This was decided by analyzing what months a node was most prevalent and scarce. While some nodes are absent in certain months, others are common throughout the year. Seasonality was determined in those through monthly maximum and minimum occurrences.

Additionally each lightning ignited fire was tabulated with the corresponding node associated with the day of observed fire. The node associated with each of the 5 days preceding an ignition were also recorded.

To discern if lightning-ignited fires were associated with specific nodes, I used a bootstrapping procedure in which the count of node occurrence from 1989 to 2009 were bootstrapped utilizing the boot function in the boot package using R Studio. The frequency of the: count of each node, the count of lightning ignited fires in each node, and the count of each node 5 days preceding were each randomized 10,000 times. Confidence intervals were created for 95% and 99% as well as P values for each category.

### **3.3 Analyze lightning strikes with respect to synoptic classification (Objective 2)**

Lightning strikes were analyzed using the National Lightning Detection Network (NLDN) data from 1988–2003. Data were provided by the Texas A&M Atmospheric Sciences Department. An area from 36.318°N, 35.392°S, -88.507°W, and -81.359°E was selected for the study area. This included a 16-20 km buffer to consider the distance lightning can travel horizontally before striking the ground. All positive charges listed below 10 kA were discarded (0-9.99 kA) (Orville and Huffines 2001).

A lightning analysis was constructed from 1989 to 2003 for the Grandfather Ranger District. All lightning strikes were classified into the n/nodes produced through the SOM algorithm. Lightning strikes were tabulated by each month they occurred. Strikes were also tabulated for the day each lightning fire was observed and for the total number of strikes 7 days before a lightning ignited fire occurred. Additionally, lightning strikes were counted for what time of day they occurred.



Lightning strikes were then bootstrapped. The frequency of the count of strikes per node was randomized 10,000 times in the process. The number of strikes per each node were tabulated and tested within 95% to 99% confidence intervals. P values for each node were also generated. Determination was made if lightning occurred disproportionately in certain synoptic types more or less than others.

### **3.4 Describe the environmental variables for each lightning-ignited fire event**

#### **(Objective 3)**

A detailed understanding of the conditions that occurred prior to, on, and post lightning ignition lends to the understanding of how natural ignitions occur across a particular landscape. To this end environmental variables were gathered for each day a lightning ignited fire occurred from 1989 to 2009. This included: acres burned, the date the fire burned out, Palmer Drought Severity Index (PDSI) for the month and the 6 month PDSI average, maximum and minimum temperature, precipitation the day of and the total precipitation of the previous 7 days, the average wind speed, and relative humidity. Additionally for events that occurred from 1989 to 2002, the number of lightning strikes that occurred the day of ignition and the number of strikes that occurred the previous 7 days were included. For events that occurred from 2003 to 2009 wind direction, maximum, minimum and gusts, relative humidity maximum and minimum, and fuel moisture maximum and minimum were recorded. The date of each fire, the number of acres burned, and the date the fire burned out were recorded from NIFMID. PDSI was obtained from the National Center for Academic Research and University Corporation for Atmospheric Research or NCAR UCAR. Maximum and minimum temperatures as well as precipitation totals were collected

from the GHCN Grandfather Mountain weather station. The 1989 to 2002 events include wind speed and relative humidity data from WAYN Mountain Research Station, Waynesville, NC and the Greensboro Piedmont Triad International Airport, NC weather station. Lightning data was sourced from the NLDN dataset. Events from 2003 to 2009 had wind, relative humidity, and fuel moisture data from Remote Automated Weather Station (RAWS) GDCN7 at Grandfather Mountain, NC. Weather surface maps from 1989 to 2002 are from the National Oceanic and Atmospheric Administration (NOAA) Daily Weather Map series. Weather surface maps from 2003 to 2009 are from the NOAA National Centers for Environmental Prediction (NCEP) daily weather map series.

### **3.5 Evaluate whether vegetation patterns are associated with lightning-ignited fires**

#### **(Objective 4)**

Point pattern analysis was used to diagnose whether the spatial distribution of *Hudsonia montana*, an endemic shrub, was associated with the location of fire. Locations of *Hudsonia montana* were shared with the Texas A&M Biogeography Lab from the Forest Service, United States Department of Agriculture. First, lightning ignition locations and locations of *Hudsonia montana* were loaded into ArcGIS 10.2. Ripley K analysis was run on both files to determine spatial pattern across the landscape. Secondly, the fire locations, all classifications of ignition source, and *Hudsonia montana* locations were loaded into Passage2 software. Passage2 software provides the user specific controls used in Ripley K analysis and allowed for bivariate analysis while ArcGIS 10.2 did not. Second order bivariate analysis were run on both anthropogenic and natural ignitions and *Hudsonia montana* locations.

Second order bivariate analysis was also conducted on only lightning ignited fires and *Hudsonia montana* locations.

Ripley's K analysis was done through creating distance matrixes from the locations of *Hudsonia montana* and fire ignitions. Distance matrixes are created from the variable points provided. Once a distance matrix is created the program allows for second order analysis. Randomization test were used with 99 replaces at an interval of 95%. Bivariate tests were done using the type (fire or plant) and treated test patterns independent of current locations. The results were then exported into Microsoft Excel and LHAT was recalculated along with the 2.5% and 97.5% values. LHAT displayed the spatial distribution along the landscape. This coupled the confidence intervals allow for graphical illustration of spatial aggregation, normal distribution, or hyper distribution. LHAT was determined using the equation in Equation 1.

$$\text{LHAT} = \sqrt{(\bar{K}/\pi)} - D$$

**Equation 1.** LHAT equation.

## 4. RESULTS

### 4.1 Objective 1 results

#### 4.1.1 Synoptic clusters

Synoptic classifications were created using 500mb geopotential heights from NARR reanalysis data from 1989-2009. Preliminary work with this data suggested using a 4x3 SOM and 5x5 SOM. Variance with both SOM's were calculated. Between groups variance is the variance between the different synoptic types. Within group variance is the variance between the observations within each synoptic type. It is better to have a higher between variance and lower within variance. Between groups variance, within group variance, and total variance were lowest in 4x3 SOM (Table 1). Although 5x5 SOM has a higher between group variance, the within group variance and total are much lower in the 4x3 SOM. Although the between group is lower in the 4x3 than the 5x5 the much lower within and total variance of the 4x3 SOM suggests it better groups the local climatology over the Grandfather Ranger District than the 5x5 SOM.

SOM	Between	Within	Total
4x3	-0.52	13.52	13
5x5	10.78	43.39	54.17

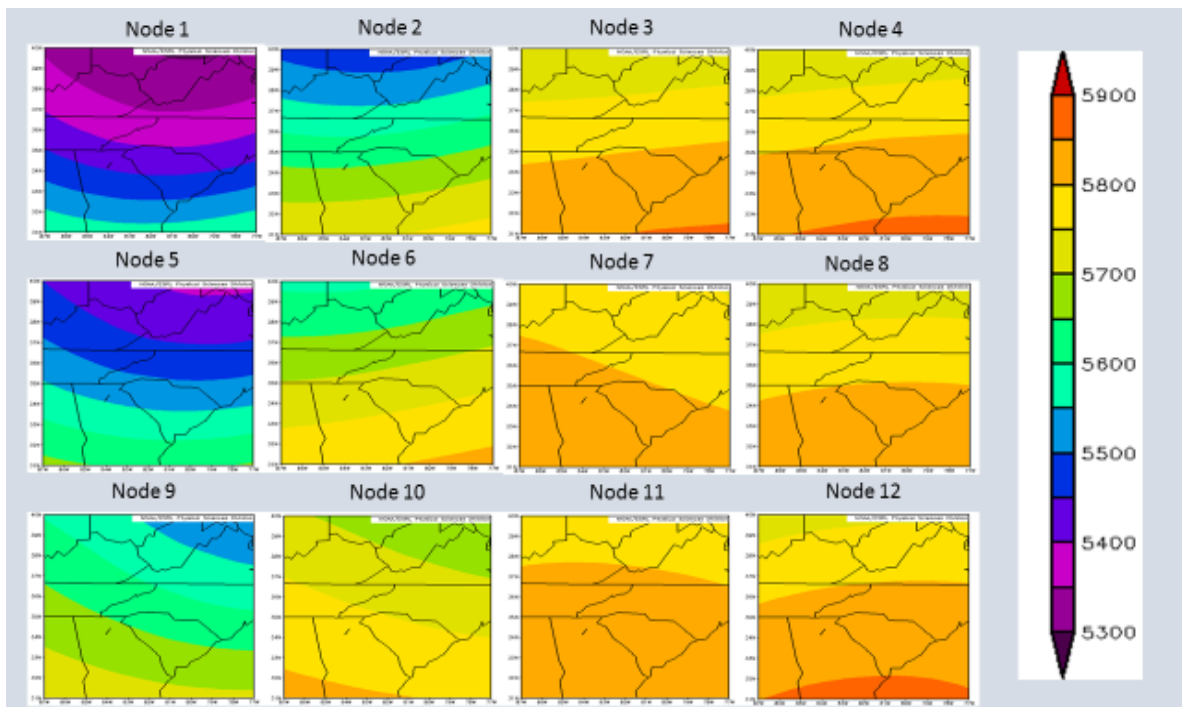
**Table 1.** SOM variance.

Both SOMs were used in examining the number of lightning ignited fires and lightning strikes. The 4x3 SOM and 5x5 SOM created similar distributional groupings.

Analysis of both SOM with respect to lightning strikes and lightning ignited fires presented easier with smaller clusters. This led to selection of the 4x3 SOM for both parsimony and lower total variance. The 4x3 SOM was then solely used for this research.

#### 4.1.2 Node descriptions

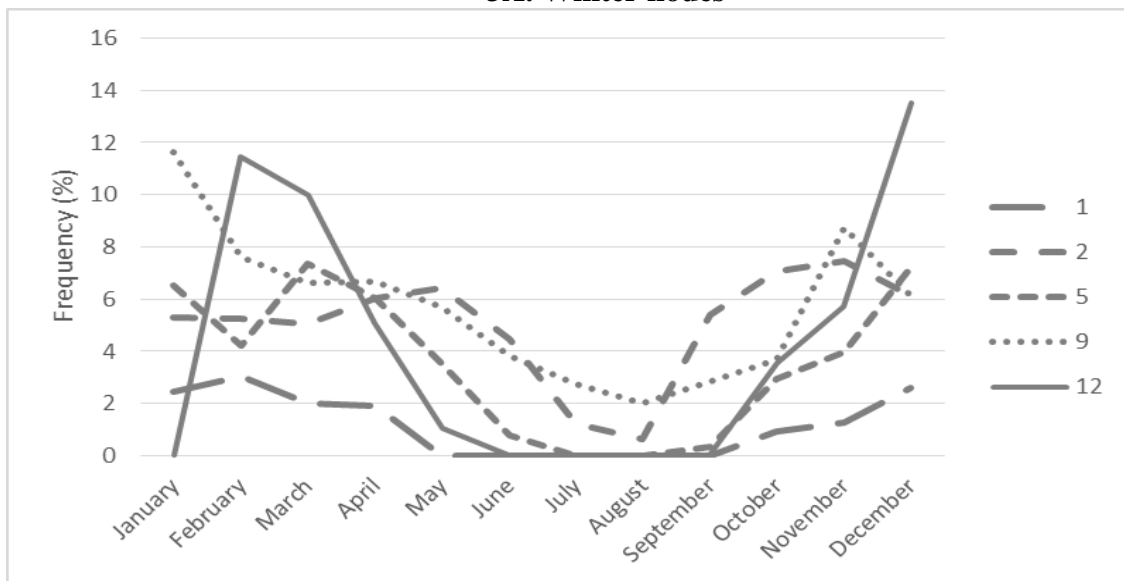
Each node is listed by output from the SOM creation (Figure 2). Node 1 and Node 12 are the most different. The 12 node SOM are displayed in Figure 3. The 4x3 SOM is represented by clusters of 500mb geopotential heights from 1989-2009.



**Figure 2.** 500mb geopotential height clusters from 12 synoptic types from 1989-2009.

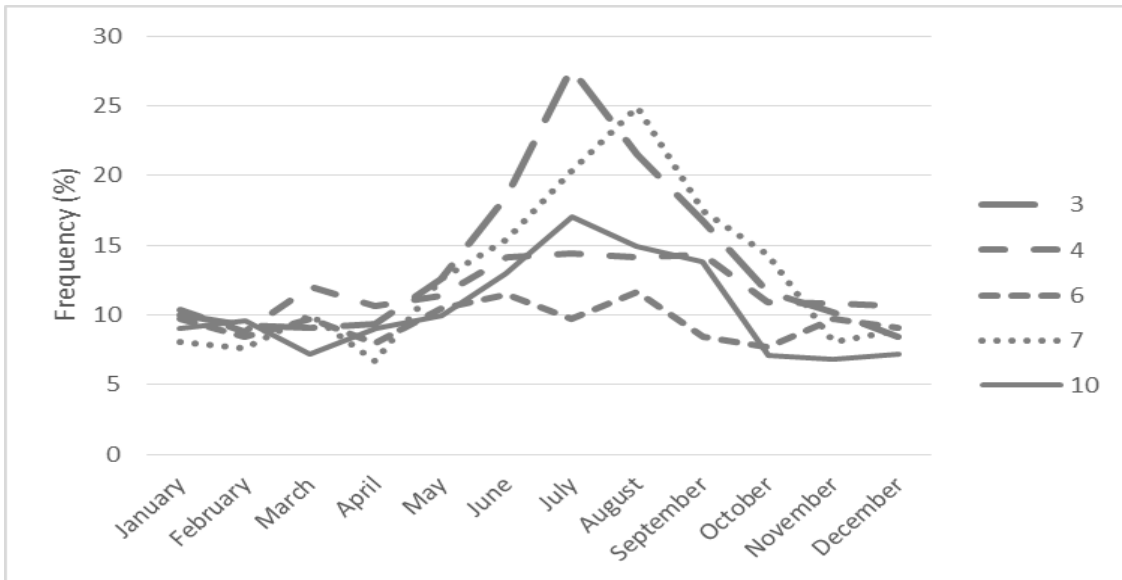
The frequency of occurrence for each node are displayed in Table 2. Each node has a seasonal pattern of occurrence and are displayed in Figure 3. Nodes 1, 2, 5, 9, and 12 are most prevalent in the winter months. Nodes 3, 4, 6, 7, and 10 are the more prevalent in summer months. Nodes 8, and 11 are transitional, or spring and fall months. The months listed are the total number of occurrences in that month from 1989 to 2009. This permitted the analysis of each month throughout the temporal selection for simpler study of how the synoptic classifications occur seasonal. Peaks and losses of occurrences in each month were used to select seasonal classification.

### 3A. Winter nodes



**Figure 3.** Seasonal distributions of synoptic types by frequency of occurrence in each month. Synoptic types generated from daily 500 mb geopotential heights from 1989-2009. Winter nodes are in 3A, summer nodes are in 3B, and transitional nodes are in 3C.

### 3B. Summer nodes



### 3C. Transitional nodes

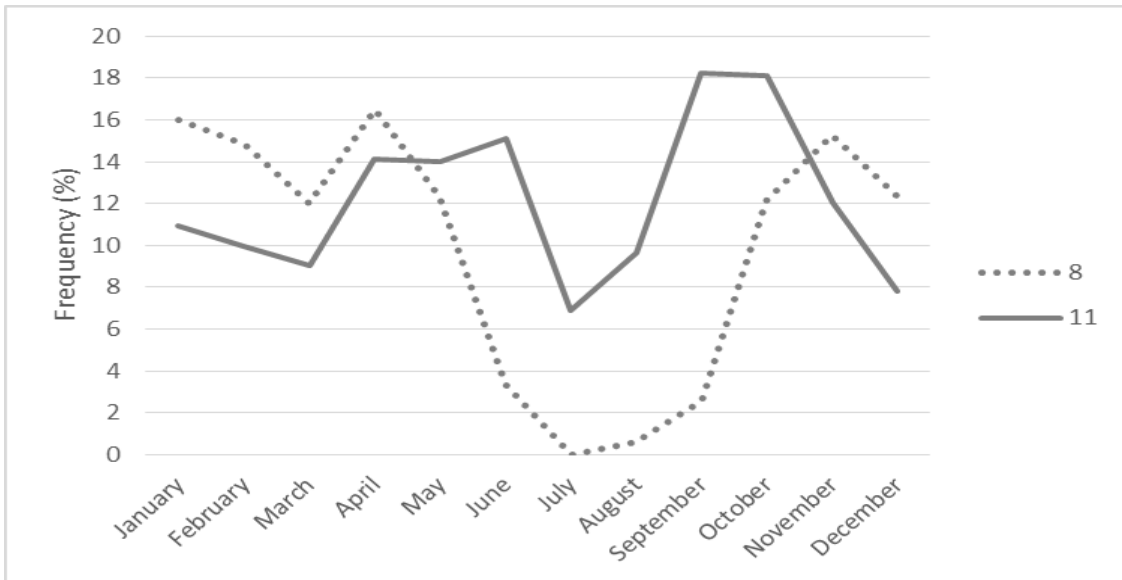


Figure 3. continued

**Table 2.** Number of occurrences of each node, daily from 1989-2009.

Node	Occurance
1	88
2	381
3	1049
4	903
5	269
6	720
7	983
8	737
9	425
10	790
11	923
12	402

### **Node 1**

The cluster pattern for node 1 demonstrates meridional flow. Node 1 occurred only 1.1% of the time from 1989 to 2009. The low occurrence of node 1 (n=88) is significant ( $P=7.96E-05$ ). Low geopotential heights ranging from 5300 to 5400 meters over the study area (Figure 2). This pattern suggest a low pressure system in which a frontal boundary has already passed. Node 1 occurred most often in the winter months, peaking in February. Although due to its low frequency of occurrence it only made up 3% of the climatic patterns that occurred in February. This cluster does not present in May, June, July, August, September, or October. Only five lightning strikes occurred in this synoptic pattern from 1989 to 2003 and zero lightning ignited fires occurred from 1989 to 2009.

### **Node 2**

Node 2 also presents meridional flow, although weaker than node 1. The low occurrence of node 2 (n=381) is significant ( $P=0.0159$ ). Node 2 occurred 5% of the time



from 1989-2009. The geopotential heights are approximately 5600 meters above sea level and moderate temperatures. This cluster appeared most often in May, October and November (7%) and presented fewest in July and August (1%). Only one lightning ignited fire occurred under this pattern from 1989-2009, but 6,518 lightning strikes occurred during 1989 to 2003.

### **Node 3**

Node 3 is the first node to present zonal flow over the southeast. There is a southwest to northeast tilt. The geopotential heights over Grandfather Ranger District are approximately 5,750 to 5,800 meters above the surface. Node 3 (n=1,049) was strongly significant in occurrence ( $P=8.71E-4$ ) occurring 13% of the time from 1989 to 2009. This cluster was most prevalent in the summer, accounting for 28% of days in July and only 8% in December. There were 3 lightning ignited fires under this synoptic pattern and 76,567 lightning strikes.

### **Node 4**

Node 4 is quite similar to node 3, as zonal flow occurring with a slight tilt from the southwest to the northeast. However node 4 has higher geopotential heights occurring further north than node 3. The 500mb height is approximately 5,750 to 5,850 meters above the surface. Node 4 was present for 7 lightning ignited fires and 99,945 lightning strikes. This cluster occurred most often over the summer months peaking from June to September with 14% of the days in each month; adversely it bottomed in February only being present during 8% of the days. This synoptic pattern occurred 11.8% of the time and occurrence (n=903) of this node was significant ( $P=0.014$ ) occurring more than expected during the time frame.

## **Node 5**

The pattern displays meridional flow with the second lowest 500mb geopotential heights among the different clusters. Geopotential heights range from 5,450 to 5,550 meters above the surface. This pattern was mostly prevalent in winter months peaking in January, March, and December at 7% of the total days. Adversely, this pattern was absent for all days in July, August, and September. The low occurrence, only 3.5% of the time, of node 5 was strongly significant ( $n=269$ ,  $P=0.0018$ ). There were no lightning ignited fires and 4,196 lightning strikes associated with this synoptic type.

## **Node 6**

Node 6 displays weak meridional flow with geopotential heights ranging from 5,650 to 5,750 meters above the surface. This pattern occurred throughout the year with no distinct seasonal pattern, although slightly peaking in August with 12% of days and bottoming in September, October, February, and April with 8% of the days. Node 6 occurred 9.4% of the time with the occurrence ( $n=720$ ) being normal ( $P=0.39$ ). There were 38,252 lightning strikes and 4 fires from lightning ignition with this node.

## **Node 7**

Node 7 returns the cluster to zonal flow with a strong tilt from northwest to southeast, more than likely the result of an advancing high pressure system. Geopotential heights range from 5,750 to 5,850 meters. This cluster ( $n=984$ ) occurred significantly more than most at 12.8% of the time ( $P=0.003$ ). The higher geopotential heights are congruent with this node being more associated with summer seasonal patterns. Node 7 was most prevalent in August at 25% of the days and least common in winter months and April at 8% and 7% of the days

respectively. Some 93,423 lightning strikes occurred during this synoptic type with 4 fires caused by lightning ignition.

### **Node 8**

This synoptic type shows zonal flow from west to east. The 500mb geopotential heights approximately range from 5,750 to 5,800 meters. Only 2 fires were ignited by lightning strikes from 1989 to 2009, and 15,254 strikes occurred from 1989-2003. While this pattern has higher geopotential heights it is associated with winter and transitional months. Node 8 peaked in April at 17% of the days of the month but is absent in July. This cluster appears normally (n=737, P=0.187) about 9.6% of the time.

### **Node 9**

Node 9 is meridional flow from north to south. This node (n=425) appeared 5.5% of the time and had significantly low occurrence (P=0.037). Node 9 was most prevalent in winter, peaking in January with 12% of the days and bottoming in August at 2% of the days. Only 1 fire was ignited by lightning from 1989 to 2009 and only 4,102 lightning strikes spawned from this synoptic type. The geopotential heights range from 5,600 to 5,650 meters above the surface. This cluster suggests the backend of a low pressure system that has previously advanced through the area.

### **Node 10**

Node 10 demonstrated meridional flow and geopotential heights ranging from 5,700 to 5,750 meters above the surface. The meridional flow is from north to south. The occurrence (n=790) of this synoptic type was normal (P=0.124) at 10.3% of the time. Node 10 occurred throughout the year but peaked in summer with 17% of the total days in July and

only 7% of the total days in October through December. There were 34,937 lightning strikes that occurred during node 10 and 5 lightning ignited fires.

### **Node 11**

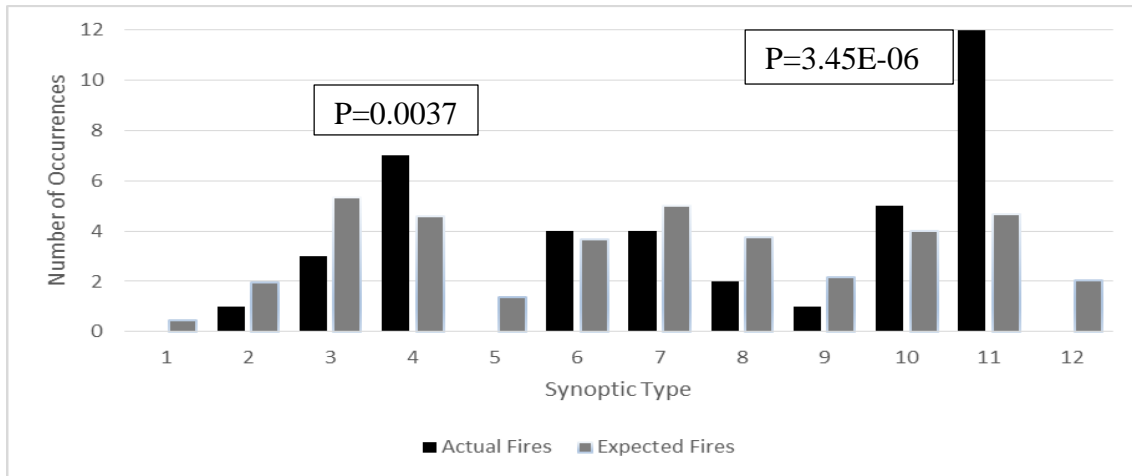
Node 11 has meridional flow from south to north, associated with high pressure. The geopotential heights are the highest in northern southeast for all synoptic types. The 500mb geopotential heights range from 5,800 to 5,850 meters above the surface. This node occurred (n=923) significantly higher than normal ( $P=0.009$ ) at 12% of the time. Node 11 is most associated with transitional seasonality and peaked in September and October at 18% of the days. It is not evenly bimodal as April and May are 14% of the days. This node occurred least often in July at only 7% of the days. There were 67,415 lightning strikes from 1989-2003 and 12 lightning ignited fires from 1989 to 2009 associated with this synoptic type.

### **Node 12**

Node 12 demonstrates meridional flow from south to north along a high pressure gradient. The geopotential heights range from 5,800 to 5,850 meters above the surface. Unlike node 11 the highest geopotential heights do not range as far north but a strong meridional flow is more present than in node 11. This synoptic pattern (n=402) was significantly lower in occurrence ( $P=0.02$ ) with only 5.2% of time. This node is most associated with winter as it peaked in December, February, and March. Synoptic type 12 was absent June, July, August, and September from 1989-2009. There were no lightning ignited fires associated with this synoptic type and 6,489 lightning strikes occurred with it.

### 4.1.3 Association of lightning ignited fires with synoptic types

Node 11 occurred the most often when a lightning strike ignited a fire. Bootstrapping was completed to analyze a random distribution and a t-test on node distribution was also completed to determine significance (Figure 4). Bootstrap analysis found that lightning ignitions in nodes 4 and 11 occurred more often than expected ( $P=0.0037$ ,  $P=3.45E-06$ ). Lightning ignitions occurred less often than expected in nodes 1, 5, and 12 ( $n=0$ ,  $P=0.0088$ ).

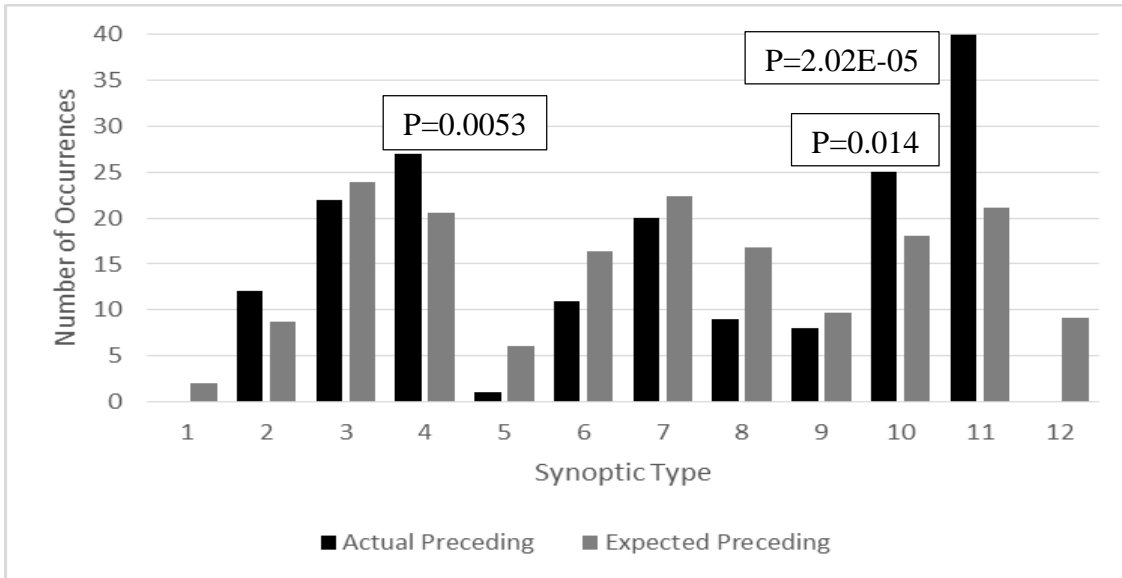


**Figure 4.** Expected number of fires and actual number of fires in each synoptic type.

Bootstrapping analysis was also done for the 5 days preceding the lightning ignited fire. This analysis mirrored the results of the bootstrapping for the synoptic type that occurred the day of ignition (Figure 5). Node 11 occurred 40 times in days leading up to a lightning ignited fire, occurring much more often than expected ( $P=2.02E-05$ ). Node 4 also occurred much more often than expected in the days preceding natural ignition ( $n=27$ ,  $P=0.0053$ ). Node 10 occurred more than expected ( $n=25$ ,  $P=0.014$ ). Node 5 occurred once in

days preceding a lightning ignition, occurring much less often than expected ( $P=0.003$ ).

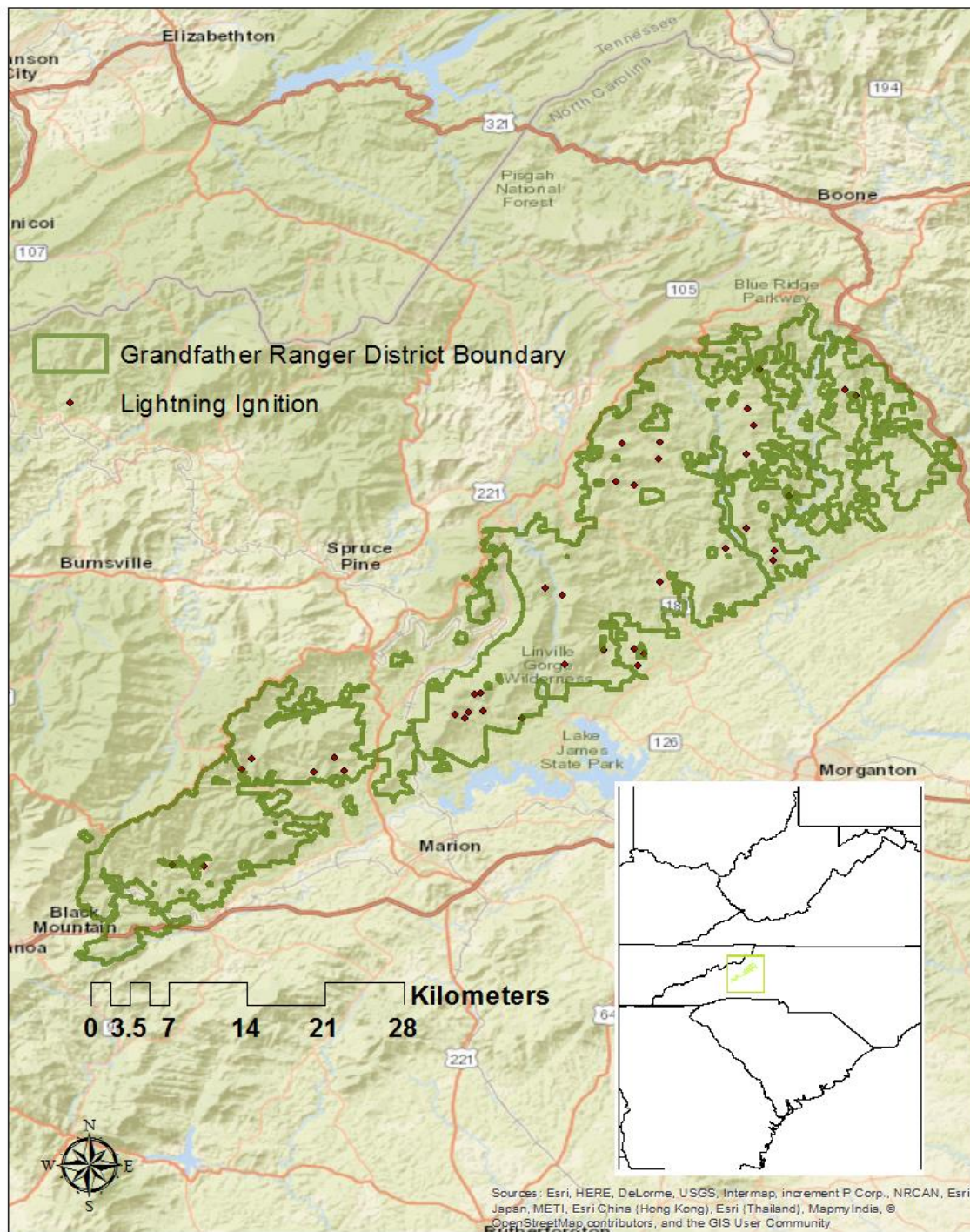
Likewise, nodes 1 and 12 were absent in the five days preceding a natural ignition occurring much less often than expected ( $P=0.0027$ ).



**Figure 5.** Expected and actual number of times a synoptic type appeared in the five days preceding a fire.

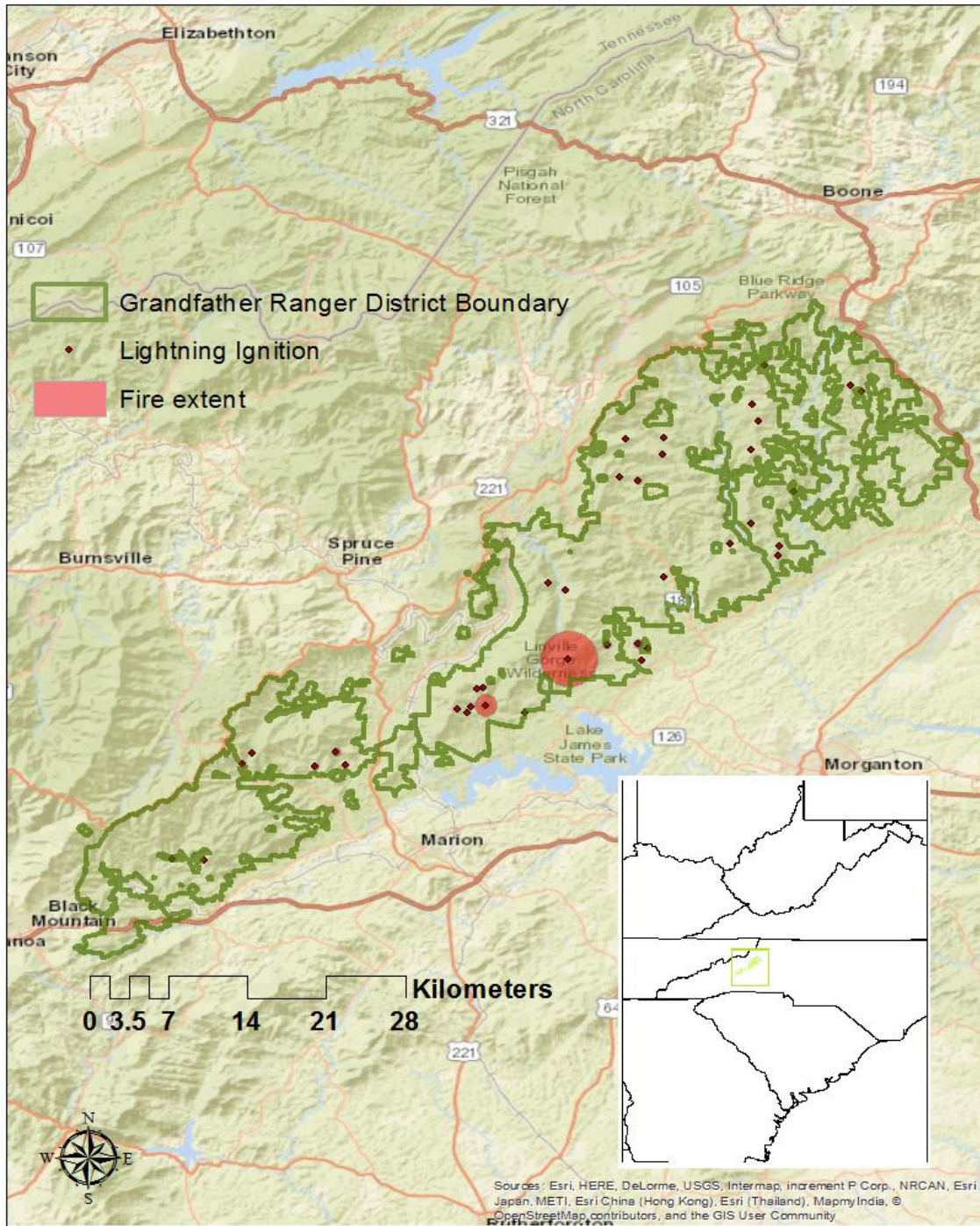
#### *4.1.4 Locations of fires in the Grandfather Mountain Ranger District*

Lightning ignitions were mapped (Figures 6-7). A histogram was created for the fire extent of the lightning-ignitions (Figure 8). Additionally anthropogenic ignited fires were also mapped (Figures 9-10) and a histogram was also created for those fire extents (Figure 11). Fire size was plotted by buffering the radius of acres burned. This technique creates and a circle around the ignition point without factoring in terrain or other assumptions.



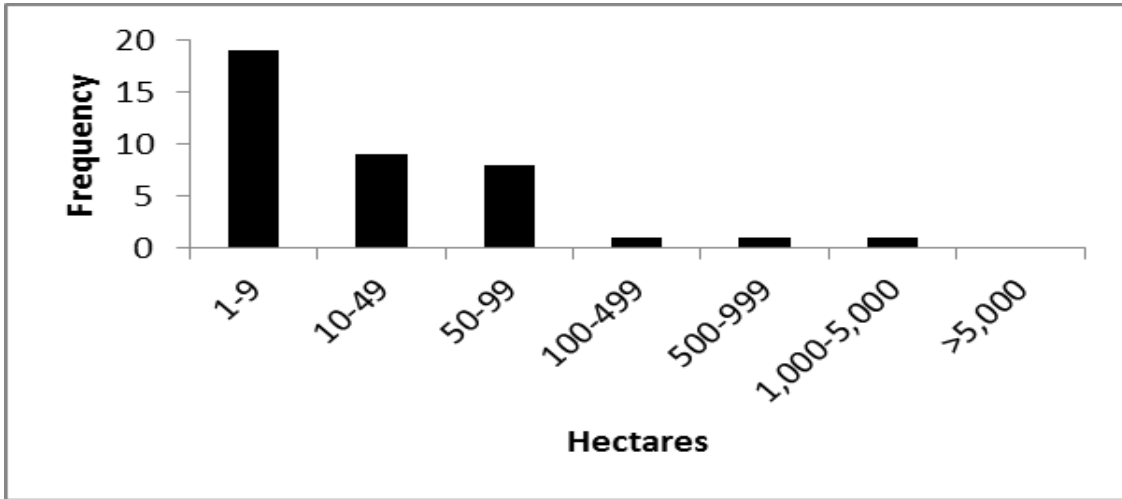
**Figure 6.** Map of Grandfather Ranger District showing lightning-ignitions.

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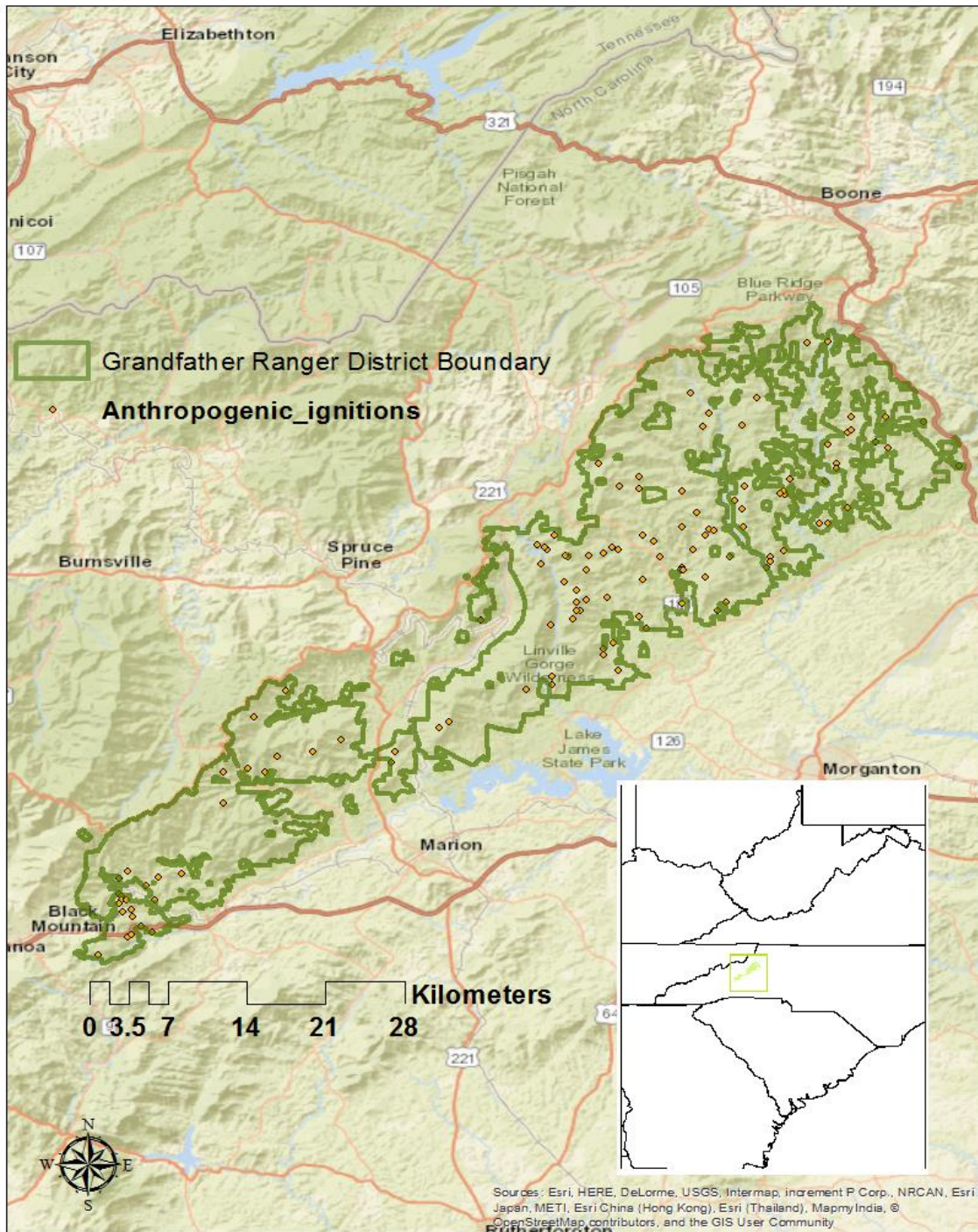


**Figure 7.** Map of Grandfather Ranger District showing the extent of lightning ignited fires. Source: Maps throughout this thesis were created using ArcGIS® software by Esri. ArcGIS® and ArcMap™ are the intellectual property of Esri and are used herein under license. Copyright© Esri. All rights reserved. For more information about Esri® software, please visit [www.esri.com](http://www.esri.com).

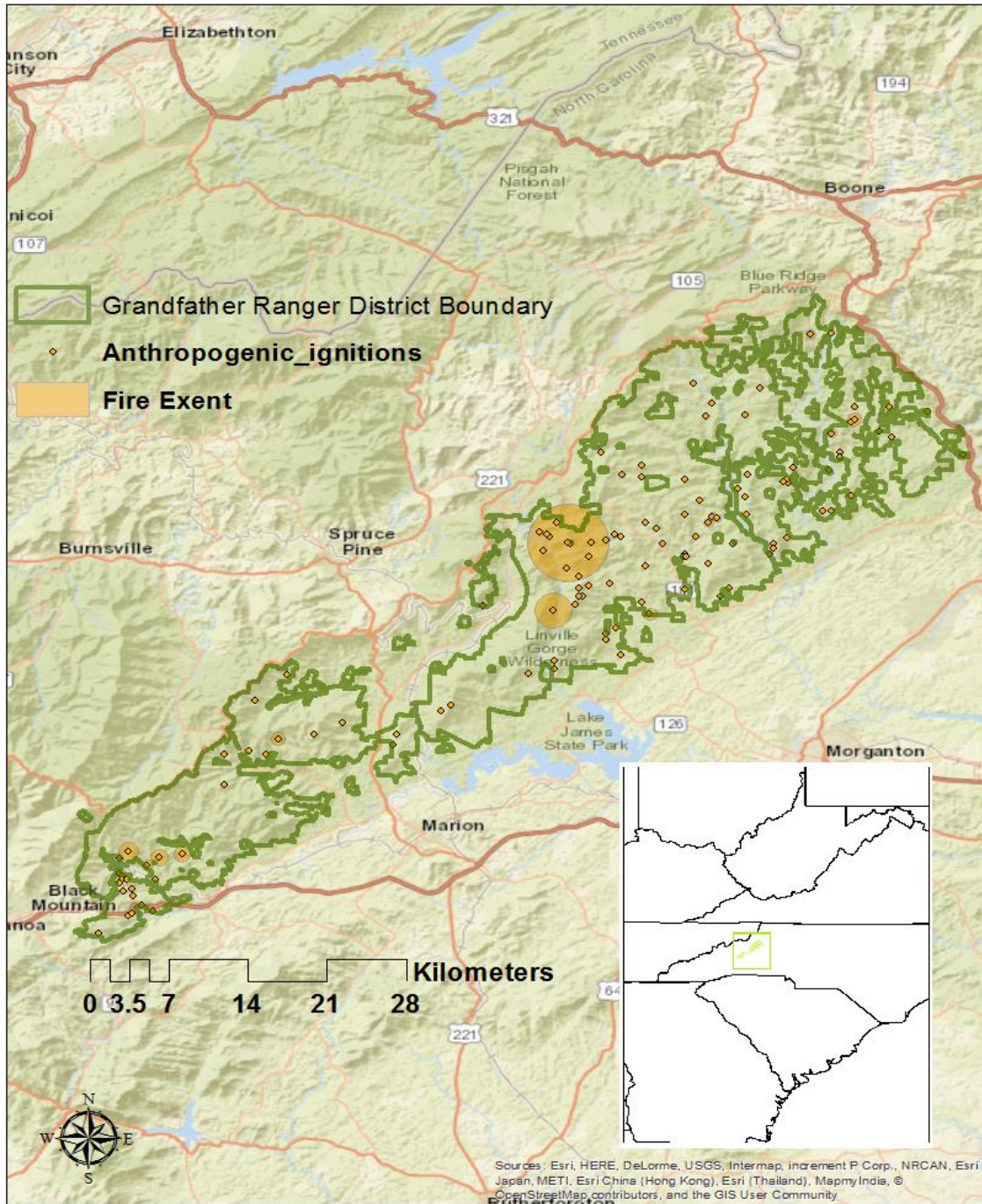




**Figure 8.** Histogram of lightning-ignited fires area burned by hectares.

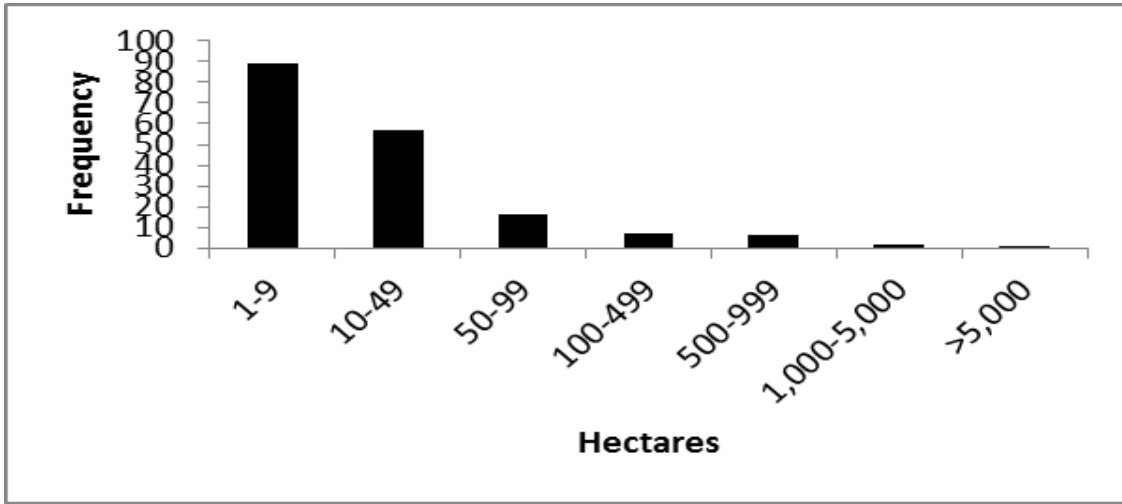


**Figure 9.** Map of Grandfather Ranger District showing anthropogenic-ignitions.  
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**Figure 10.** Map of Grandfather Ranger District showing the extent of anthropogenic ignitions.

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**Figure 11.** Histogram of anthropogenic ignitions areas burned by hectare.

#### 4.1.5 Drought conditions impact on acreage burned by lightning-ignition

The majority of burned acres occurred during periods of moderate drought (Table 3). Slightly more acres burned during near normal drought conditions than severe drought conditions. Interestingly the six month average of PDSI created a different result than the PDSI of the month of ignition. Lightning-ignitions burned more acreage in near normal conditions with moderate drought incurring more burned acreage than severe drought.

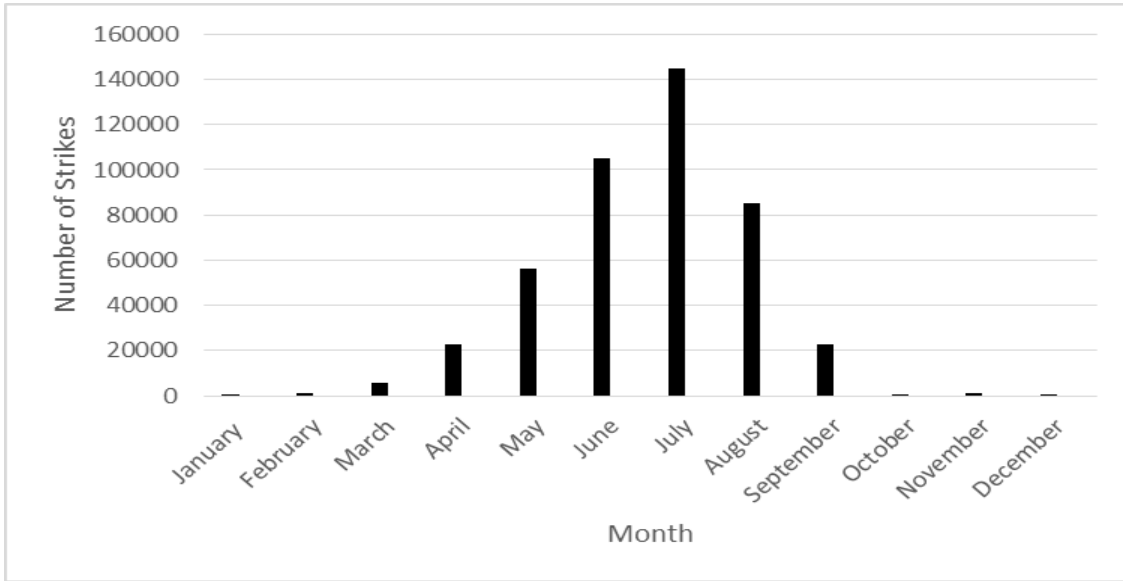
**Table 3.** Acreage burned under different drought conditions.

	SEVERE DROUGHT	MODERATE DROUGHT	NEAR NORMAL	UNUSUALLY MOIST
MONTH OF FIRE	202.2	6110.1	282	1
6 MONTH AVERAGE	165.1	235.1	6159.1	36

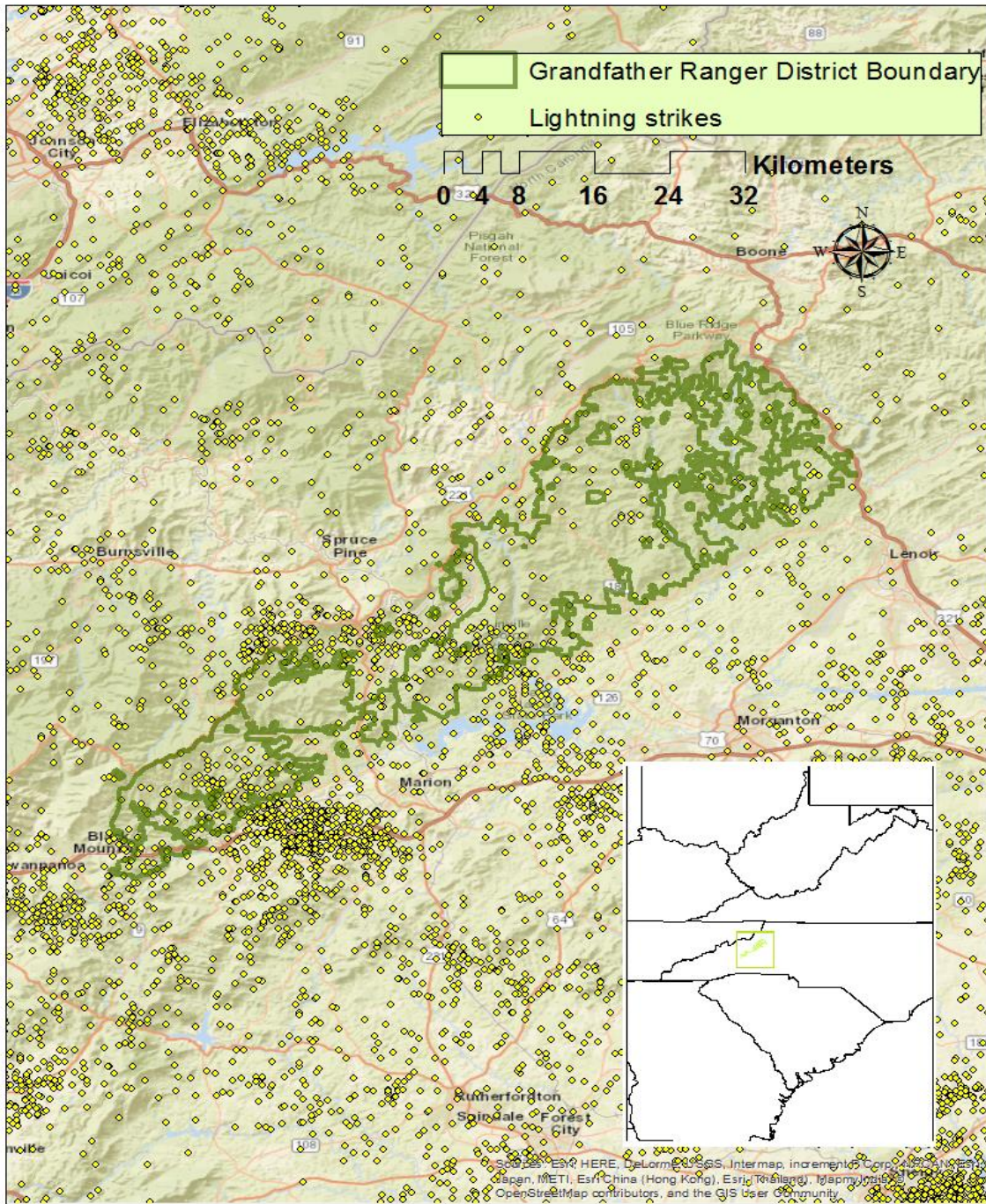
## 4.2 Objective 2 results

### 4.2.1 *Lightning climatology*

Lightning strikes were most prevalent in summer, accounting for 75% of the strikes throughout the year, 19% in spring, 6% in fall, and less than a percent in winter. The largest amount of strikes occurred in July (Figure 12), in which 32% of all the lightning strikes during the time period occurred. The date with the highest amount of lightning strikes was associated with node 11. Slightly over half of all strikes (59%) occurred during the afternoon and evening between 1400-1800 Eastern Daylight Time. Approximately 21% of all lightning strikes occurred in the evening (1900-2200 EDT), while night (2300-0600) and morning (0700-1300) accounted for 10% of lightning strike occurrences. Lightning strikes occurred throughout the entire study area during the time period, however an example of a small subset, in July 1998 there appears to be a cluster around the Linville Gorge Wilderness area (Figure 13).



**Figure 12.** Lightning strikes per month from 1989-2003.

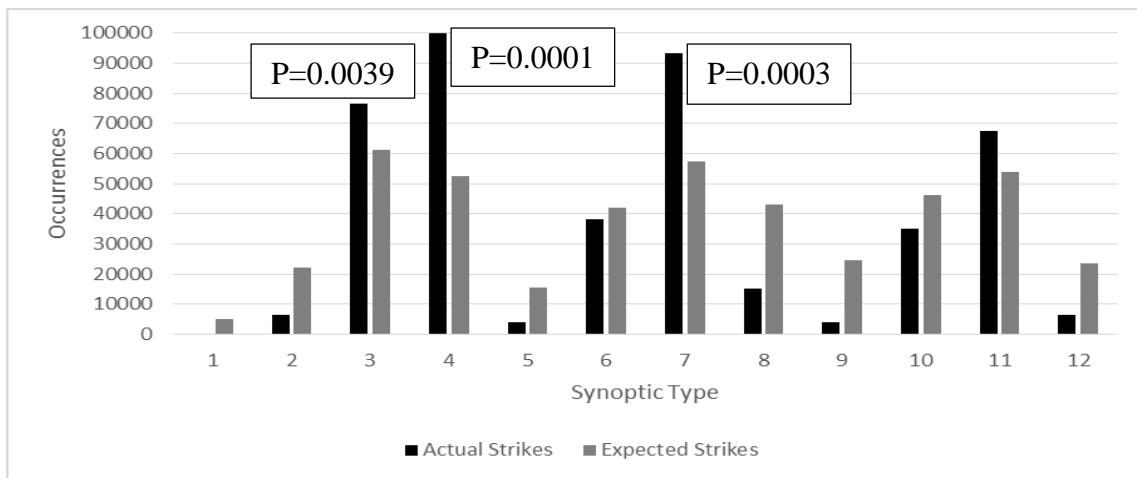


**Figure 13.** Map of Grandfather Ranger District showing lightning strike locations in July 1998.

Source: Maps throughout this thesis were created using ArcGIS® software by Esri. ArcGIS® and ArcMap™ are the intellectual property of Esri and are used herein under license. Copyright© Esri. All rights reserved. For more information about Esri® software, please visit [www.esri.com](http://www.esri.com).

#### 4.2.2 Synoptic patterns associated with lightning

Lightning strikes occur most often in node 4, followed by node 7 (Figure 14). The distribution of strikes in each node flows in natural breaks. The second tier has nodes 3 and 11 with the third and four highest amount of strikes in each synoptic pattern, respectively. The third tier contains nodes 6 and 10. Nodes 2, 5, 8, 9, and 12 all have lower amounts of lightning strikes while node 1 only is only associated with 5 lightning strikes.



**Figure 14.** Expected and actual number of lightning strikes in each synoptic type.

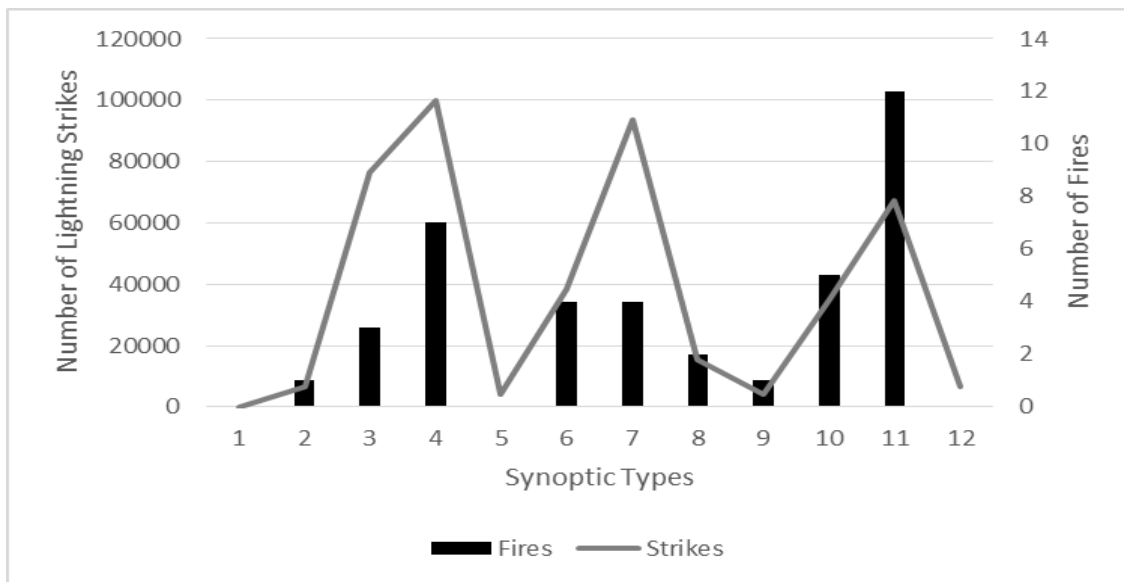
Bootstrap analysis was done using the lightning strikes. A t-test on node distribution was also completed to determine significance. Higher amounts of lightning strikes than expected occurred in nodes 3, 4, and 7 (P=0.0039, P=0.0001, and P=0.0003). Node 11 also had a higher departure from expected in the number of strikes, although not as high as the previous nodes (P=0.0178). Node 1 was found to have much less than expected occurrences of lightning strikes (P=0.0055). Nodes 2, 5, 9, and 12 were all found to have a significantly lower occurrence of strikes than expected (P=0.0162, P=0.0110, P=0.0109, and P=0.0161)



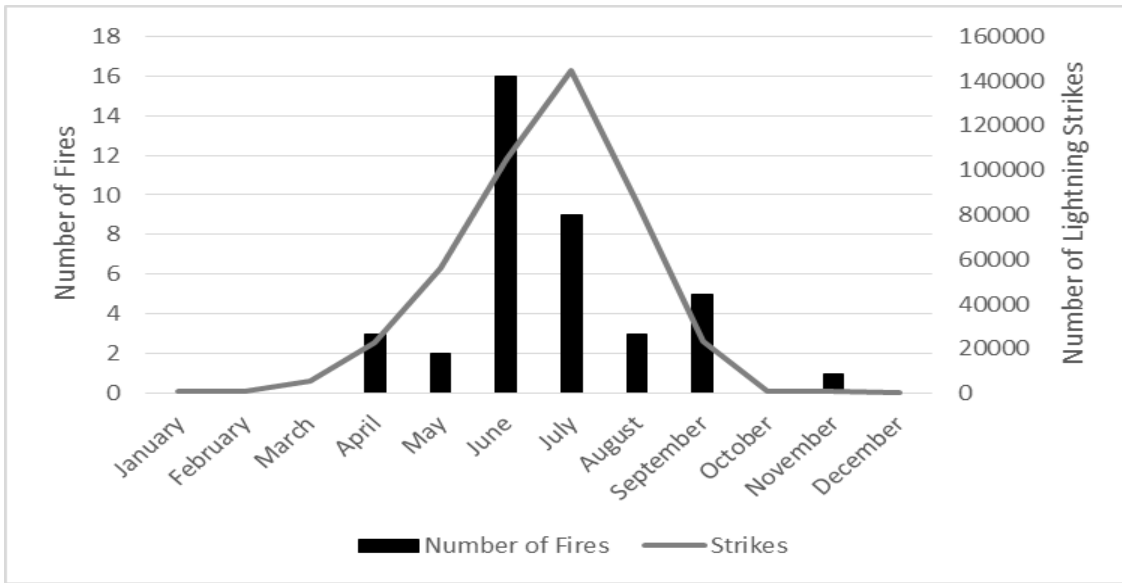
Nodes 6, 8, and 10 had normal amounts of lightning strikes, not varying statistically from the expected number of lightning strikes ( $P=0.9286$ ,  $P=0.06719$ , and  $P=0.8343$ ).

#### 4.2.3 Lightning and lightning ignited fires

Lightning ignitions and lightning strikes peaked under different synoptic types (Figure 15). Lightning occurred most under synoptic type 4, while lightning ignitions peaked under synoptic type 11. Lightning ignitions occurred most often in June from 1989-2009, while lightning strikes occurred most often in July during that period (Figure 16).



**Figure 15.** Number of lightning strikes (1989-2003) and lightning ignitions (1993-2009) in each synoptic type.



**Figure 16.** Number of lightning strikes (1989-2003) and lightning ignitions (1993-2009) in each month.

### 4.3 Objective 3 results

#### 4.3.1 Description of lightning ignited fire days

This section includes a brief synopsis of the weather conditions present the day of a lightning ignited fire. A weather map is included for each day a lightning ignited fire occurred. Weather maps from 1993 to 2000, each daily at 7:00 a.m. or 1200 UTC, are from the National Oceanic and Atmospheric Administration (NOAA) Daily Weather Map series. Weather maps from 2006 to 2009 are NOAA Weather Prediction Center (WPC) Daily Weather Maps, each also at 7:00 a.m. or 1200 UTC. Each event is detailed with a surface or forecast map and a description of the wind, rain, temperature maximum and minimum, Palmer Drought Severity Index (PDSI) for the month and six months average, and number of acres burned. Additionally, each event includes the synoptic type, and 500mb geopotential

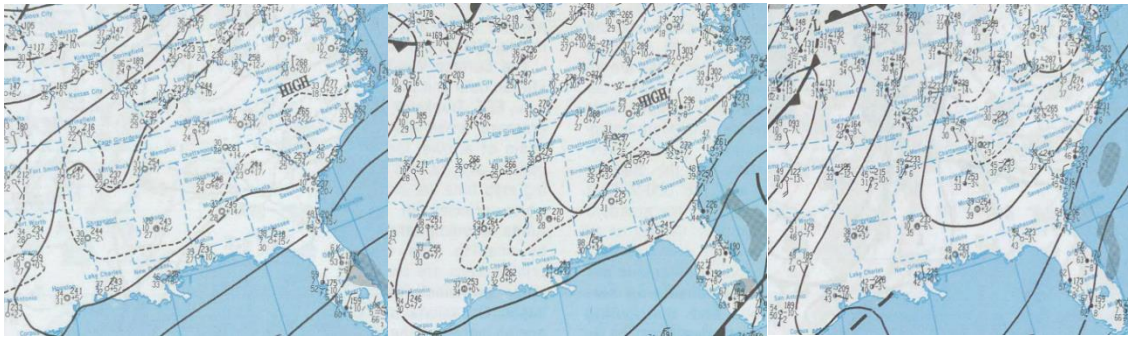
height map for the day of the event. Events from 1993 to 2000 have the number of lightning strikes that occurred that day and the week prior to event (Table 4). Events from 2006 to 2009 have the relative humidity maximum and minimum, wind maximum and minimum, wind gust speed, and wind direction (Table 5).

**Table 4.** Fire, location, acres burned, PDSI, synoptic type, lightning, and weather conditions for each lightning ignited fire event from 1993 to 2000 in the Grandfather Ranger District of the Pisgah National Forest, North Carolina. Fire data is from the National Interagency Fire Management Integrated Database. Palmer Drought Indices are from the Climate Prediction Center, NOAA. Temperatures and precipitation totals are from the GHCN station at Grandfather Mountain, NC. Wind speed and relative humidity data are from GHCND station at Greensboro Piedmont Triad International Airport, NC; and WAYN station at the Mountain Research Station in Waynesville, NC. Lighting Data is from the National Lightning Detection Network.

Fire, location, acres burned, PDSI, synoptic types, weather conditions, and lightning strikes for each event 1993-2002																	
Event	Date	Hectares Burned	Fire out	Latitude (DD)	Longitude (DD)	PDSI	PDSI 6 month (Average)	Node	Precipitation (mm)	Precipitation past week (mm)	Precipitation during fire (mm)	Maximum Temperature (C)	Minimum Temperature (C)	Average Wind Speed (kph)	Relative Humidity (%)	Lightning Strikes	Strikes in the past week
1	11/24/1993	6.07	11/27/1993	35.9250	-81.7233	-2.95	-2.25	11	0.0	2.8	48.6	12.2	5.6	1.8	Missing	0	6
2	9/4/1997	1.21	9/7/1997	36.0367	-81.7383	0.34	1.64	10	0.0	46.5	0.0	15.6	7.8	7.1	67	0	1185
3	6/16/1998	0.81	6/25/1998	35.7633	-82.0767	1.46	2.37	6	0.0	81.4	15.5	22.2	13.9	11.4	67	1078	1914
4	6/19/1998	12.14	6/25/1998	35.7617	-82.1433	1.46	2.37	4	0.0	14.5	11.2	21.7	16.7	9.2	90	42	1205
5	6/23/1998	0.81	7/10/1998	35.7533	-82.1517	1.46	2.37	11	7.6	7.6	72.9	22.8	12.8	8.0	84	2193	1447
6	6/30/1998	0.81	7/12/1998	35.6733	-82.1817	1.46	2.37	3	34.3	7.9	65.0	21.1	13.9	12.4	72	351	1763
7	7/2/1998	0.20	7/12/1998	35.9350	-81.7617	-0.89	0.85	10	3.6	47.5	17.5	15.6	11.7	6.3	79	2	4580
8	7/19/1998	48.56	7/30/1998	36.0217	-81.8450	-0.89	1.85	3	0.0	0.0	55.6	22.8	12.8	14.8	82	1216	482
9	7/19/1998	40.47	7/30/1998	35.8517	-81.8600	-0.89	1.85	3	0.0	0.0	55.6	22.8	12.8	14.8	82	1216	482
10	7/21/1998	0.20	7/30/1998	35.7950	-81.9250	-0.89	1.85	11	0.0	0.0	55.6	23.3	17.2	11.3	83	946	2002
11	7/21/1998	0.20	7/30/1998	35.7950	-81.9717	-0.89	1.85	11	0.0	0.0	55.6	23.3	17.2	11.3	83	946	2002
12	7/22/1998	0.20	7/30/1998	35.8000	-81.9683	-0.89	1.85	4	0.0	0.0	55.6	25.6	17.8	10.8	82	817	2948
13	9/9/1998	0.81	9/16/1998	35.7983	-81.9800	-2.11	0.36	9	15.7	46.7	15.7	10.0	-1.1	9.8	66	0	1963
14	4/9/1999	56.66	4/18/1999	35.9333	-81.7217	-2.25	-2.35	4	6.1	0.5	18.8	17.8	9.4	12.2	56	29	91
15	8/16/1999	4.86	8/20/1999	35.8525	-81.8353	-2.34	-2.14	11	0.0	22.4	23.4	21.7	15.0	3.9	Missing	0	628
16	6/13/2000	12.14	6/19/2000	35.8969	-81.8928	-2.29	-2.36	11	0.0	20.1	19.2	24.4	15.6	4.8	Missing	68	1
17	6/18/2002	6.47	6/30/2002	35.8383	-81.8317	-2.29	-2.36	6	0.0	30.2	54.8	18.9	8.9	3.1	67	0	877

**Event 1: 1993-11-24**

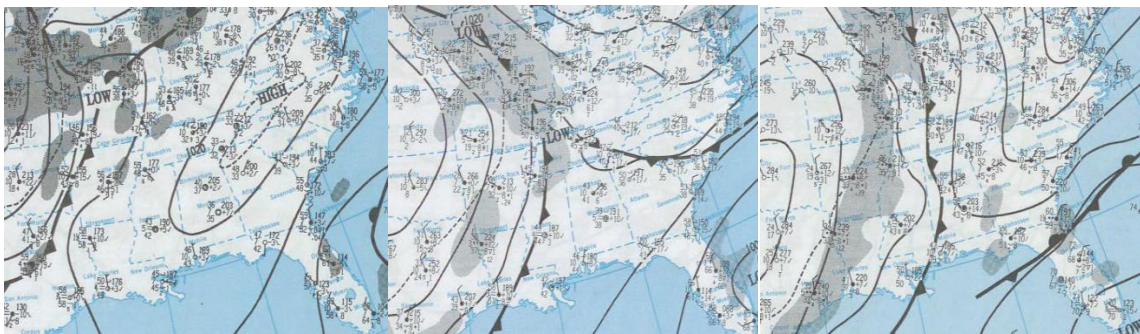
The region was in a moderate drought (PDSI -2.95). The day of the fire was associated with synoptic type 11 (Figures 17H-I). Little rain, 2.8 mm, fell the week prior to ignition while none fell the day the fire started (Table 4). The average wind speed was approximately 2 kph (Table 4). High pressure persisted over western North Carolina three days before ignition until three days after ignition (Figures 17A-F). A low pressure system with a cold front moved in from the west and entered North Carolina three days after the lightning ignition (Figures 17D-G). The wildfire burned fifteen acres over four days (Table 4). While the fire burned a total of 48.6 mm precipitation fell (Table 4).



**Figure 17A.** 19931121

**Figure 17B.** 19931122

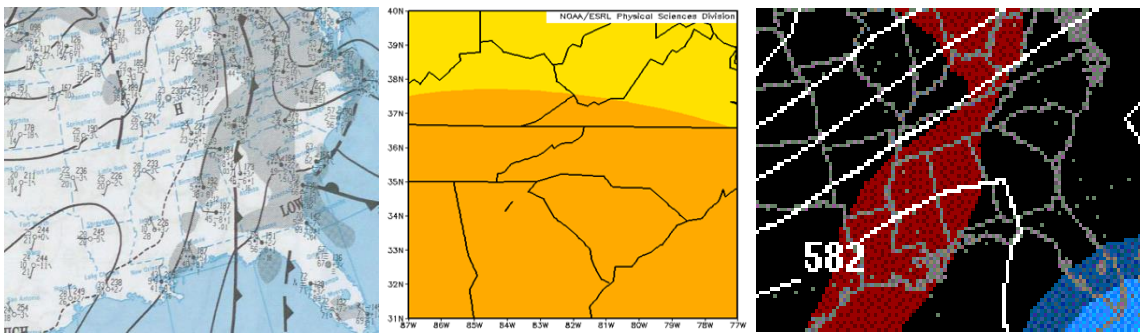
**Figure 17C.** 19931123



**Figure 17D.** 19931124

**Figure 17E.** 19931125

**Figure 17F.** 19931126



**Figure 17G.** 19931127

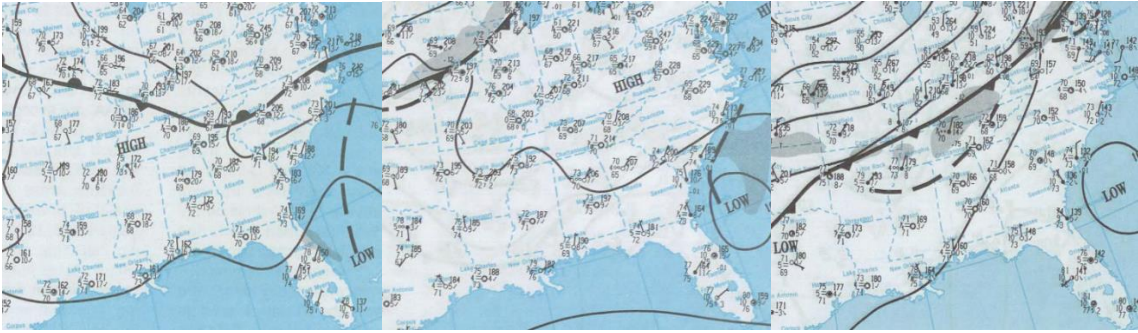
**Figure 17H.** Node 11

**Figure 17I.** 500mb 19931124

**Figure 17A-I.** Surface maps from the NOAA Daily Weather Map archive for 1993-11-21 through 1993-11-27, synoptic type, and 500 mb geopotential height map for 1993-11-24.

**Event 2: 1997-9-4**

Western North Carolina was near normal in drought severity (PDSI 0.34). The synoptic type was node 10 (Figures 18H-I). A total of 46.5 mm fell the week prior to ignition (Table 4). No precipitation fell the day of ignition or during the duration of the wildfire (Table 4). Winds were low at 7 kph (Table 4). Three days prior to ignition a stationary front sat over western North Carolina before being replaced with high pressure and having a cold front move through the day before ignition (Figures 18A-D). High pressure from the north persisted over North Carolina the day of ignition until at least three days after (Figures 18D-G). Three acres burned over four days (Table 4).



**Figure 18A.** 19970901

**Figure 18B.** 19970902

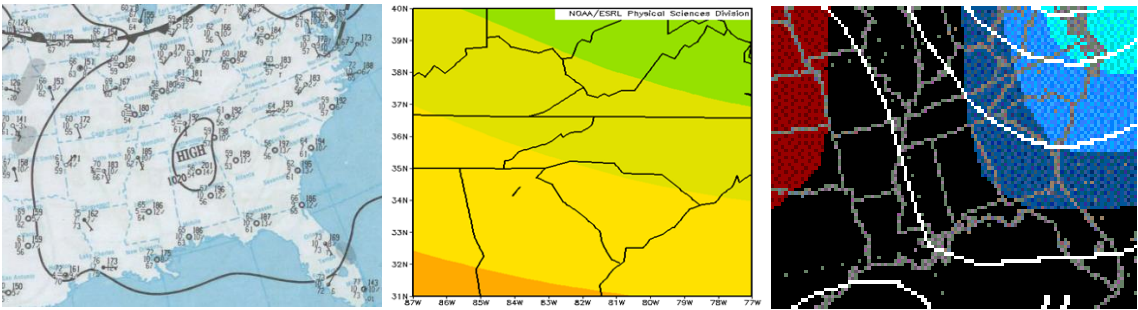
**Figure 18C.** 19970903



**Figure 18D.** 19970904

**Figure 18E.** 19970905

**Figure 18F.** 19970906



**Figure 18G.** 19970907

**Figure 18H.** Node 10

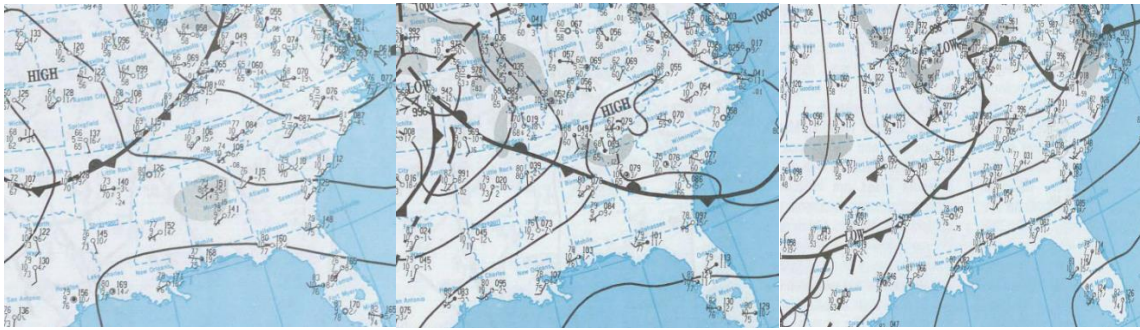
**Figure 18I.** 500mb 19970904

**Figure 18A-I.** Surface maps from the NOAA Daily Weather Map archive for 1997-9-1 through 1997-9-7, synoptic type, and 500 mb geopotential height map for 1997-9-4.



**Event 3: 1998-6-16**

The study area was near normal in drought severity index (1.46). The synoptic type 6 displayed a gradient of cold air with zonal flow at 500 mb (Figures 19H-I). A total of 81.4 mm of rain fell the week prior to the wildfire (Table 4). No rain fell the day of ignition, however, 15.5 mm fell while the fire burned (Table 4). Winds were 11 kph (Table 4). A stationary front persisted in the southeastern United States two days before ignition until two days after ignition (Figures 19B-F). The stationary front sat over western North Carolina the day of ignition (Figure 19D). Grandfather Ranger District had two acres burn before extinguishing on June 25, 1998 (Table 4).



**Figure 19A.** 19980613

**Figure 19B.** 19980614

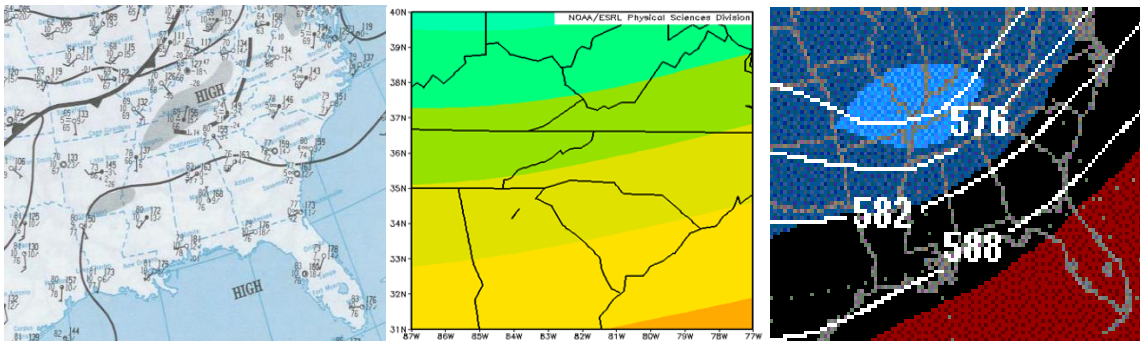
**Figure 19C.** 19980615



**Figure 19D.** 19980616

**Figure 19E.** 19980617

**Figure 19F.** 19980618



**Figure 19G.** 19980619

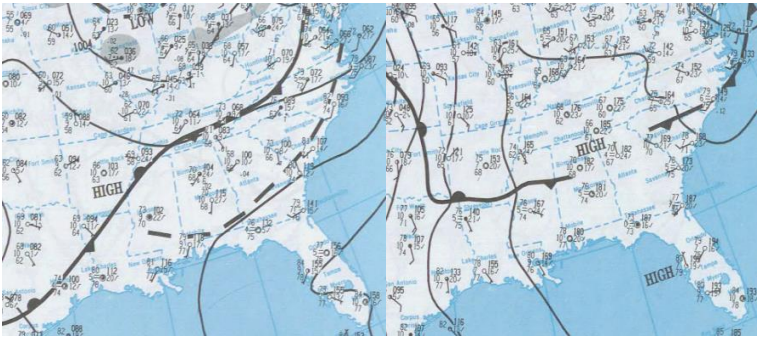
**Figure 19H.** Node 6

**Figure 19I.** 500mb 19980616

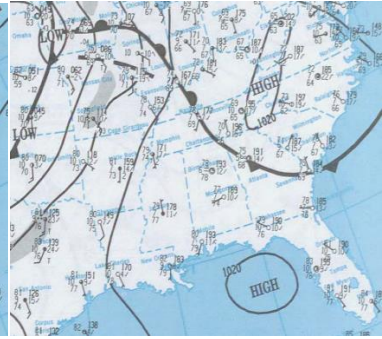
**Figure 19A-I.** Surface maps from the NOAA Daily Weather Map archive for 1998-6-13 through 1998-6-19, synoptic type, and 500 mb geopotential height map for 1998-6-16.

**Event 4: 1998-6-19**

There was near normal drought severity (PDSI 1.46) over the Grandfather Ranger District. The 500 mb geopotential heights were zonal flow with warm gradient stemming from the south agreeing with the synoptic type of node 4 (Figures 20H-I). The week prior saw 14.5mm of precipitation fall while none fell on the day of ignition, and 11.2 mm fell while the fire burned (Table 4). The average wind speed was 9 kph the day of ignition (Table 4). The surface weather maps show a stationary front moving across western North Carolina two days prior to ignition and being replaced by high pressure (Figures 20A-G). The day of ignition there is a surface trough just northwest of the national forest in the lee of the highest terrain. The wildfire burned thirty acres before going out on June 25<sup>th</sup> (Table 4).

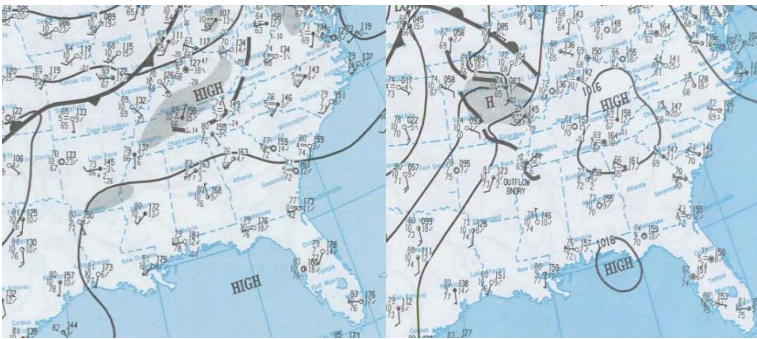


**Figure 20A.** 19980616

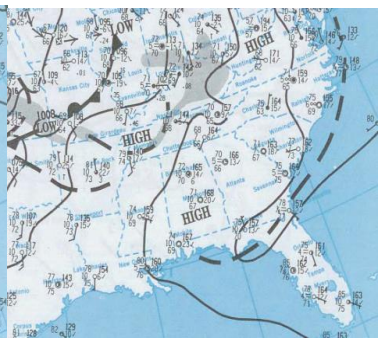


**Figure 20B.** 19980617

**Figure 20C.** 19980618

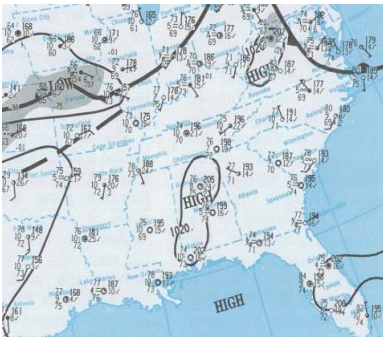


**Figure 20D.** 19980619

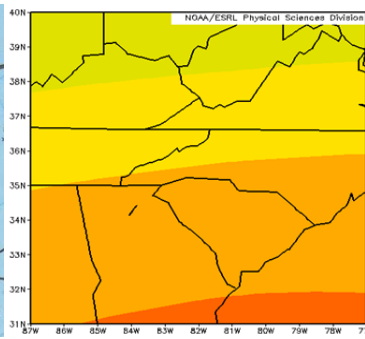


**Figure 20E.** 19980620

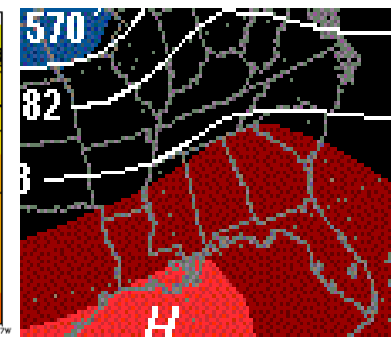
**Figure 20F.** 19980621



**Figure 20G.** 19980622



**Figure 20H.** Node 4

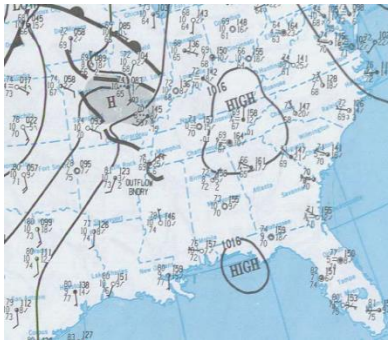


**Figure 20I.** 500mb 19980619

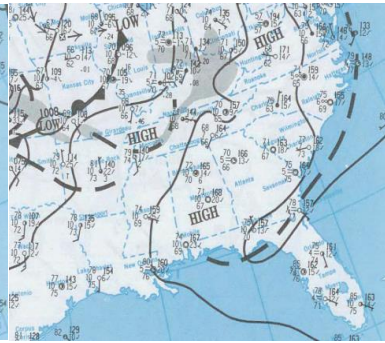
**Figure 20A-I.** Surface maps from the NOAA Daily Weather Map archive for 1998-6-16 through 1998-6-22, synoptic type, and 500 mb geopotential height map for 1998-6-19.

**Event 5: 1998-6-23**

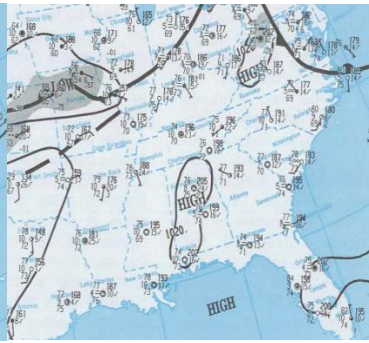
Just like previous events in June, 1998, the study area was near normal for drought severity (PDSI 1.46). Ridging was occurring over the study area at 500 mb and was reflected in the synoptic type of node 11 (Figures 21H-I). Only 7.6 mm of precipitation fell over the week prior to ignition (Table 4). An additional 7.6 mm fell on the day of ignition, with a total of 72.9mm falling while the fire burned (Table 4). Winds blew at an average of 8 kph (Table 4). The surface maps show high pressure sitting over top of the Pisgah National Forest for the three days prior and post ignition (Figures 21A-G). The high pressure system stretches from central Alabama into northern West Virginia covering the majority of the Southern Appalachians on the day of ignition (Figure 21D). Two acres burned over eighteen days extinguishing July 10<sup>th</sup> (Table 4).



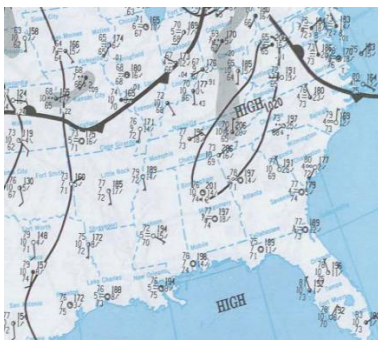
**Figure 21A.** 19980620



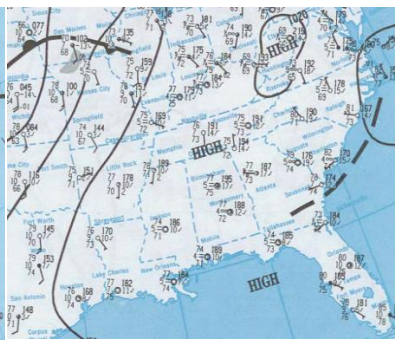
**Figure 21B.** 19980621



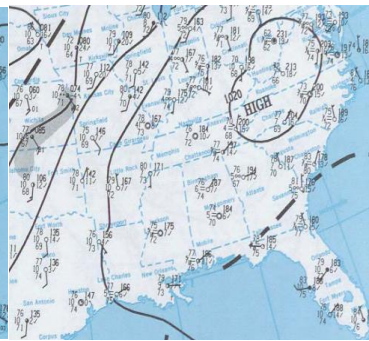
**Figure 21C.** 19980622



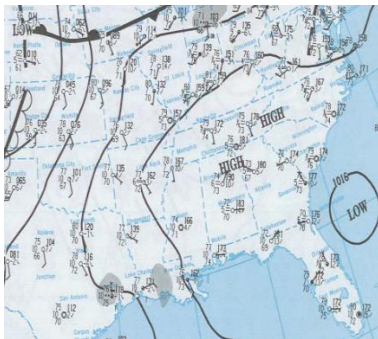
**Figure 21D.** 19980623



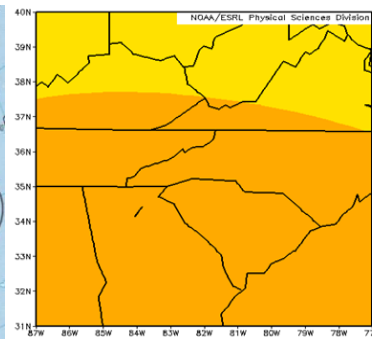
**Figure 21E.** 19980624



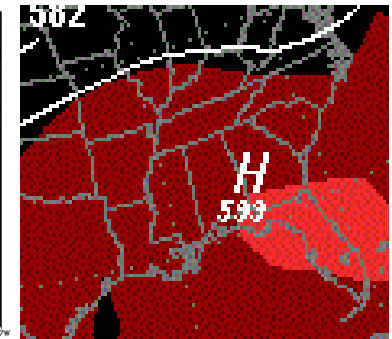
**Figure 21F.** 19980625



**Figure 21G.** 19980626



**Figure 21H.** Node 11

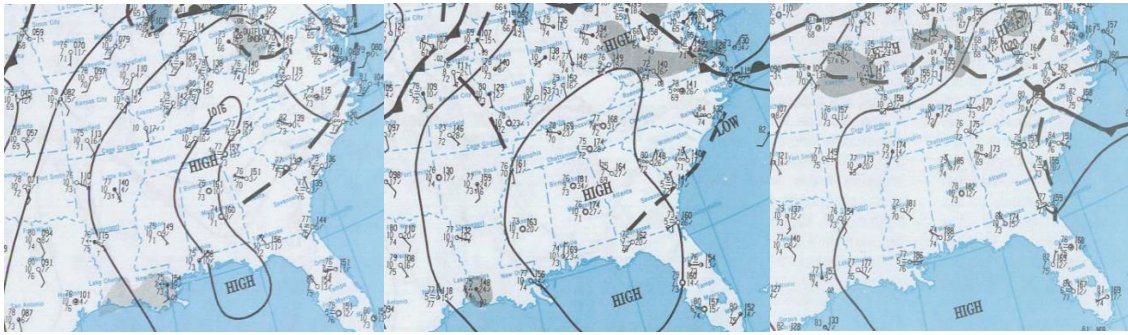


**Figure 21I.** 500mb 19980623

**Figure 21A-I.** Surface maps from the NOAA Daily Weather Map archive for 1998-6-20 through 1998-6-26, synoptic type, and 500 mb geopotential height map for 1998-6-23.

**Event 6: 1998-6-30**

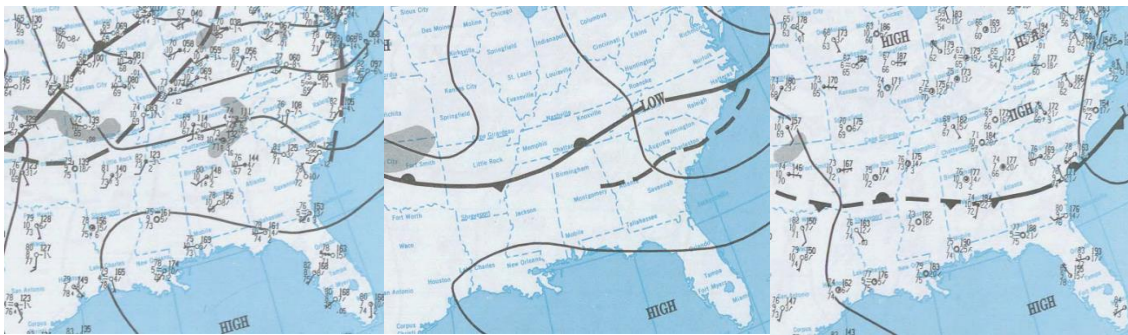
This wildfire occurred during near normal drought conditions as well (PDSI 1.46). The synoptic type associated was node 3 (Figures 22H-I). Rain only amounted to 7.9 mm the week prior to the wildfire (Table 4). A larger amount of 34.3 mm fell the day of with a total of 65 mm falling while the fire burned (Table 4). The average wind speed was 12 kph (Table 4). The surface weather maps displayed high pressure extended over the region prior to ignition (Figures 22A-C). The day of ignition a surface trough approached from the west with a stationary front behind it (Figure 22D). The day after the surface trough had moved through and the stationary front extended through the region (Figure 22E). High pressure then moved in and remained (Figures 22F-G). This wildfire burned two acres and extinguished on July 12<sup>th</sup> (Table 4).



**Figure 22A.** 19980627

**Figure 22B.** 19980628

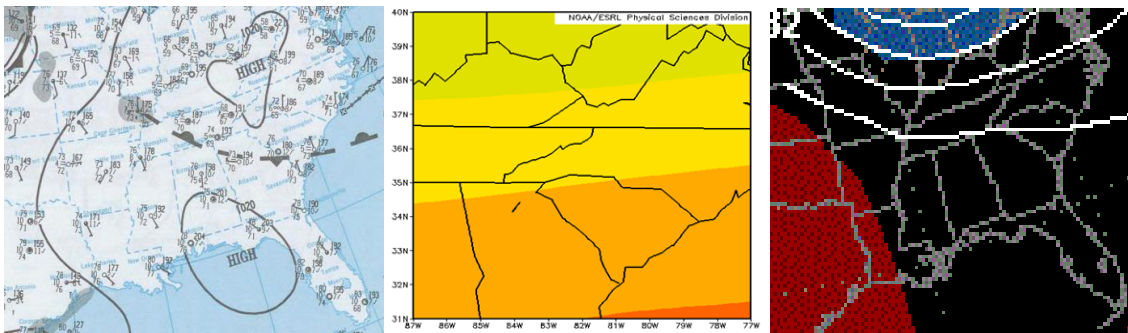
**Figure 22C.** 19980629



**Figure 22D.** 19980630

**Figure 22E.** 19980701

**Figure 22F.** 19980702



**Figure 22G.** 19980703

**Figure 22H.** Node 3

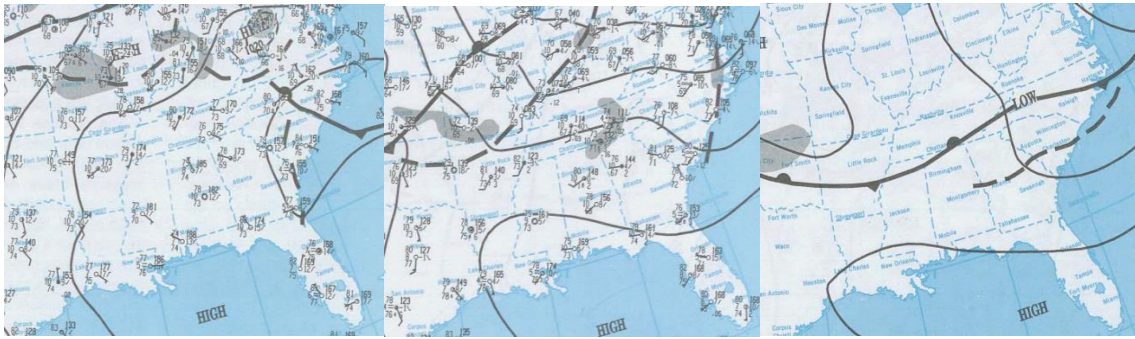
**Figure 22I.** 500mb 19980630

**Figure 22A-I.** Surface maps from the NOAA Daily Weather Map archive for 1998-6-27 through 1998-7-3, synoptic type, and 500 mb geopotential height map for 1998-6-30.



**Event 7: 1998-7-2**

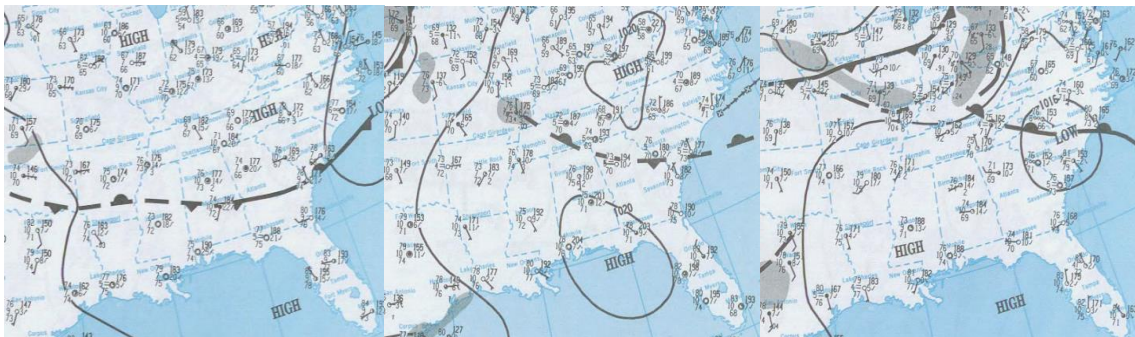
The drought severity was near normal (PDSI -0.89) for the study area. The 500 mb geopotential heights showed a gradient of warm to cool air aloft from the Gulf of Mexico to New England and was associated with Node 10 (Figures 23H-I). The area received 47.5 mm of precipitation the week prior and an additional 3.6 mm the day of ignition (Table 4). Another 13.9 mm fell while the fire burned (Table 4). Winds blew at an average of 6 kph on the surface (Table 4). The days preceding the ignition saw a stationary front move in and through the region (Figures 23A-C) before giving way to high pressure (Figures 23D-E). The day of ignition had high pressure which remained until two days after ignition when a low moved into the eastern part of the state and another stationary front sat over the region (Figures 23D-G). A half-acre burned for 11 days extinguishing on July 12<sup>th</sup> (Table 4).



**Figure 23A.** 19980629

**Figure 23B.** 19980630

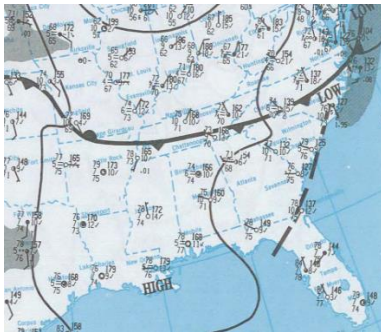
**Figure 23C.** 19980701



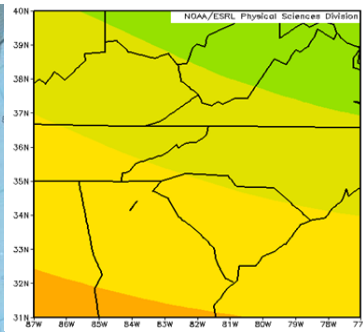
**Figure 23D.** 19980702

**Figure 23E.** 19980703

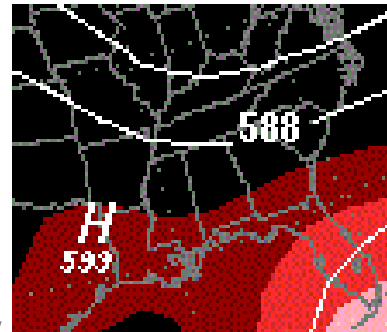
**Figure 23F.** 19980704



**Figure 23G.** 19980705



**Figure 23H.** Node 10

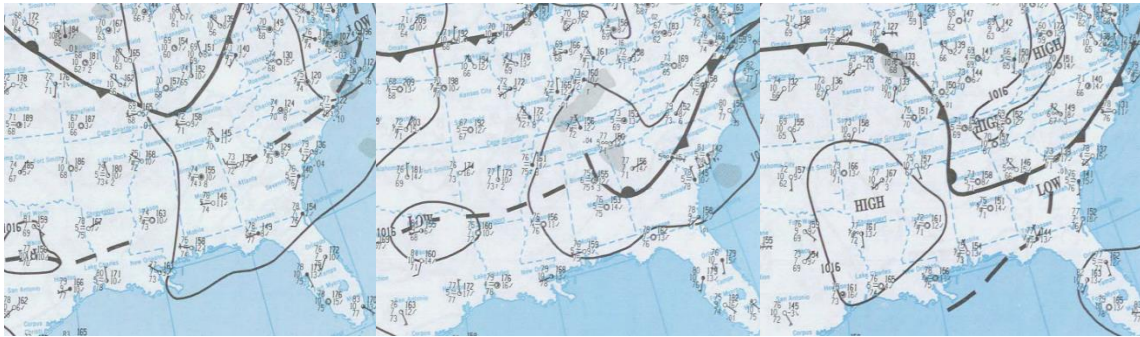


**Figure 23I.** 500mb 19980702

**Figure 23A-I.** Surface maps from the NOAA Daily Weather Map archive for 1998-6-29 through 1998-7-5, synoptic type, and 500 mb geopotential height map for 1998-7-2.

### **Event 8 and 9: 1998-7-19**

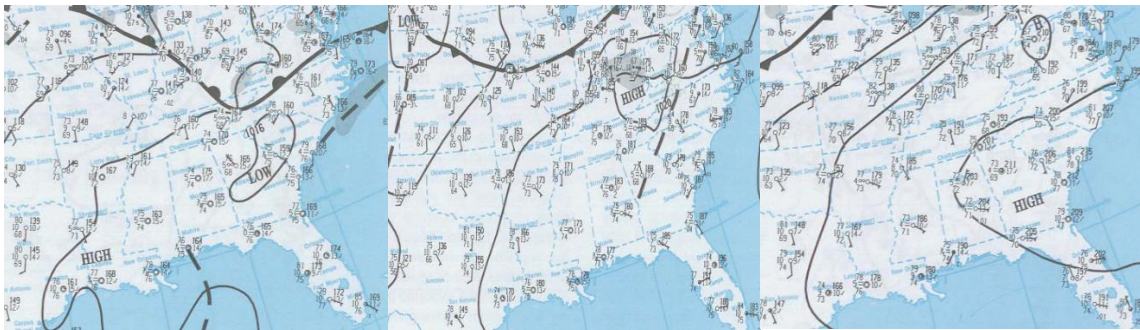
The Grandfather Ranger District was in near normal drought status (PDSI -0.89). Node 3 was associated with day of ignition (Figures 24H-I). No precipitation fell the week prior or day of ignitions (Table 4). Both fires had 55.6 mm of rain fall while they burned (Table 4). The day of ignition had winds blowing at 15 kph on average (Table 4). The day's preceding ignition had a stationary front that moved throughout the southeastern United States (Figures 24A-C). Western North Carolina transitioned from a low to warm front that has moved into the area. The warm front extends from Iowa to western North Carolina before turning and beginning to become an occluded front (Figure 24D). The days post ignition had a surface trough east of Grandfather Ranger District and high pressure move into the region (Figures 24E-G). Two wildfires burned 120 and 100 acres before both being extinguished twelve days later on July 30<sup>th</sup> (Table 4).



**Figure 24A.** 19980716

**Figure 24B.** 19980717

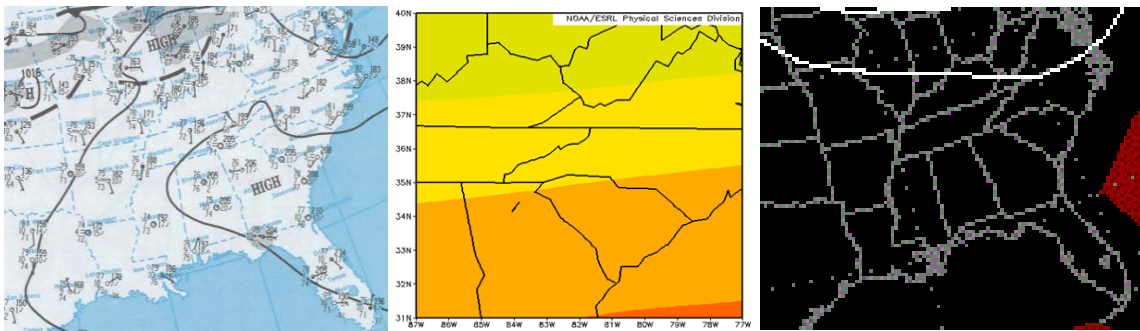
**Figure 24C.** 19980718



**Figure 24D.** 19980719

**Figure 24E.** 19980720

**Figure 24F.** 19980721



**Figure 24D.** 19980722

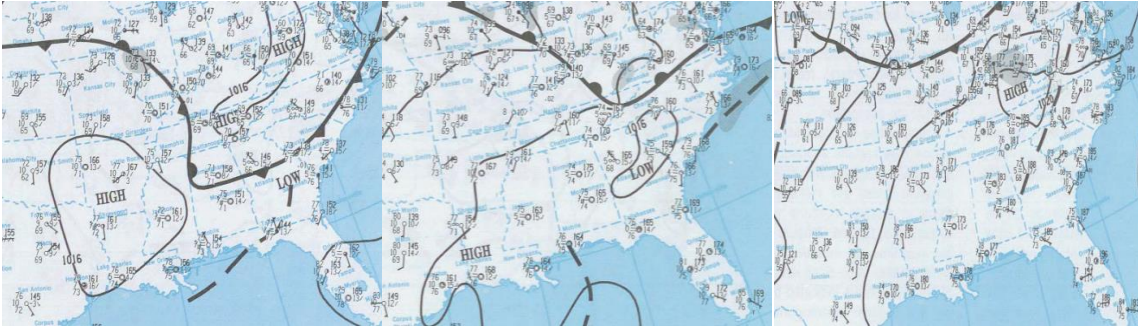
**Figure 24E.** Node 3

**Figure 24F.** 500mb 19980719

**Figure 24A-I.** Surface maps from the NOAA Daily Weather Map archive for 1998-7-16 through 1998-7-22, synoptic type, and 500 mb geopotential height map for 1998-7-19.

### **Events 10 and 11: 1998-7-21**

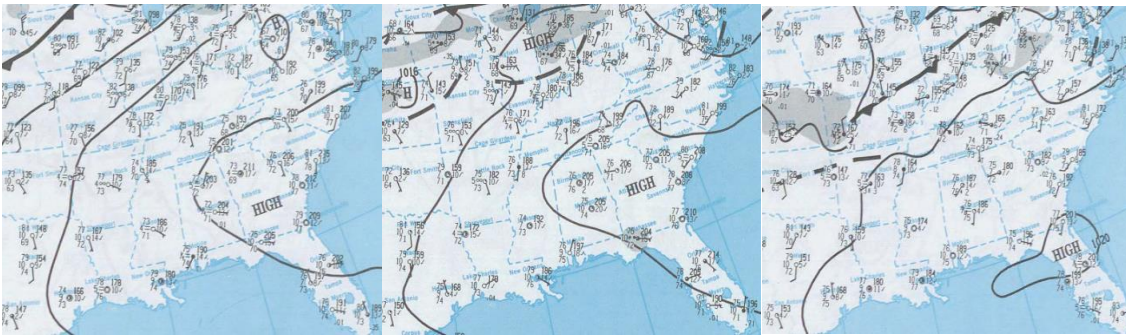
The area was in near normal drought severity (PDSI -0.89). The synoptic type associated with July 21<sup>st</sup> was node 11 (Figures 25H-I). Just like the previous days ignitions there was no rain the week before of day of ignition, and had 55.6 mm of rain fall while the fires burned. Winds blew at 11 kph on average (Table 4). The days preceding the natural ignition had high pressure and a warm front moved through the region (Figures 25A-C). The surface maps shows an area of high pressure extending from the Atlantic over the south eastern United States the day of ignition (Figure 25D). Post ignition a cold front began to approach the southeast from northwest (Figures 25F-G). The two fires both burned a half acre each and extinguished ten days later on July 30<sup>th</sup> (Table 4).



**Figure 25A.** 19980718

**Figure 25B.** 19980719

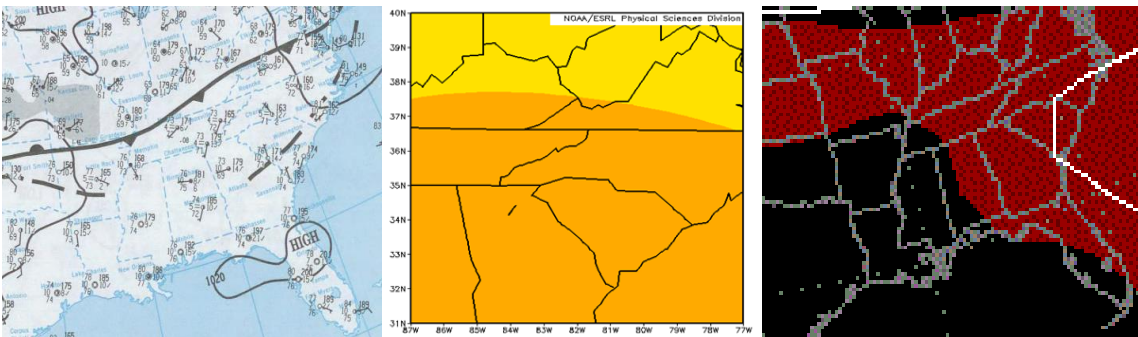
**Figure 25C.** 19980720



**Figure 25D.** 19980721

**Figure 25E.** 19980722

**Figure 25F.** 19980723



**Figure 25G.** 19980724

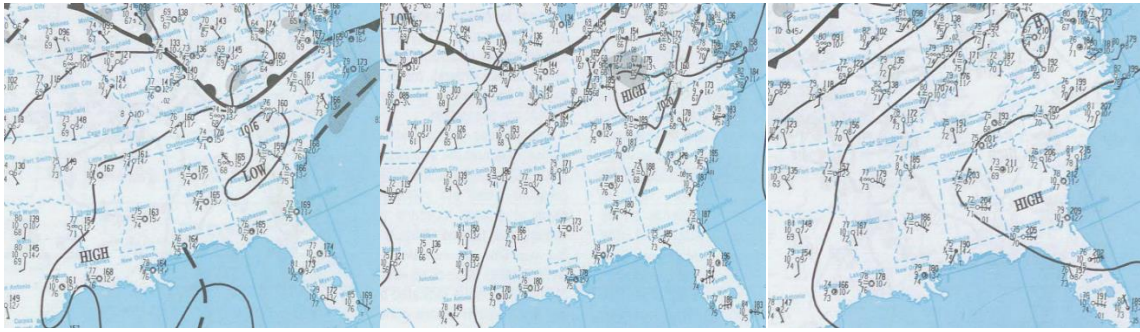
**Figure 25H.** Node 11

**Figure 25I.** 500mb 19980721

**Figure 25A-I.** Surface maps from the NOAA Daily Weather Map archive for 1998-7-18 through 1998-7-24, synoptic type, and 500 mb geopotential height map for 1998-7-21.

**Event 12: 1998-7-22**

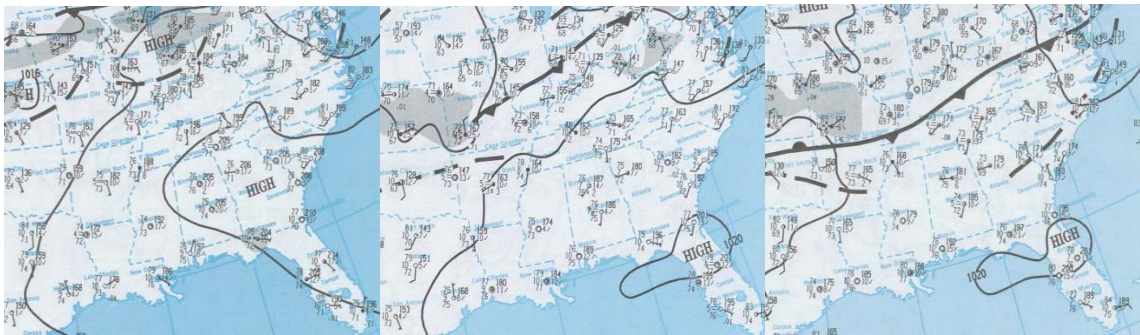
This July day was the same for drought severity as the previous, with near normal conditions (PDSI -0.89). The 500 mb geopotential heights were associated with node 4 (Figures 26H-I). No rain fell the week prior or day of ignition, but the wildfires were inundated with 55.6 mm while it burned (Table 4). Winds were averaged at 11 kph (Table 4). High pressure extended over the region prior to and after the day of ignition (Figures 26A-F). A cold front moved in as the fire was burning and became a stationary front over the region three days post ignition (Figures 26F-G). The lightning strikes ignited and burned a half-acre that burned for nine days extinguishing on July 30<sup>th</sup> (Table 4).



**Figure 26A.** 19980719

**Figure 26B.** 19980720

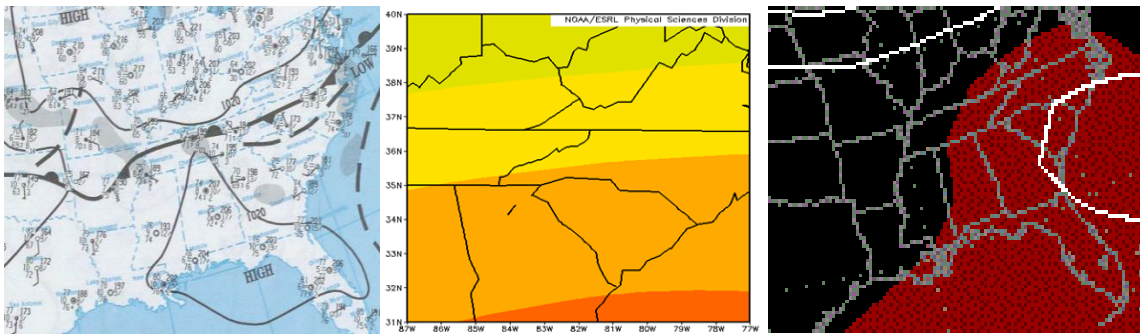
**Figure 26C.** 19980721



**Figure 26D.** 19980722

**Figure 26E.** 19980723

**Figure 26F.** 19980724



**Figure 26G.** 19980725

**Figure 26H.** Node 4

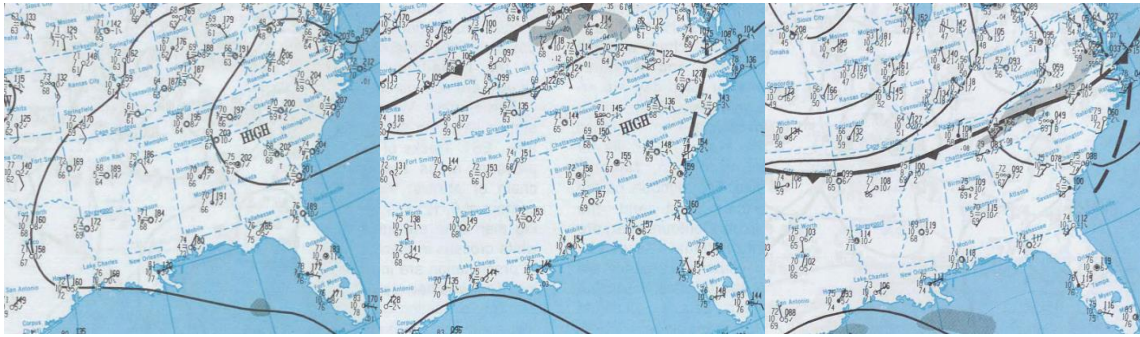
**Figure 26I.** 500mb 19980722

**Figure 26A-I.** Surface maps from the NOAA Daily Weather Map archive for 1998-7-19 through 1998-7-25, synoptic type, and 500 mb geopotential height map for 1998-7-22.



**Event 13: 1998-9-9**

Grandfather Ranger District was in a moderate drought (PDSI -2.11). The synoptic type associated was node 9 (Figures 27H-I). While in the moderate drought, 46.7 mm of precipitation fell the week prior to ignition (Table 4). An additional 15.7 mm fell the day of ignition with no more falling before the wildfire extinguished (Table 4). Wind blew at about 10 kph (Table 4). The surface maps show high pressure over the region before the ignition with a cold front moving through the area the day before ignition (Figures 27A-C). Once the cold front moved through high pressure, extending from the Great Lakes and then moving southeast, dominated the region post ignition (Figures 27D-G). Two acres burned over six days before going on September 16<sup>th</sup> (Table 4).



**Figure 27A.** 19980906

**Figure 27B.** 19980907

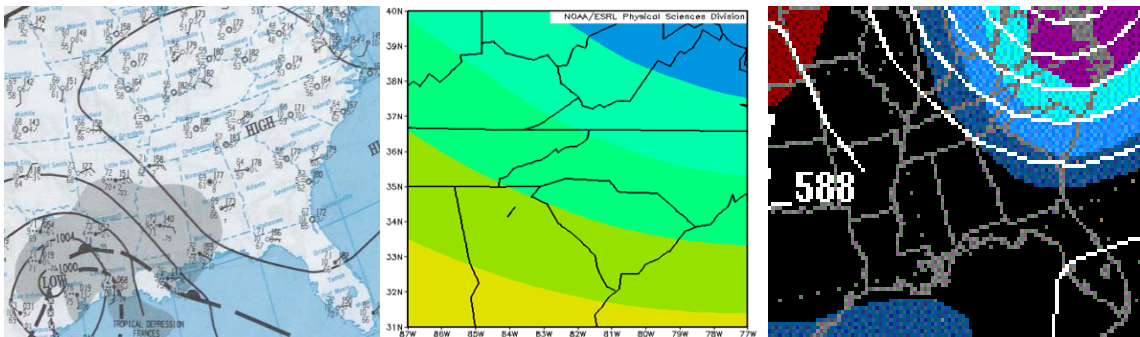
**Figure 27C.** 19980908



**Figure 27D.** 19980909

**Figure 27E.** 19980910

**Figure 27F.** 19980911



**Figure 27G.** 19980912

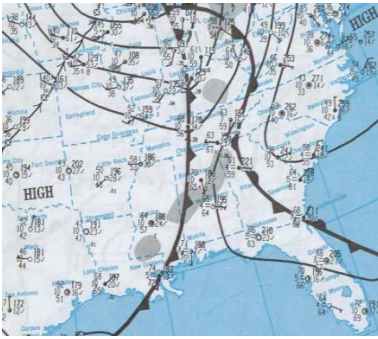
**Figure 27H.** Node 9

**Figure 27I.** 500mb 19980909

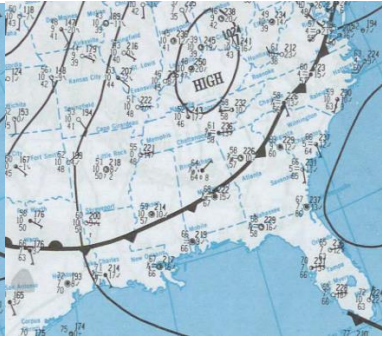
**Figure 27A-I.** Surface maps from the NOAA Daily Weather Map archive for 1998-9-6 through 1998-9-12, synoptic type, and 500 mb geopotential height map for 1998-9-9.

**Event 14: 1999-4-9**

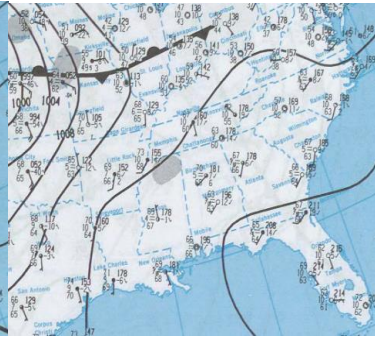
The study area was in a moderate drought (PDSI -2.25). The synoptic type was associated with node 4 (Figures 28H-I). Only a half mm of precipitation fell the week prior with 6 mm falling the day of the wildfire (Table 4). A total of almost 19 mm fell while the fire burned (Table 4). The winds blew on average of 12 kph (Table 4). The surface maps show a cold front moved through the region two days before ignition (Figures 28A-B). A large low pressure was in the southern Great Lakes region behind an occluded front that moved through western North Carolina two days post ignition (Figures 28D-G). The wildfire burned for five days over 140 acres (Table 4).



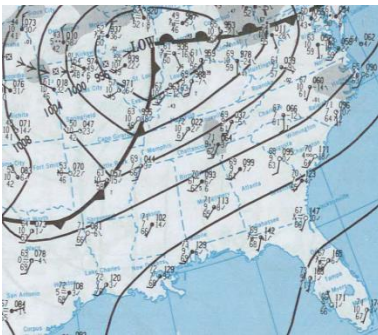
**Figure 28A.** 19990406



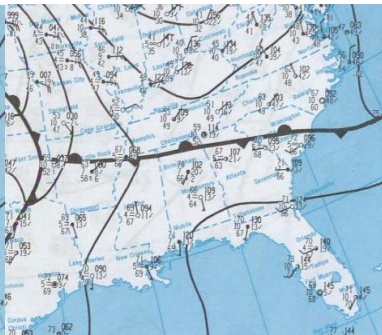
**Figure 28B.** 19990407



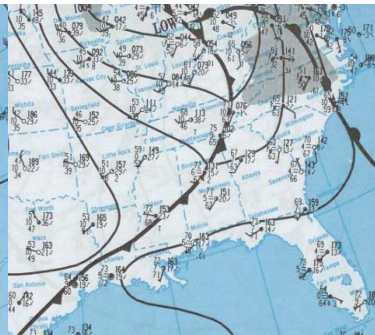
**Figure 28C.** 19990408



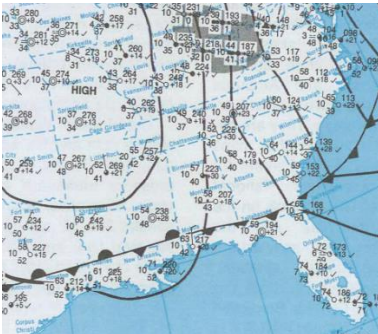
**Figure 28D.** 19990409



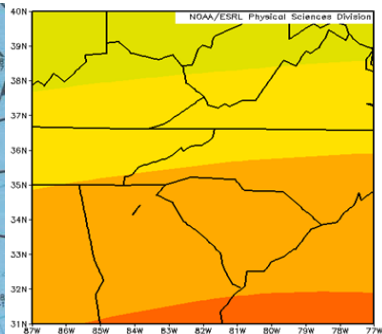
**Figure 28E.** 19990410



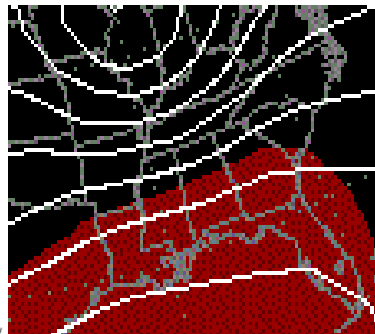
**Figure 28F.** 19990411



**Figure 28G.** 19990412



**Figure 28H.** Node 4

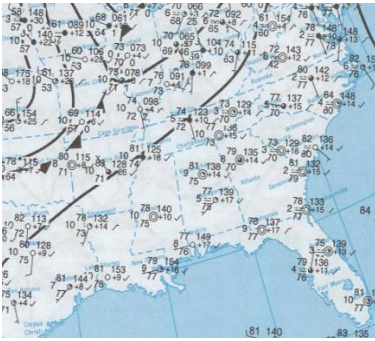


**Figure 28I.** 500mb 19990409

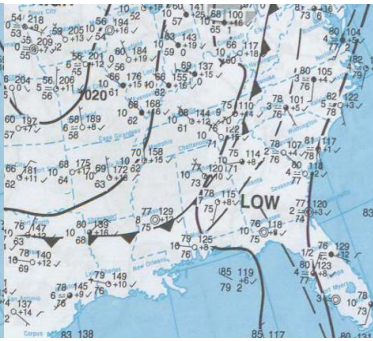
**Figure 28A-I.** Surface maps from the NOAA Daily Weather Map archive for 1999-4-6 through 1999-4-12, synoptic type, and 500 mb geopotential height map for 1999-4-9.

**Event 15: 1999-8-16**

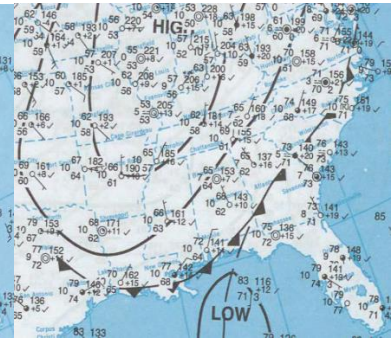
The study area was experiencing a moderate drought (PDSI -2.34). The synoptic type 11 was associated with high pressure (Figures 29H-I). A total of 22 mm of precipitation fell the week before the fire (Table 4). No precipitation fell the day of ignition and 23 mm fell while the fire burned (Table 4). Winds were low, averaged at 4 kph (Table 4). A cold front moved through western North Carolina two days prior to ignition (Figures 29B-C). A large high pressure system then sat over much of the east coast, extending from Canada down to Georgia and out to Missouri. The high pressure moved through with a cold front pushing in behind it that moved through the area two days post ignition (Figures 29E-G). The wildfire burned twelve acres over four days (Table 4).



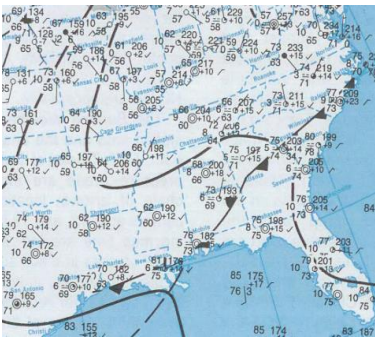
**Figure 29A.** 19990813



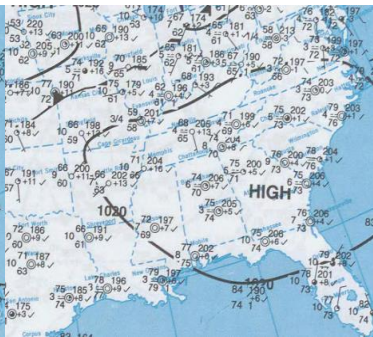
**Figure 29B.** 19990814



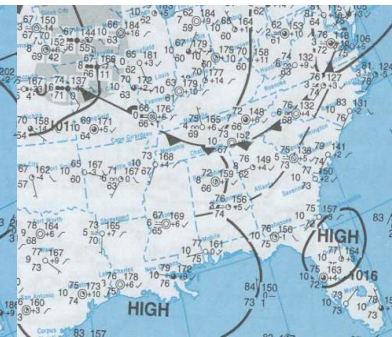
**Figure 29C.** 19990815



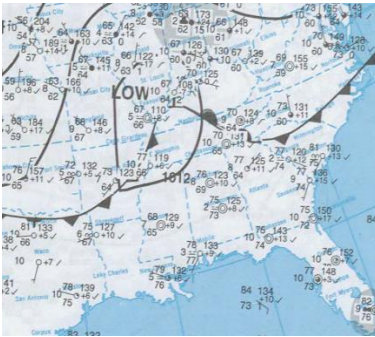
**Figure 29D.** 19990816



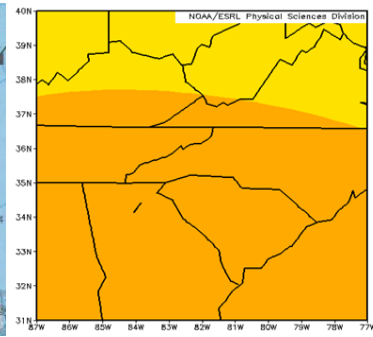
**Figure 29E.** 19990817



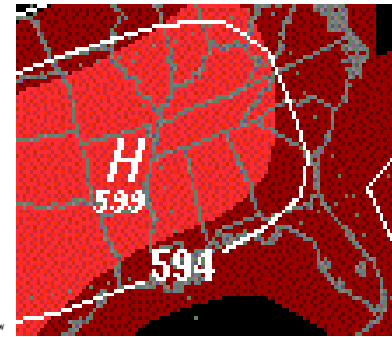
**Figure 29F.** 19990818



**Figure 29G.** 19990819



**Figure 29H.** Node 11

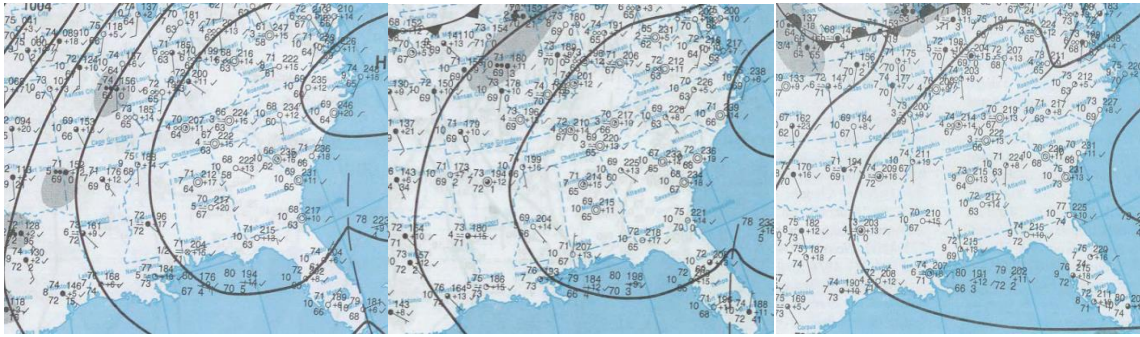


**Figure 29I.** 500mb 19990816

**Figure 29A-I.** Surface maps from the NOAA Daily Weather Map archive for 1999-8-13 through 1999-8-19, synoptic type, and 500 mb geopotential height map for 1999-8-16.

**Event 16: 2000-6-13**

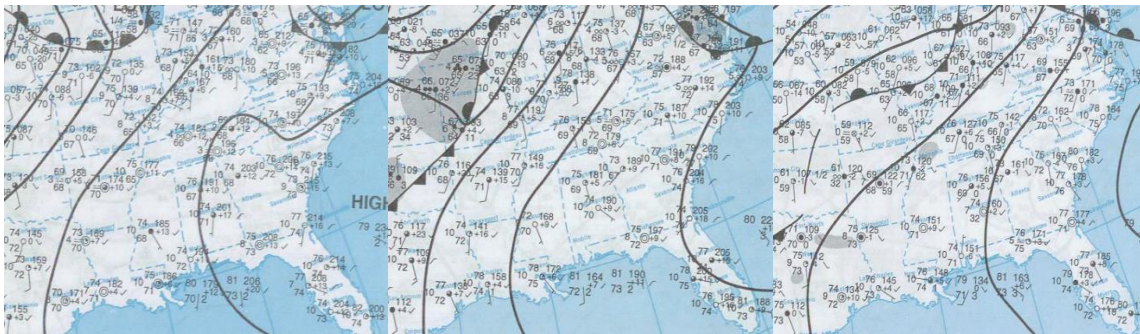
Western North Carolina was in moderate drought severity (PDSI -2.29). The high pressure aloft was associated with synoptic type 11 (Figures 30H-I). A moderate amount of 20 mm of precipitation fell the week prior, although none fell the day of ignition (Table 4). Another 24 mm of rain fell while the fire burned (Table 4). Winds were averaged at approximately 5 kph (Table 4). Prior to ignition and after the fire started, a high pressure system, extending off the Atlantic Ocean dominated the southeastern United States (Figures 30A-G). The high pressure system was weakened by a frontal system that moved through the northeast, but remained over the southeast for duration of the collected surface maps (Figures 30C-G). The wildfire burned thirty acres over seven days (Table 4).



**Figure 30A.** 20000610

**Figure 30B.** 20000611

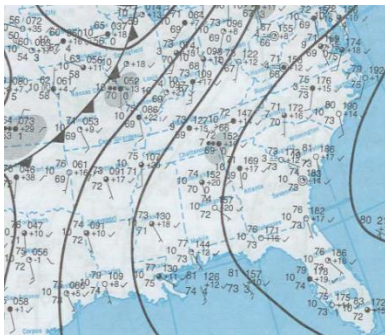
**Figure 30C.** 20000612



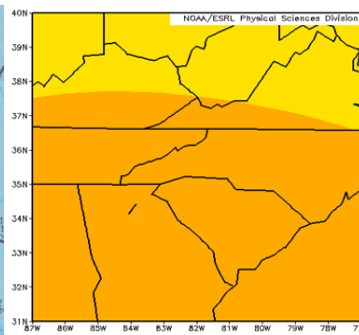
**Figure 30D.** 20000613

**Figure 30E.** 20000614

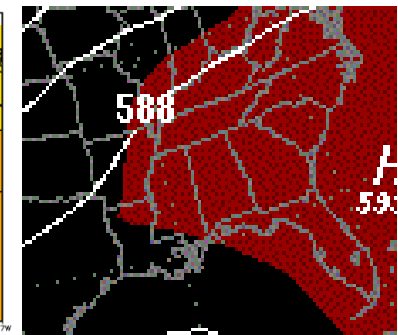
**Figure 30F.** 20000615



**Figure 30G.** 20000616



**Figure 30H.** Node 11



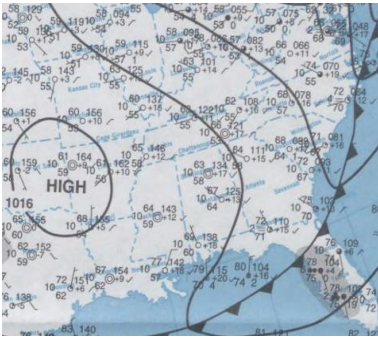
**Figure 30I.** 500mb 20000613

**Figure 30A-I.** Surface maps from the NOAA Daily Weather Map archive for 2000-6-10 through 2000-6-16, synoptic type, and 500 mb geopotential height map for 2000-6-13.

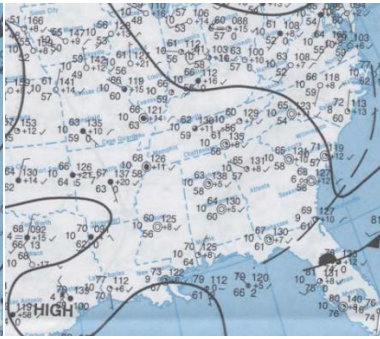


**Event 17: 2002-6-18**

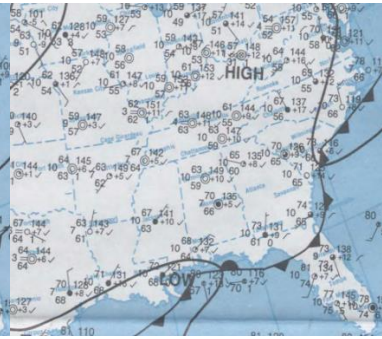
The study region was under moderate drought severity (PDSI -2.29). The synoptic type was node 6 (Figures 31H-I). Approximately 30 mm fell the week prior to the wildfire (Table 4). No precipitation fell the day of ignition but nearly 55 mm fell while the fire burned. Wind was low, averaged at 3 kph (Table 4). A high pressure system was situated over the area prior to and after the wildfire ignition (Figures 31A-G). A cold front had moved through the area prior to three days before and remained to the southeast of the study area up until the day after ignition (Figures 31A-E). The wildfire burned sixteen acres and extinguished on June 30<sup>th</sup> (Table 4).



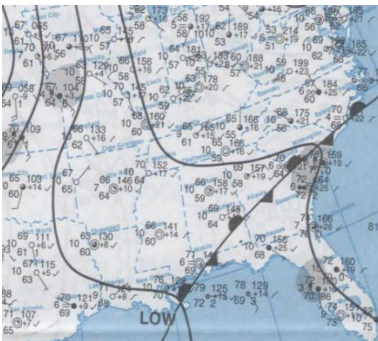
**Figure 31A.** 20020615



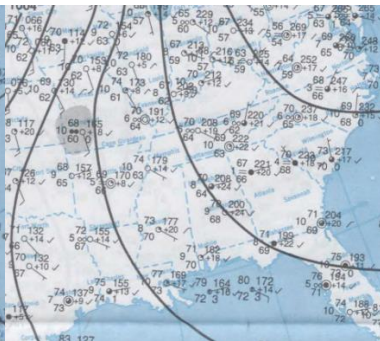
**Figure 31B.** 20020616



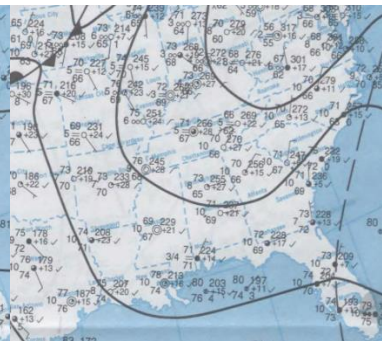
**Figure 31C.** 20020617



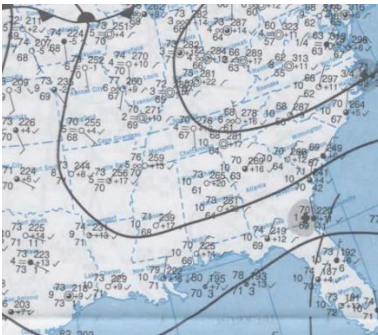
**Figure 31D.** 20020618



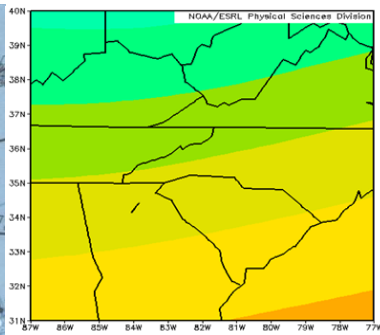
**Figure 31E.** 20020619



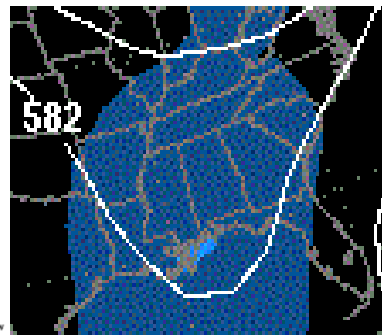
**Figure 31F.** 20020620



**Figure 31G.** 20020621



**Figure 31H.** Node 6



**Figure 31I.** 500mb 20020618

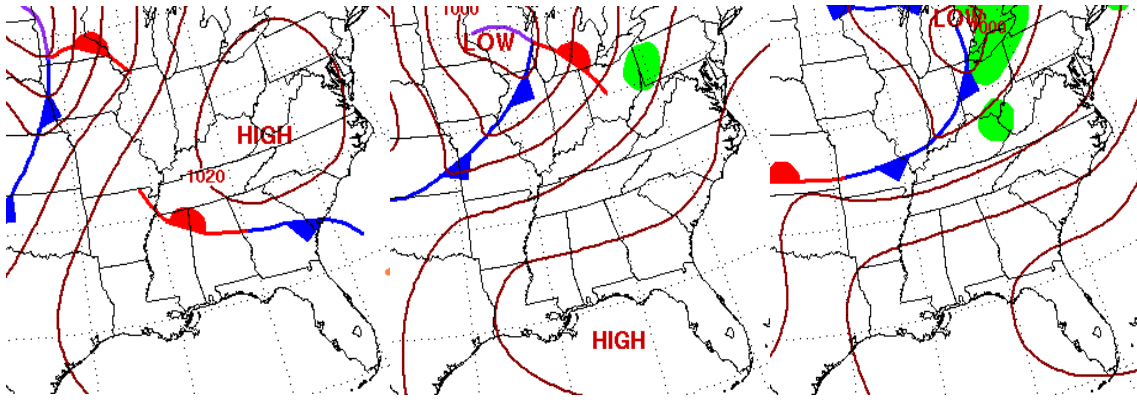
**Figure 31A-I.** Surface maps from the NOAA Daily Weather Map archive for 2002-6-15 through 2002-6-21, synoptic type, and 500 mb geopotential height map for 2002-6-18

**Table 5.** Fire location, acres burned, PDSI, synoptic type and, environmental conditions for each lightning-ignited fire event from 2006 to 2009 in the Grandfather Ranger District of the Pisgah National Forest, North Carolina. Fire data is from the National Interagency Fire Management Integrated Database. Palmer Drought Indices are from the Climate Prediction Center, NOAA. Temperatures and precipitation totals are from the GHCN station and, wind and relative humidity are from the GDCN7 station at Grandfather Mountain, NC.

Fire, location, hectares burned, PDSI, synoptic type, and weather conditions for each event from 2006-2009																			
Event	Date	Latitude (DD)	Longitude (DD)	Hectares Burned	Fire out	PDSI	PDSI 6 month (Average)	Node	Precipitation (mm)	Precipitation previous 7 days (mm)	Precipitation during fire (mm)	Maximum Temperature (C)	Minimum Temperature (C)	Wind Max (kph)	Wind Min (kph)	Wind Gust (kph)	Wind Direction	RH Max (%)	RH Min (%)
18	5/27/2006	35.7517	-82.0692	0.40	5/29/2006	-1.87	-0.97	11	20.1	20.3	20.1	20.0	12.8	8.0	1.6	29.0	SSE	100	29
19	7/20/2006	35.9786	-81.7100	0.40	7/23/2006	0.39	-0.95	7	0.5	12.3	17.2	23.3	16.1	4.8	0.0	20.9	S	100	35
20	6/8/2007	35.6744	-82.2078	2029.50	8/15/2007	-2.30	-1.19	11	0.0	24.2	306.0	22.2	15.6	4.8	0.0	14.5	SW	100	40
21	6/8/2007	35.6744	-82.2078	331.84	7/25/2007	-2.30	-1.19	11	0.0	24.2	239.3	22.2	15.6	4.8	0.0	14.5	SW	100	40
22	6/9/2007	36.0822	-81.7336	1.21	6/10/2007	-2.30	-1.19	4	0.0	16.8	0.0	22.2	15.6	11.3	1.6	29.0	SSW	98	41
23	6/11/2007	36.0125	-81.7442	27.11	6/30/2007	-2.30	-1.19	10	0.0	5.1	141.5	21.7	12.8	6.4	0.0	12.9	NW	92	35
24	6/25/2007	36.0222	-81.8139	0.04	6/30/2007	-2.30	-1.19	11	15.2	6.4	100.6	22.2	13.3	6.4	0.0	12.9	NNW	97	52
25	7/6/2007	36.0083	-81.8150	2.02	7/20/2007	-2.36	-1.71	10	2.8	24.4	46.2	22.8	14.4	9.7	0.0	17.7	N	95	47
26	8/19/2007	35.9903	-81.8497	0.04	8/21/2007	-3.20	-2.12	4	0.0	4.4	0.0	25.6	16.7	6.4	0.0	12.9	NNW	99	28
27	8/27/2007	35.9867	-81.8350	0.81	8/31/2007	-3.20	-2.12	7	0.3	6.4	30.5	24.4	15.6	6.4	0.0	24.1	NNE	100	53
28	9/5/2007	35.8400	-81.8906	6.07	9/30/2007	-3.56	-2.53	11	0.0	57.9	69.6	24.4	13.9	6.4	0.0	11.3	NW	85	26
29	9/9/2007	35.8017	-81.9569	2.02	9/20/2007	-3.56	-2.53	11	0.0	0.3	65.6	22.8	15.6	6.4	0.0	19.3	NNE	92	31
30	5/5/2008	35.7514	-82.0936	0.20	5/6/2008	-3.04	-3.16	6	0.0	20.6	0.3	18.3	10.6	8.0	0.0	19.3	N	80	31
31	6/11/2008	36.0608	-81.6564	0.45	6/15/2008	-3.33	-3.16	4	35.6	66.0	57.7	24.4	14.4	11.3	0.0	27.4	WNW	93	42
32	6/16/2008	35.9514	-81.7447	0.20	6/20/2008	-3.33	-3.16	10	0.3	59.2	0.6	21.7	11.7	6.4	0.0	14.5	SE	88	34
33	6/18/2008	35.9078	-81.8142	12.14	7/3/2008	-3.33	-3.16	2	0.0	58.3	94.5	22.8	11.7	8.0	1.6	19.3	SE	89	28
34	6/24/2008	35.8486	-81.8267	14.77	7/15/2008	-3.33	-3.16	3	0.0	61.0	137.7	20.0	11.7	6.4	0.0	16.1	S	92	34
35	6/30/2008	35.9028	-81.9067	38.45	7/11/2008	-3.33	-3.16	6	8.6	44.5	92.5	22.8	13.3	6.4	0.0	17.7	N	87	51
36	7/16/2008	35.8150	-81.9639	0.61	7/22/2008	-3.37	-3.11	7	0.0	84.3	4.0	21.1	10.6	8.0	0.0	16.1	Missing	79	41
37	4/24/2009	36.0658	-81.6653	6.88	4/27/2009	-1.48	-1.83	8	0.0	32.8	12.7	21.7	9.4	8.0	1.6	22.5	SSW	75	15
38	4/24/2009	36.0503	-81.7433	0.81	4/27/2009	-1.48	-1.83	8	0.0	32.8	12.7	21.7	9.4	8.0	1.6	22.5	SSW	75	15
39	9/14/2009	35.8161	-81.9589	0.40	9/18/2009	2.35	1.14	7	0.0	16.3	41.2	17.8	10.0	4.8	1.6	12.9	SE	100	56

**Event 18: 2006-5-27**

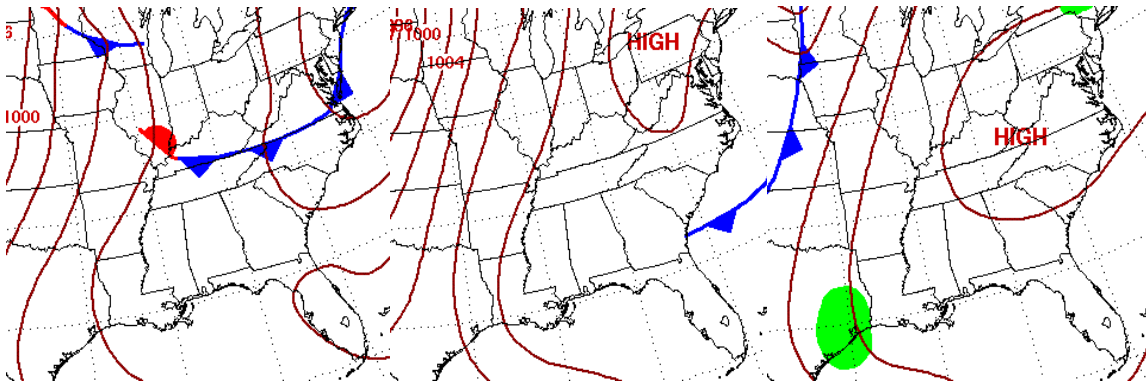
Drought severity over the area was near normal (PDSI -1.87). The study area was dominated with high pressure and associated with synoptic type 11 (Figures 32H-I). Grandfather Ranger District received 20 mm of precipitation in the seven days leading up to the wildfire (Table 5). The study area had another 20 mm fall the day of the wildfire with no more falling while the wildfire burned (Table 5). Wind blew mostly from the south southeast from 1 kph to 8 kph, gusting at 29 kph (Table 5). The surface weather maps show a high pressure system three days before the fire that moves out as a cold front moved across Western North Carolina, with a cold front moving west towards western North Carolina (Figures 32A-C). The day of the lightning ignited fire a cold front moved through the Grandfather Ranger District (Figure 32D). Following the cold front a high pressure system moved back into the region (Figures 32E-G). The wildfire burned one acre over a three day period (Table 5).



**Figure 32A.** 20060524

**Figure 32B.** 20060525

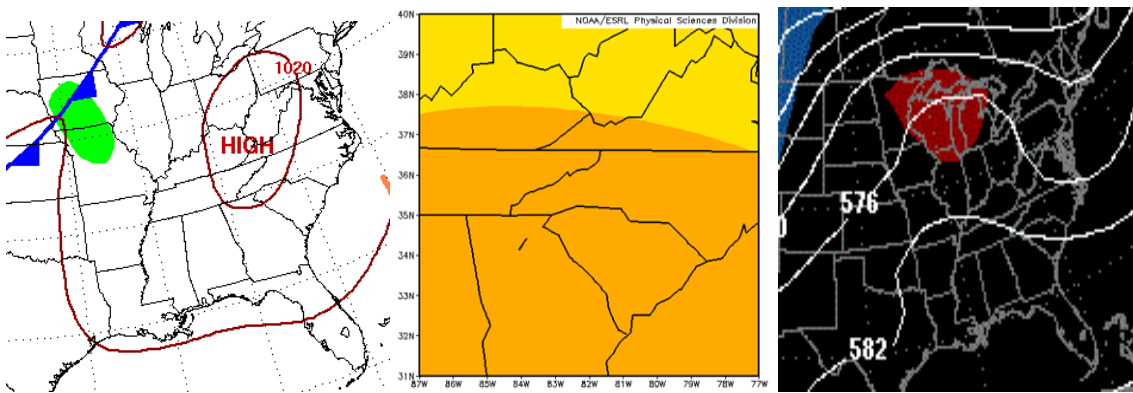
**Figure 32C.** 20060526



**Figure 32D.** 20060527

**Figure 32E.** 20060528

**Figure 32F.** 20060529



**Figure 32G.** 20060530

**Figure 32H.** Node 11

**Figure 32I.** 500mb 20060527

**Figures 32A-I.** NOAA WPC Surface Analysis maps for 2006-5-24 through 2006-5-30, SOM node associated with day of fire, and 500 mb geopotential height map of the event.

**Event 19: 2006-7-20**

The drought severity was near normal (PDSI 0.39). Warm air aloft was moving in from the west, associated with node 7 (Figures 33H-I). Approximately 12 mm of rain fell in the week prior to ignition (Table 5). Very little (0.5mm) precipitation fell the day of ignition, but a total of 17 mm fell while the wildfire burned (Table 5). Winds blew from the south between 4.8 kph and not at all, but gusted up to nearly 21 kph (Table 5). A high pressure system sat over the region before weakening as a stationary front moves over the northern southeast (Figures 33A-C). The day of the lightning ignition Tropical Storm Beryl was off the coast of New Jersey after moving north from the coast of North Carolina the day before (Figure 33C-D). The days following the fire a cold front moves through the southeast including a surface trough two days after ignition in western North Carolina (Figures 33E-G). The fire burned for 4 days and extinguished July 23<sup>rd</sup> after burning one acre (Table 5).

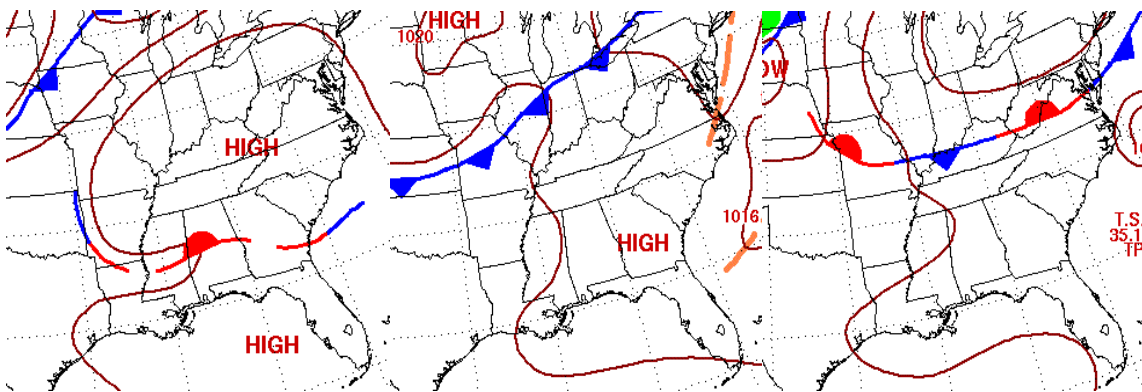


Figure 33A. 20060717

Figure 33B. 20060718

Figure 33C. 20060719

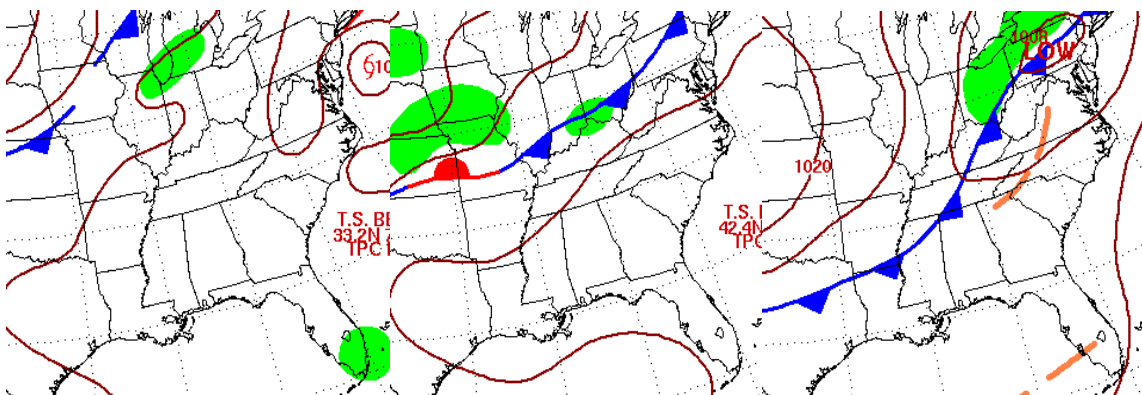


Figure 33D. 20060720

Figure 33E. 20060721

Figure 33F. 20060722

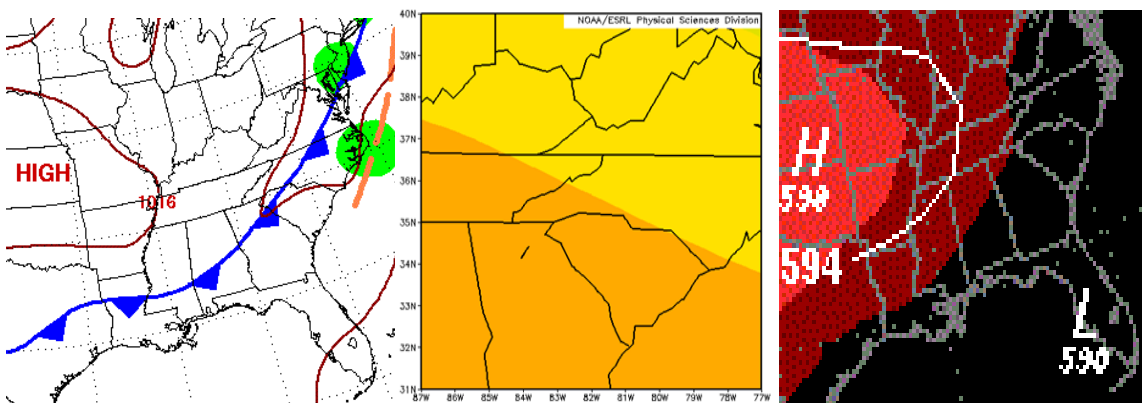


Figure 33G. 20060723

Figure 33H. Node 7

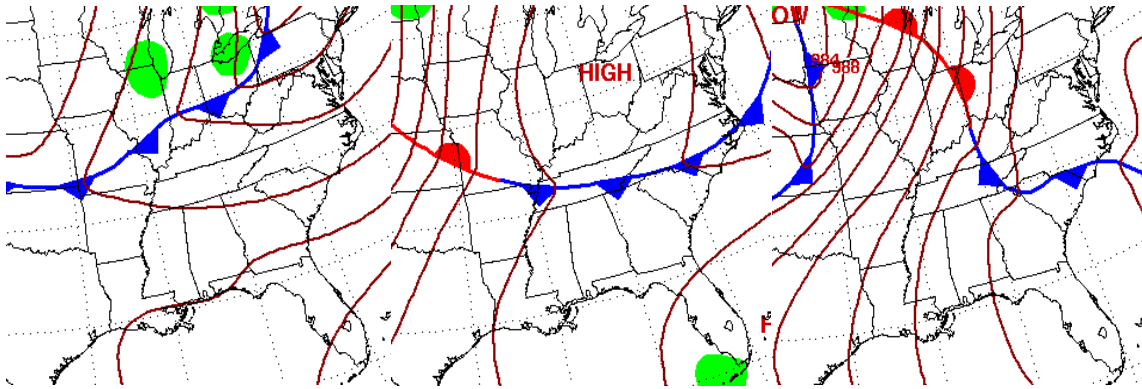
Figure 33I. 500mb 20060720

Figures 33A-I. NOAA WPC Surface Analysis maps for 2006-7-17 through 2006-7-23, SOM node associated with day of fire, and 500 mb geopotential height map of the event.

### **Events 20 and 21: 2007-6-8**

Moderate drought (PDSI -2.3) conditions applied to the study area. Synoptic type 11 was associated with the high pressure aloft (Figures 34H-I). A cold front moved through western North Carolina two days prior to the fire, which was followed by an occluded front the day before, dropping 24 mm of precipitation (Figures 34A-B). The day of ignition a high pressure system was over the region with a cold front advancing from the west, no rain fell (Figure 34D). The days post ignition had another cold front advance through the western North Carolina with a high pressure system coming in behind it (Figures 34E-G). Winds were low between 0-4 kph with 14.5 kph gusts from the southwest (Table 5). Two wildfires were ignited on this day. Event 20 burned 5,015 acres and finally extinguished August 15<sup>th</sup> after 306mm of precipitation fell on it (Table 5). Event 21 burned 820 acres, with 239 mm of precipitation falling on it while it burned, before extinguishing on July 25<sup>th</sup> (Table 5).

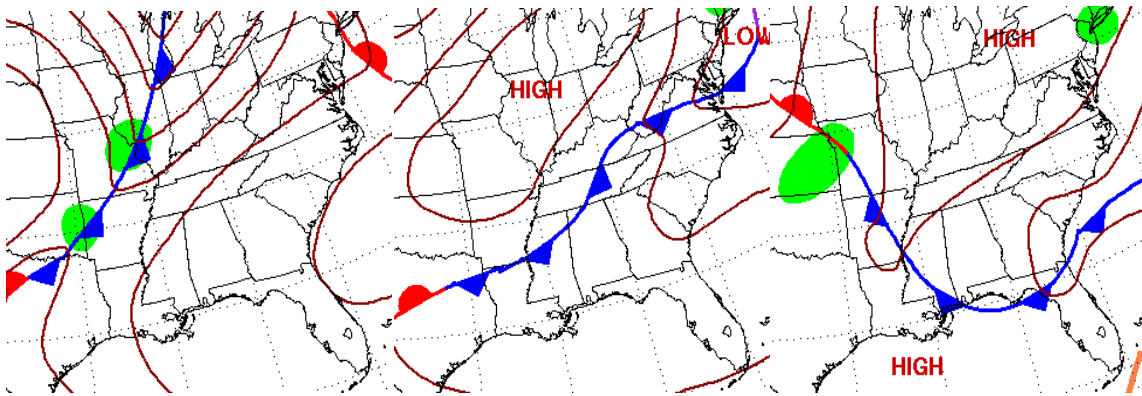




**Figure 34A.** 20070605

**Figure 34B.** 20070606

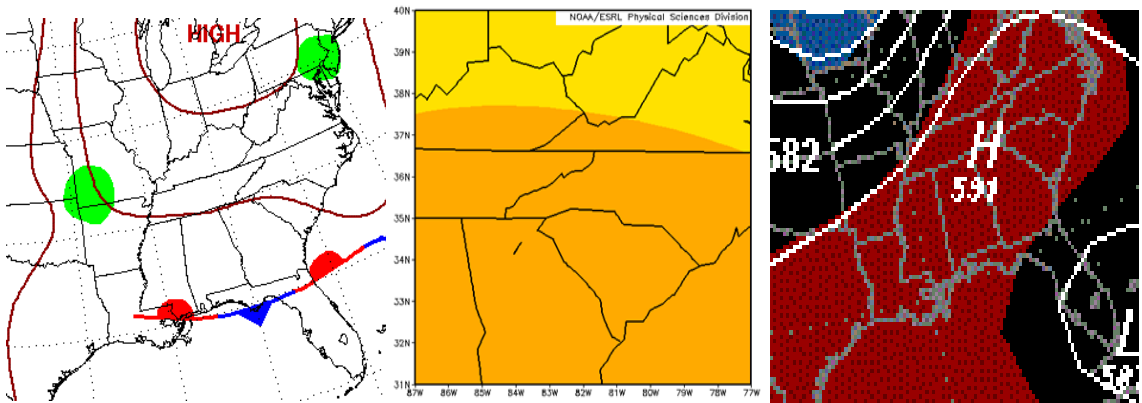
**Figure 34C.** 20070607



**Figure 34D.** 20070608

**Figure 34E.** 20070609

**Figure 34F.** 20070610



**Figure 34G.** 20070611

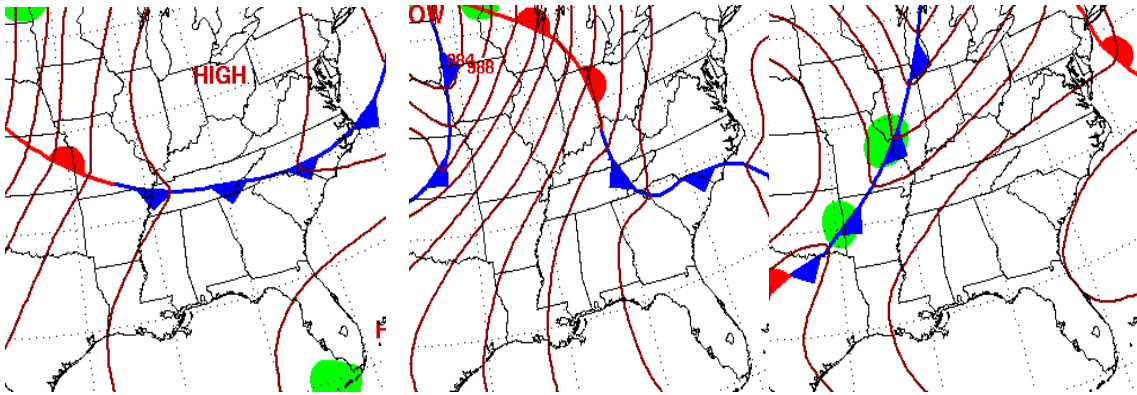
**Figure 34H.** Node 11

**Figure 34I.** 500mb 20070608

**Figures 34A-I.** NOAA WPC Surface Analysis maps for 2007-6-5 through 2007-6-11, SOM node associated with day of fire, and 500 mb geopotential height map of the event.

**Event 22: 2007-6-9**

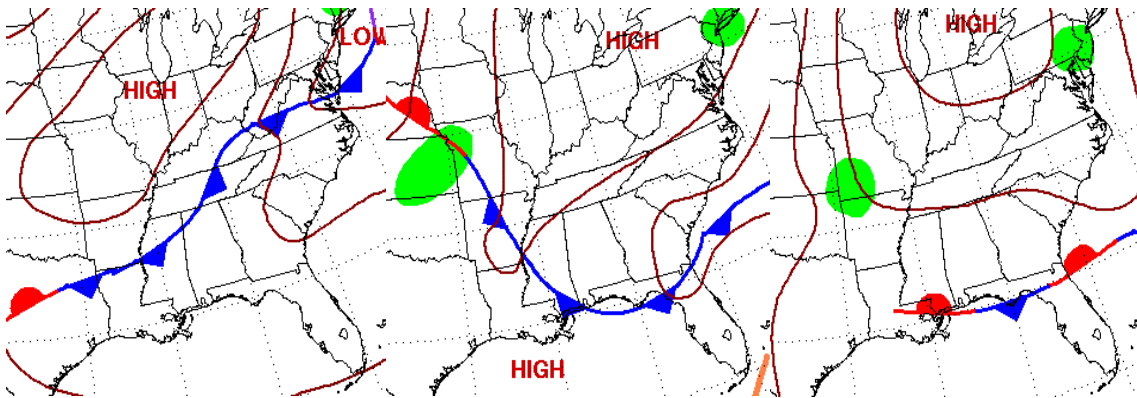
Grandfather Ranger District was in a moderate drought (PDSI -2.3). Zonal flow with ridging moving in from the Gulf of Mexico was associated with synoptic type 4 (Figures 35H-I). A cold front moved through the region two days prior to the ignition dropping nearly 17 mm of precipitation (Figures 35A-B). The day of ignition a cold front descended from the north setting up high pressure after the lightning ignited the wildfire, and no rain fell (Figures 35C- E). Winds averaged between 1.5-11 kph, gusting up to 29 kph out of the south-southwest (Table 5). The days following the ignition were dominated by a high pressure system emanating from the lower Great Lakes (Figures 35E-G). No precipitation fell while the wildfire burned (Table 5). The lightning ignition burned three acres and was extinguished the next day on June 10<sup>th</sup> (Table 5).



**Figure 35A.** 20070606

**Figure 35B.** 20070607

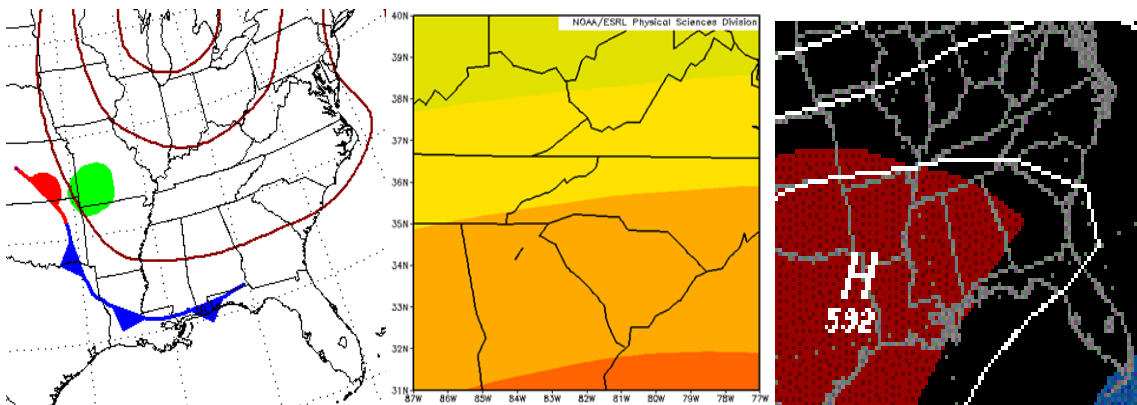
**Figure 35C.** 20070608



**Figure 35D.** 20070609

**Figure 35E.** 20070610

**Figure 35F.** 20070611



**Figure 35G.** 20070612

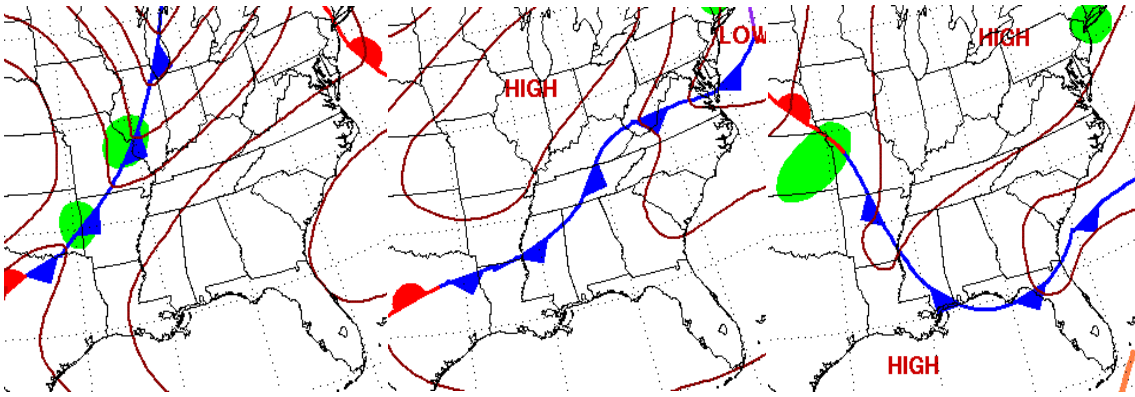
**Figure 35H.** Node 4

**Figure 35I.** 500mb 20070609

**Figures 35A-I.** NOAA WPC Surface Analysis maps for 2007-6-7 through 2007-6-12, SOM node associated with day of fire, and 500 mb geopotential height map of the event.

**Event 23: 2007-6-11**

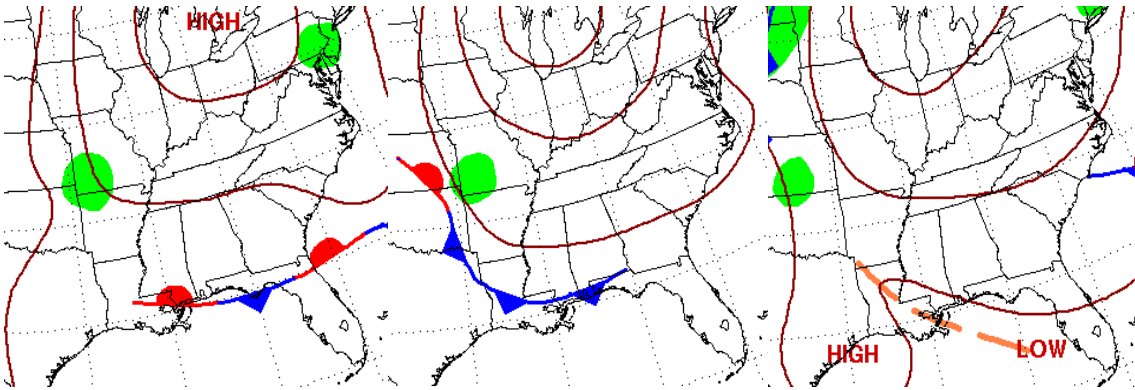
A moderate drought gripped the ranger district (PDSI -2.3). Synoptic type 10 was associated with this event (Figures 36H-I). A cold front moved through the southeast in the days prior to ignition dropping 5 mm of precipitation, with a high pressure system coming in behind it (Figures 36A-C). No precipitation fell as the high pressure system remained over the southeast emanating from the Great Lakes the day of the natural ignition until two days after when it moves northeast (Figures 36D-G). Winds from the northwest blew between 0-6 kph while gusting up to 13 kph (Table 5). A cold front passed into North Carolina three days after the ignition. The lightning ignition burned sixty seven acres and was extinguished on June 30<sup>th</sup> (Table 5). While the fire burned 141.5 mm of precipitation fell (Table 5).



**Figure 36A.** 20070608

**Figure 36B.** 20070609

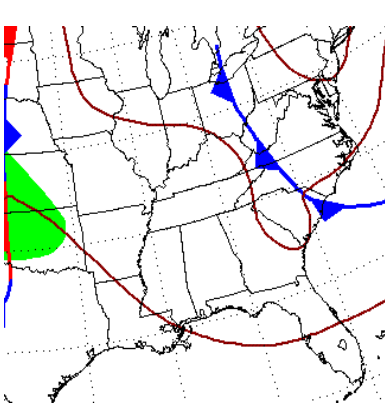
**Figure 36C.** 20070610



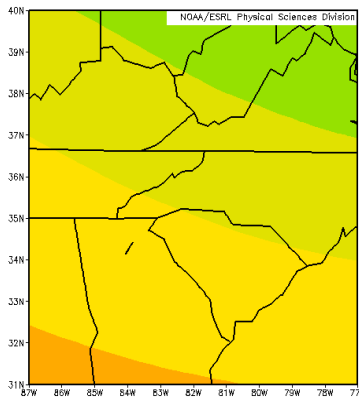
**Figure 36D.** 20070611

**Figure 36E.** 20070612

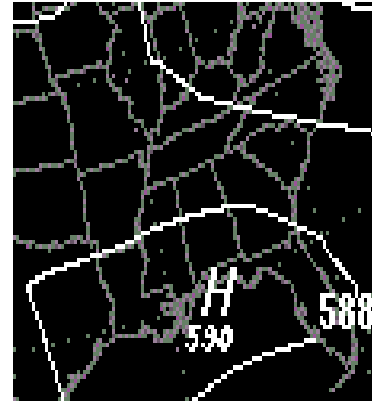
**Figure 36E.** 20070613



**Figure 36G.** 20070614



**Figure 36H.** Node 10

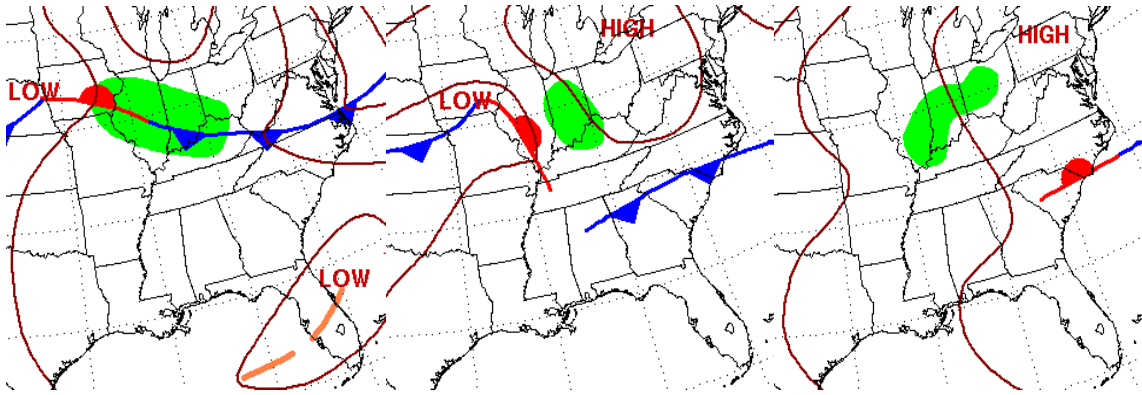


**Figure 36I.** 500mb 20070611

**Figures 36A-I.** NOAA WPC Surface Analysis maps for 2007-6-8 through 2007-6-14, SOM node associated with day of fire, and 500 mb geopotential height map of the event.

**Event 24: 2007-6-25**

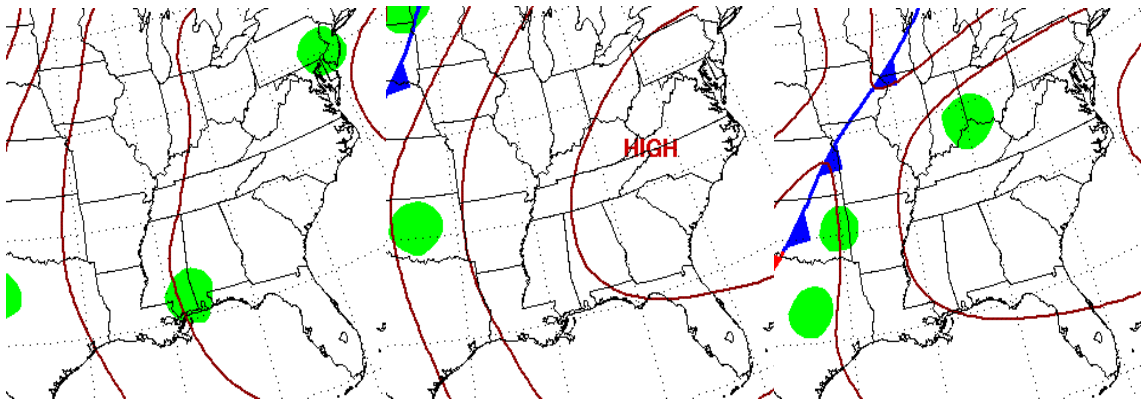
The last wildfire event of June 2007 was in a moderate drought (PDSI -2.3). Synoptic type 11 was associated with the day of ignition (Figures 37H-I). Two days prior a cold front went through North Carolina (Figures 37A-B) dropping 6.4 mm of precipitation (Table 5). A high pressure system, descending from the north, passed through following the cold front and persisted at least three days post ignition (Figures 37B-G). The day of ignition 15 mm of precipitation fell, winds blew from 0-6 kph from the north-northwest, and gusted nearly at 13 kph (Table 5). The wildfire only burned half an acre extinguishing on June 30<sup>th</sup> (Table 5).



**Figure 37A.** 20070622

**Figure 37B.** 20070623

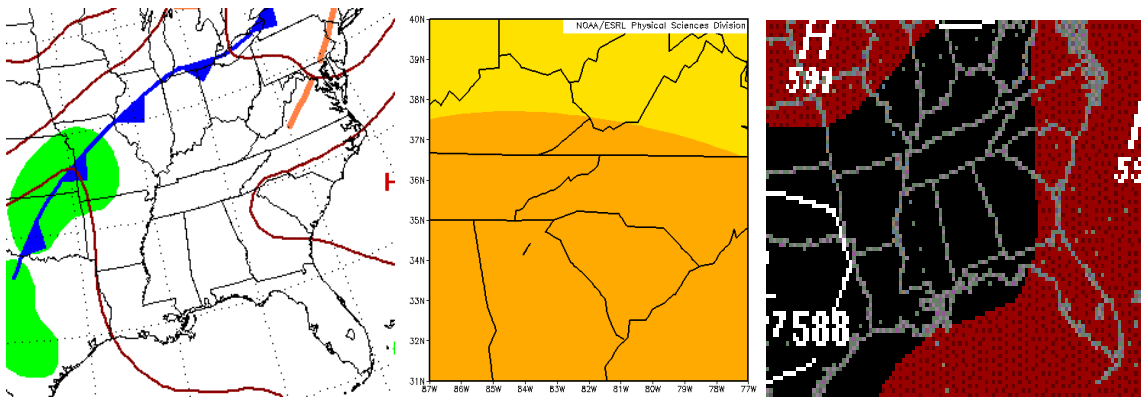
**Figure 37C.** 20070624



**Figure 37D.** 20070625

**Figure 37E.** 20070626

**Figure 37F.** 20070627



**Figure 37G.** 20070628

**Figure 37H.** Node 11

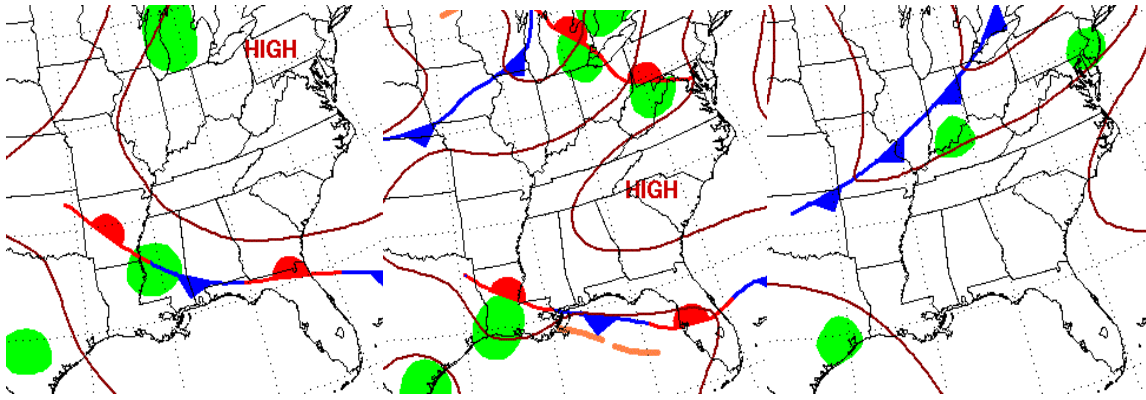
**Figure 37I.** 500mb 20070628

**Figures 37A-I.** NOAA WPC Surface Analysis maps for 2007-6-22 through 2007-6-28, SOM node associated with day of fire, and 500 mb geopotential height map of the event.

**Event 25: 2007-7-6**

The study area was still gripped in a moderate drought (PDSI -2.36). Synoptic type 10 was associated with the air aloft (Figures 38H-I). A high pressure system moved through North Carolina two days prior to the lightning ignition (Figures 38A-B). A total of 24.4 mm fell on the study region the week before ignition (Table 5). A cold front advanced from the west and moved north of the region the day before and of ignition, precipitating 2.8 mm (Figures 38C-D). Wind averaged between 0-9.7 kph, gusting up to 17.7 kph from the north (Table 5). A high pressure system moved in after the cold front and remained for the rest of the observed period (Figures 38E-G). Pockets of light rain were spread across the southeast during the week of ignition (Figures 38A-G). The wildfire extinguished on July 20<sup>th</sup> after consuming across 5 acres (Table 5).

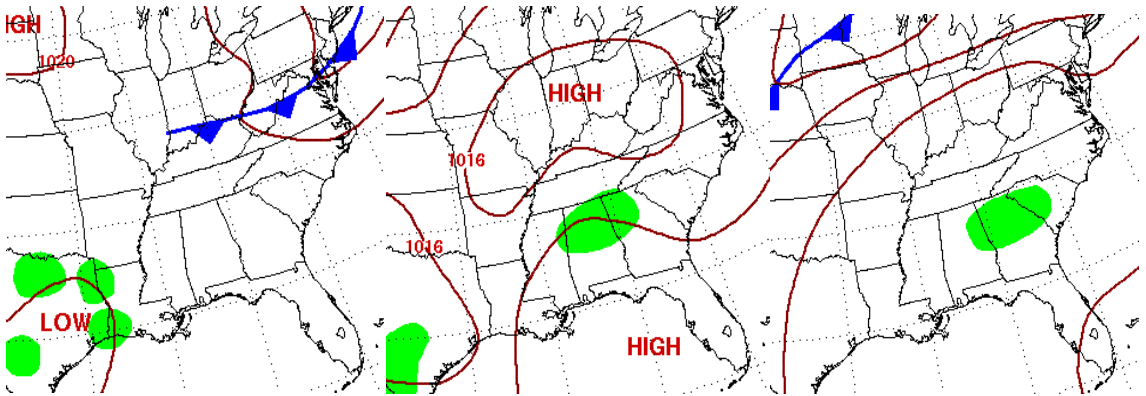




**Figure 38A.** 20070703

**Figure 38B.** 20070704

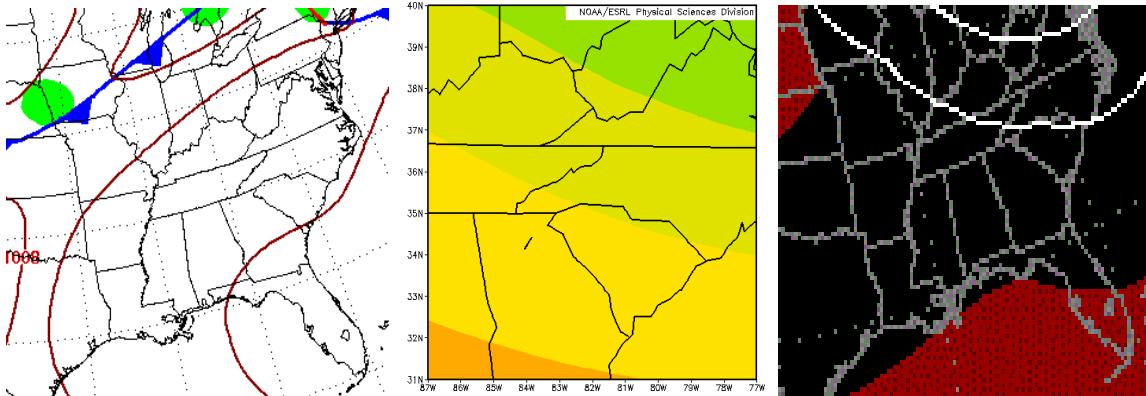
**Figure 38C.** 20070705



**Figure 38D.** 20070706

**Figure 38E.** 20070707

**Figure 38F.** 20070708



**Figure 38G.** 20070709

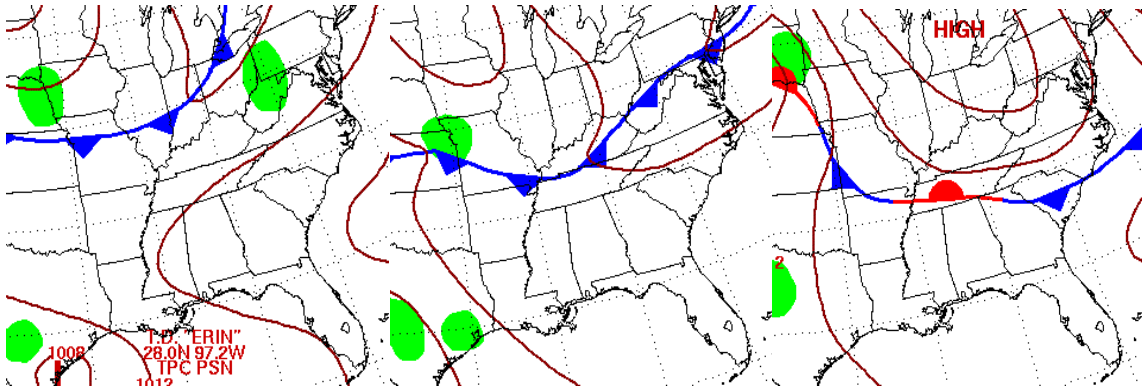
**Figure 38H.** Node 10

**Figure 38I.** 500mb 20070706

**Figures 38A-I.** NOAA WPC Surface Analysis maps for 2007-7-3 through 2007-7-9, SOM node associated with day of fire, and 500 mb geopotential height map of the event.

**Event 26: 2007-8-19**

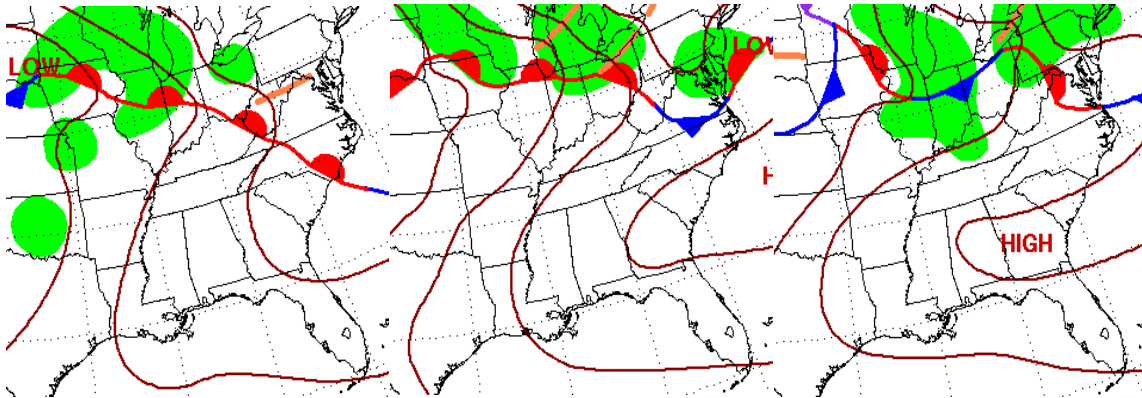
Grandfather Ranger District was in a severe drought (PDSI -3.2). The warm air aloft associated with synoptic type 4 (Figures 39H-I). A cold front moved south from the north northwest two days prior to ignition producing 4.4 mm of precipitation (Figures 39A-B). The cold front was replaced with a high pressure system and warm front that moved north through North Carolina the day of ignition (Figures 39C-D). No precipitation fell the day of ignition as winds were averaged between 0-6.4 kph from the north-northwest gusting up to 13 kph (Table 5). Following the warm front a high pressure system off the Atlantic Ocean moved in and dominated the southeastern United States (Figures 39E-G). The wildfire was very small, only burning a tenth of an acre, extinguishing three days later (Table 5).



**Figure 39A.** 20070816

**Figure 39B.** 20070817

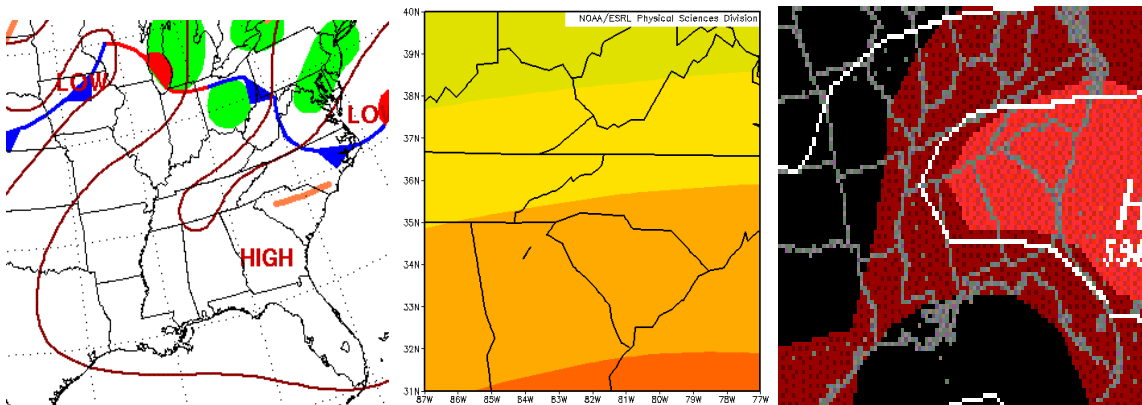
**Figure 39C.** 20070818



**Figure 39D.** 20070819

**Figure 39E.** 20070820

**Figure 39F.** 20070821



**Figure 39G.** 20070822

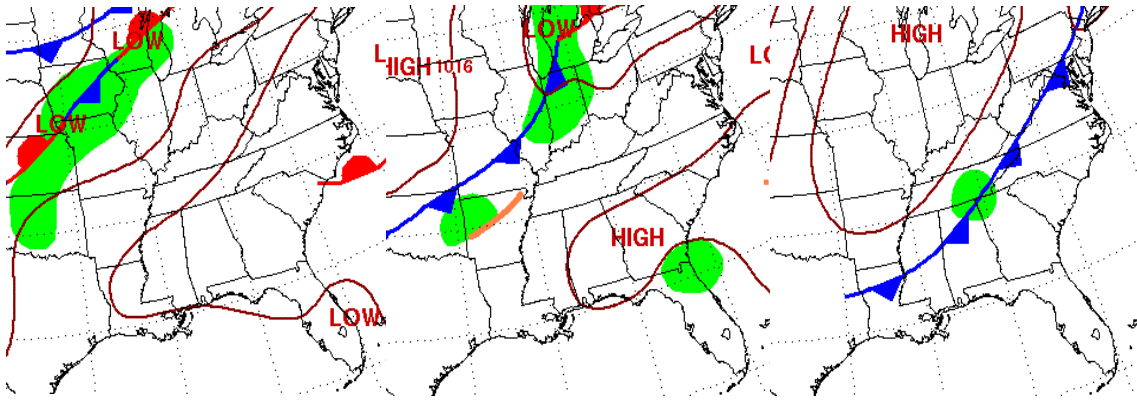
**Figure 39H.** Node 4

**Figure 39I.** 500mb 20070819

**Figures 39A-I.** NOAA WPC Surface Analysis maps for 2007-8-16 through 2007-8-22, SOM node associated with day of fire, and 500 mb geopotential height map of the event.

**Event 27: 2007-8-27**

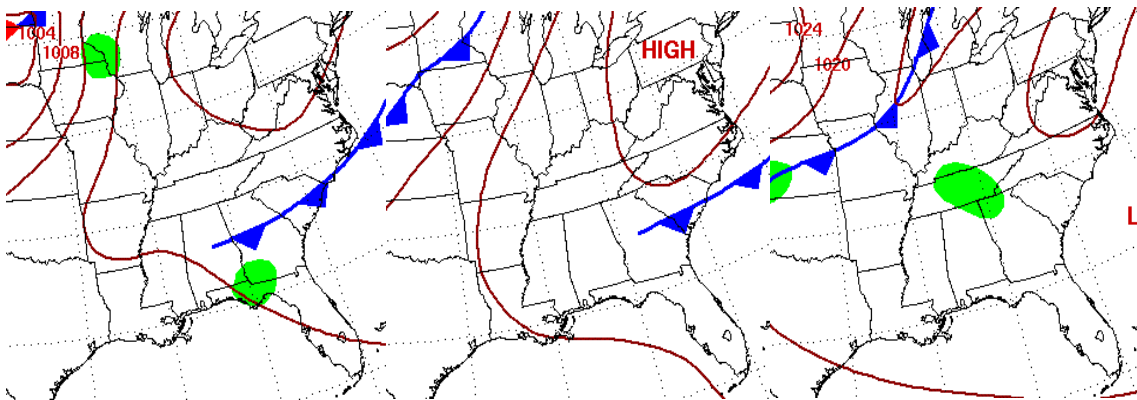
The study area was in a severe drought (PDSI  $-3.2$ ). Synoptic type 7 was associated with the day of ignition. Preceding the lightning ignition, western North Carolina was under high pressure with a cold front advancing from the west (Figures 40A-B). The cold front came through the region the day prior to lightning ignition, producing 6 mm of precipitation (Figure 40C). The day the lightning started a wildfire the cold front had passed and high pressure was moving in from the northeast (Figure 40D). Winds blew between 0-6.4 kph from the north-northeast, gusted up to 24 kph and 0.3mm of precipitation fell (Table 5). Following ignition, high pressure took over the region until being pushed out to the Atlantic Ocean from an advancing cold front from the west (Figures 40E-G). The wildfire burned two acres, extinguishing on August 31<sup>st</sup> after 30.5 mm of precipitation fell (Table 5).



**Figure 40A.** 20070824

**Figure 40B.** 20070825

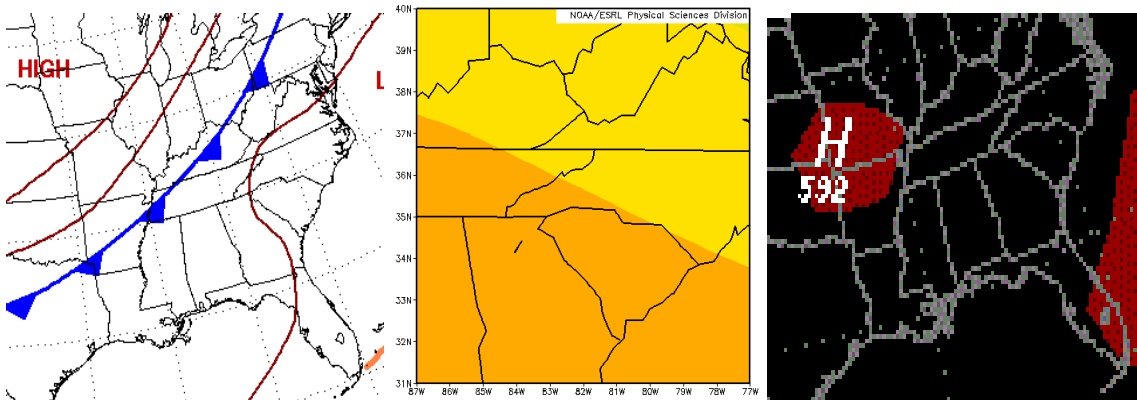
**Figure 40C.** 20070826



**Figure 40D.** 20070827

**Figure 40E.** 20070828

**Figure 40F.** 20070829



**Figure 40G.** 20070830

**Figure 40H.** Node 7

**Figure 40I.** 500mb 20070827

**Figures 40A-I.** NOAA WPC Surface Analysis maps for 2007-8-24 through 2007-8-30, SOM node associated with day of fire, and 500 mb geopotential height map of the event.

**Event 28: 2007-9-5**

Grandfather Ranger District was still in a severe drought (PDSI -3.56). Synoptic type 11 as associated with the day of ignition (Figures 41H-I). Almost 58 mm of precipitation fell the week prior to ignition (Table 5). High pressure dominated most of the eastern coast of the United States three days before, the day of, and three days after lightning fire ignition (Figures 41A-G). No precipitation fell the day of ignition while winds from the northwest averaged between 0-6.4 kph with gusts up to 11.3 kph (Table 5). The wildfire burned fifteen acres and extinguished September 30<sup>th</sup> after 69.6 mm of precipitation fell while it burned (Table 5).

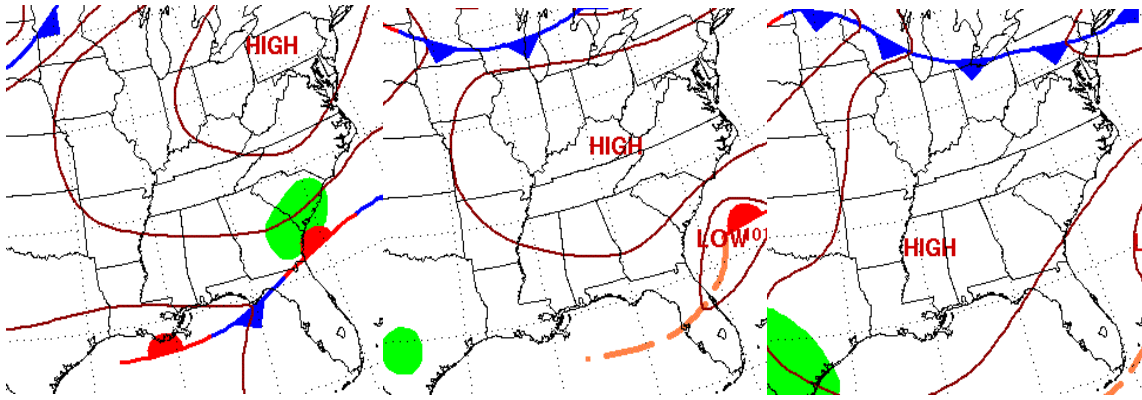


Figure 41A. 20070902

Figure 41B. 20070903

Figure 41C. 20070904

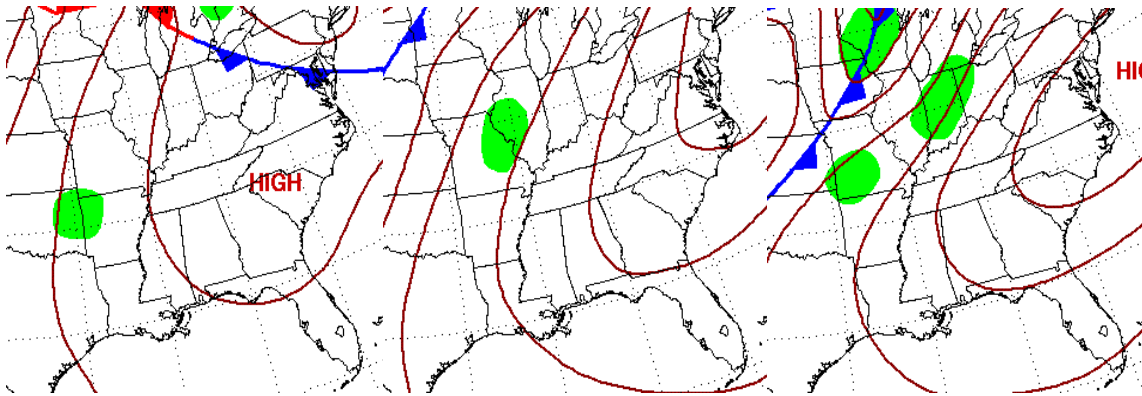


Figure 41D. 20070905

Figure 41E. 20070906

Figure 41F. 20070907

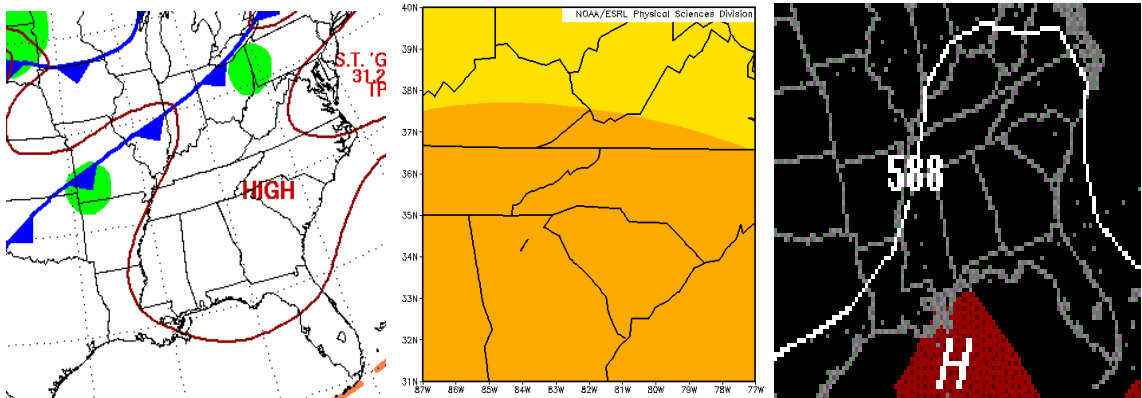


Figure 41G. 20070908

Figure 41H. Node 11

Figure 41I. 500mb 20070905

Figures 41A-I. NOAA WPC Surface Analysis maps for 2007-9-2 through 2007-9-8, SOM node associated with day of fire, and 500 mb geopotential height map of the event.

**Event 29: 2007-9-9**

The study area was still gripped by severe drought (PDSI -3.56). Node 11 was associated with the synoptic conditions (Figure 42H-I). Only 0.3 mm of precipitation fell as high pressure emanating from the Atlantic Ocean covered most of the southeastern United States in the day's preceding ignition (Figures 42A-C). A cold front approached from the west as Tropical Storm Gabrielle was off the coast of North Carolina the day of lightning ignition (Figure 42D). Winds from the north-northeast blew from 0-6.4 kph with gusts up to 19 kph and no precipitation fell the day of ignition (Table 5). A cold front moves through western North Carolina two days after wildfire ignition (Figures 42E-G). A total of 65.6 mm of precipitation fell while the fire burned five acres until extinguishing September 20<sup>th</sup> (Table 5).



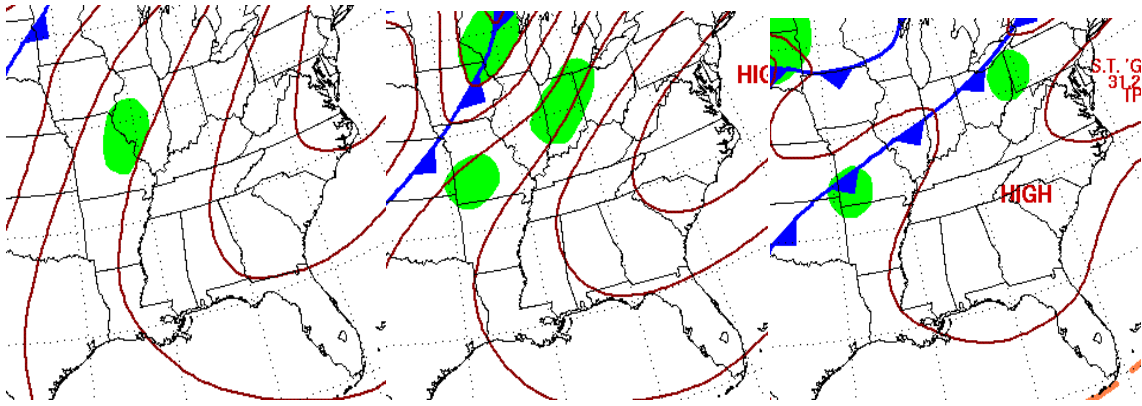


Figure 42A. 20070906

Figure 42B. 20070907

Figure 42C. 20070908

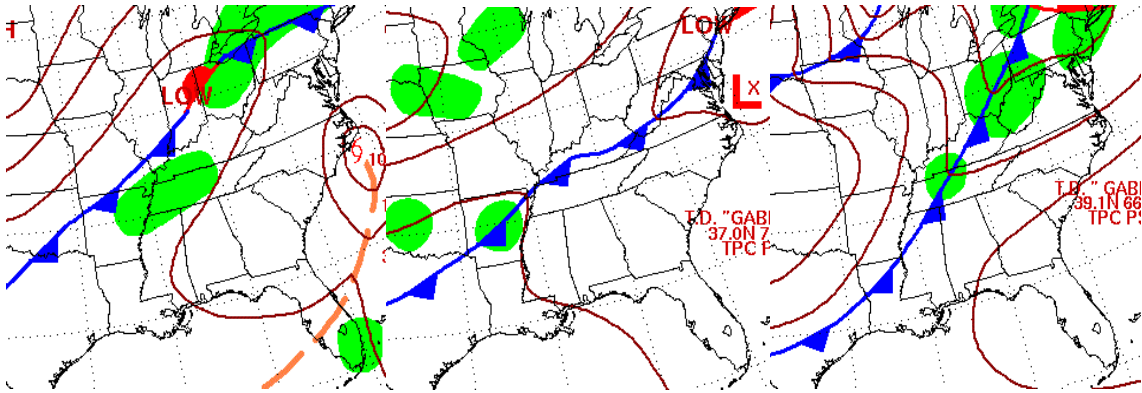


Figure 42D. 20070909

Figure 42E. 20070910

Figure 42F. 20070911

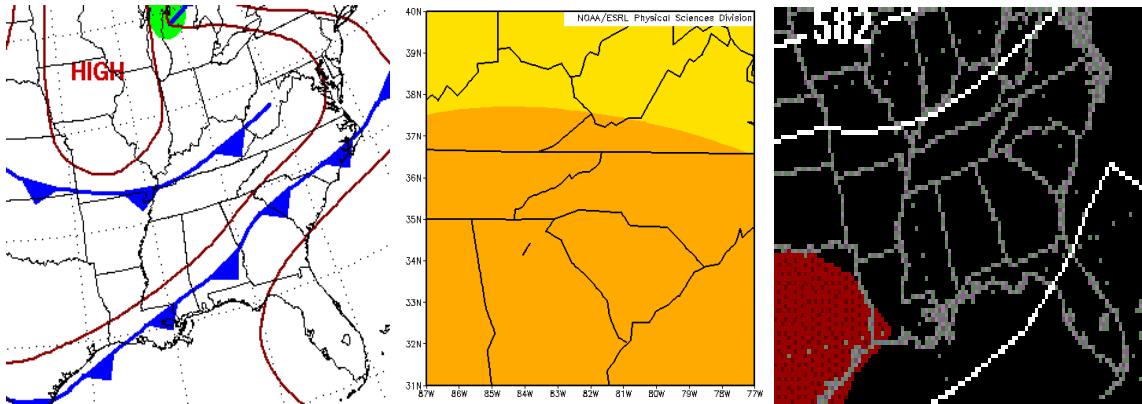


Figure 42G. 20070912

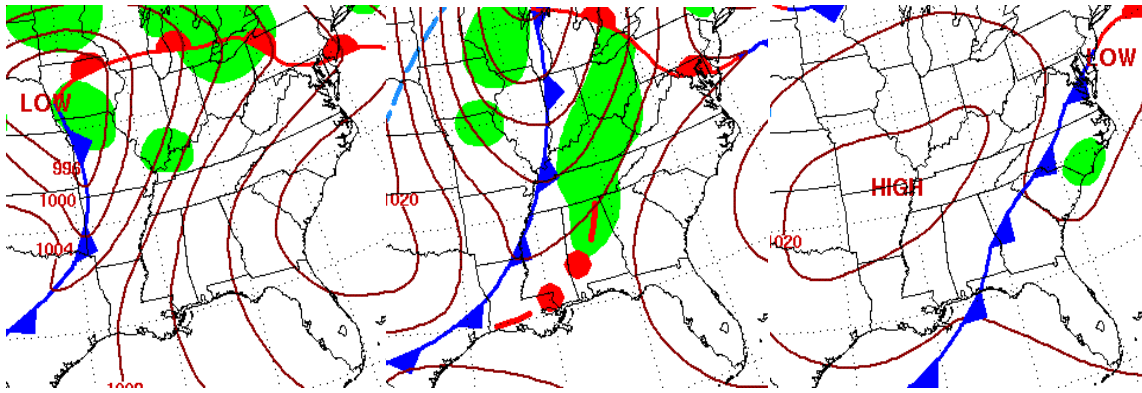
Figure 42H. Node 11

Figure 42I. 500mb 20070909

Figures 42A-I. NOAA WPC Surface Analysis maps for 2007-9-6 through 2007-9-12, SOM node associated with day of fire, and 500 mb geopotential height map of the event.

**Event 30: 2008-5-5**

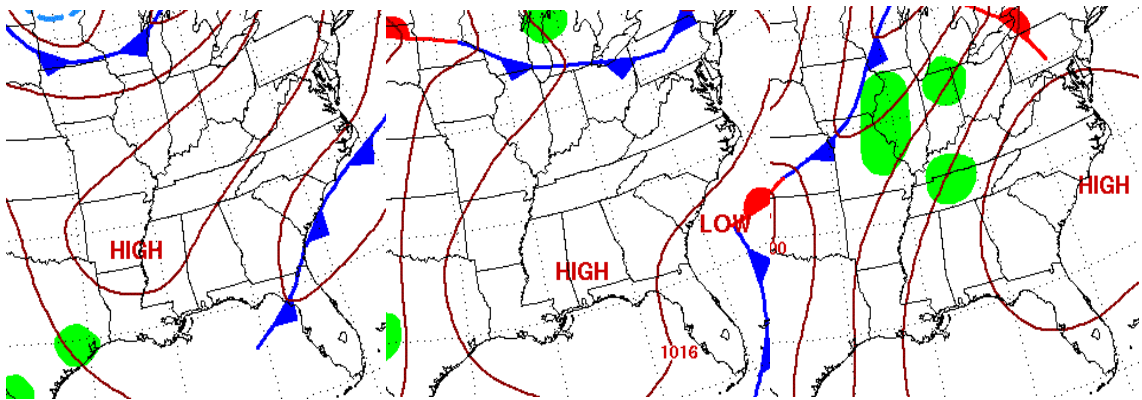
A severe drought still persisted over the study area (PDSI -3.04). Synoptic type 6 was associated with the day of ignition (Figures 43H-I). High pressure exerted across the southeast from the Atlantic Ocean as an occluded front spawning from low pressure moved northwest across the central United States (Figures 43A-B). A cold front moved through western North Carolina the day before the lightning ignition depositing 20.6 mm of precipitation as high pressure moved in behind it (Figure 43C). High pressure remained over the southeast until another occluded front approached from the southwest (Figures 43C-G). No precipitation fell the day of ignition as winds from the north blew on average of 0-8 kph with gusts up to 19.3 kph (Table 5). Only a half an acre burned before going out the next day as 0.3 mm of precipitation fell (Table 5).



**Figure 43A.** 20080502

**Figure 43B.** 20080503

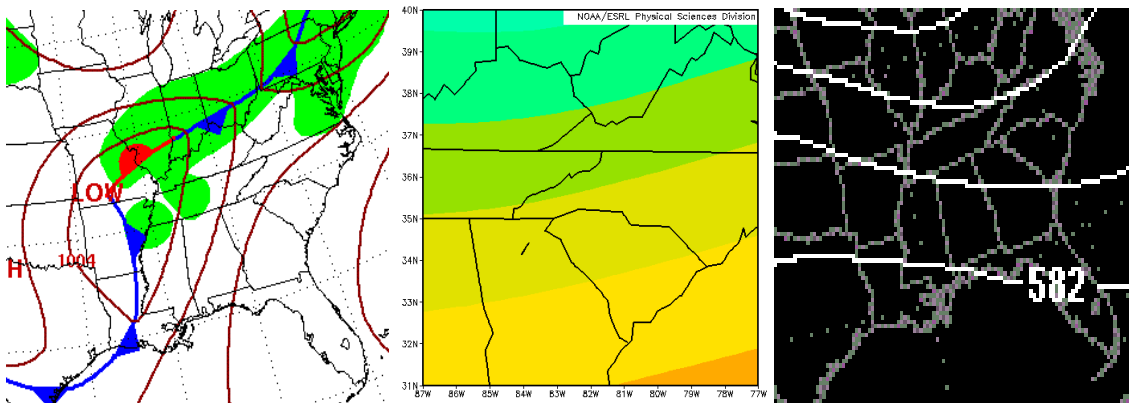
**Figure 43C.** 20080504



**Figure 43D.** 20080505

**Figure 43E.** 20080506

**Figure 43F.** 20080507



**Figure 43G.** 20080509

**Figure 43H.** Node 6

**Figure 43I.** 500mb 20080505

**Figures 43A-I.** NOAA WPC Surface Analysis maps for 2008-5-2 through 2008-5-8, SOM node associated with day of fire, and 500 mb geopotential height map of the event.

**Event 31: 2008-6-11**

Severe drought still persisted over the study region (PDSI -3.33). This event was associated with node 4 (Figures 44H-I). High pressure dominated the southeast until moving out over the Atlantic, being expelled by and advancing cold front (Figures 44A-D). The cold front moved across western North Carolina the day before the lightning ignition producing 66 mm of precipitation (Figures 44C-D). The day of ignition an additional 35.6 mm precipitated over the area with winds averaging 0-11 kph, gusting up to 27.4 kph from the west-northwest (Table 5). High pressure behind the cold front stayed in the region as another frontal system moved in from the west (Figures 44C-G). The wildfire burned an acre before extinguishing five days later after a total of 57.7mm of precipitation fell (Tables 5).

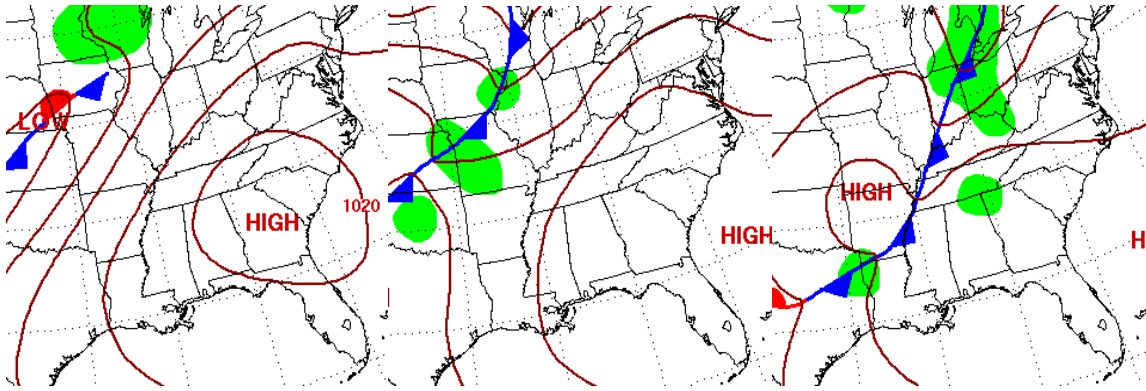


Figure 44A. 20080608

Figure 44B. 20080609

Figure 44C. 20080610

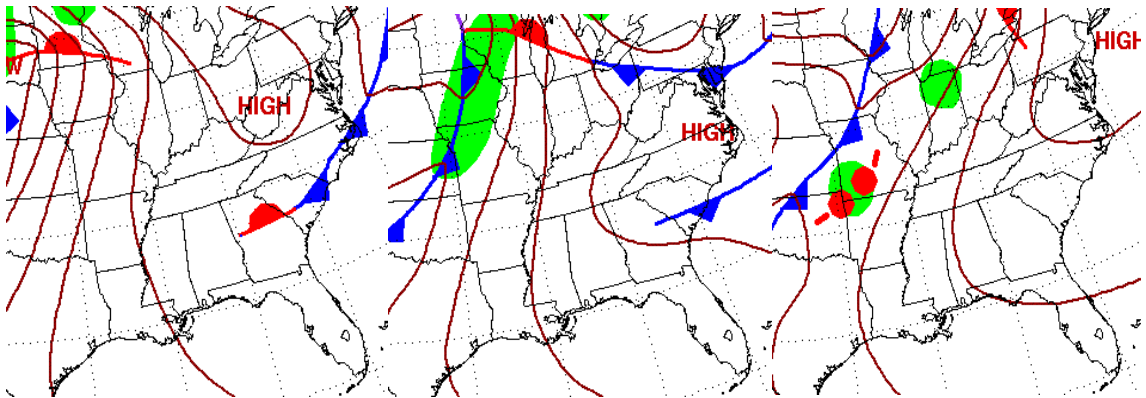


Figure 44D. 20080611

Figure 44E. 20080612

Figure 44F. 20080613

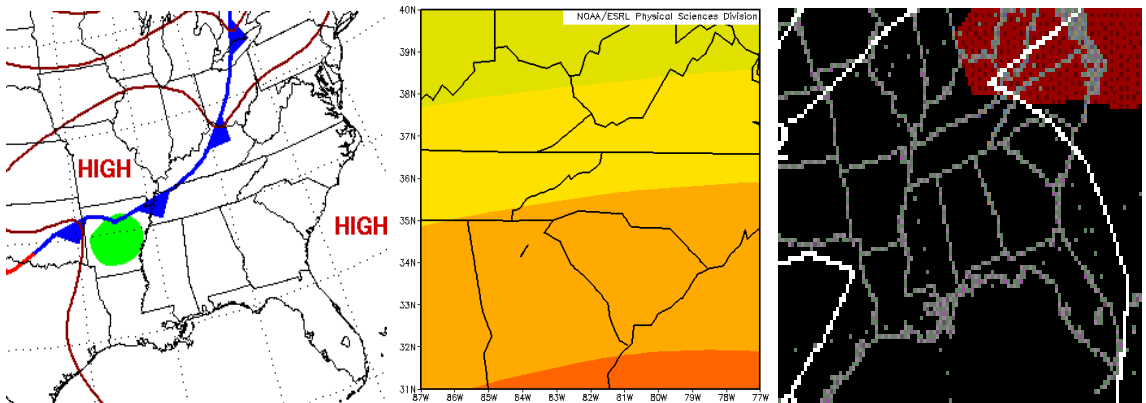


Figure 44G. 20080614

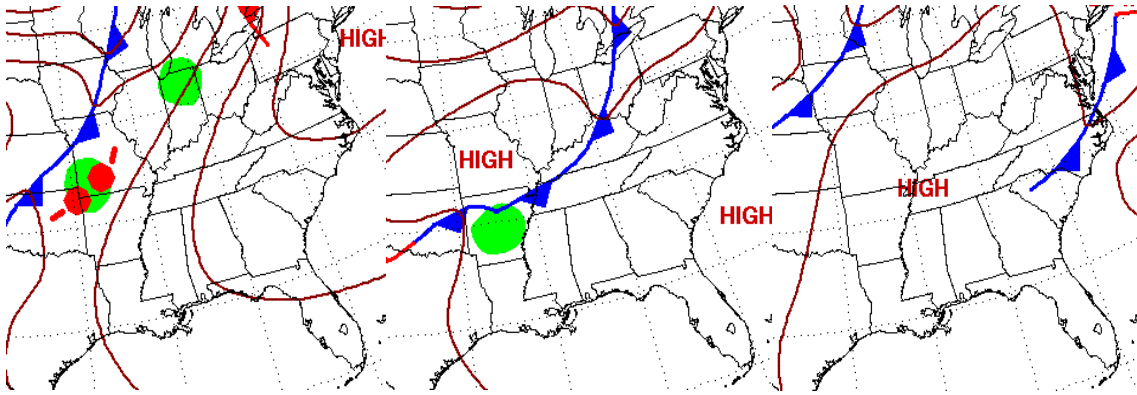
Figure 44H. Node 4

Figure 44I. 500mb 20080611

Figures 44A-I. NOAA WPC Surface Analysis maps for 2008-6-8 through 2008-6-14, SOM node associated with day of fire, and 500 mb geopotential height map of the event.

**Event 32: 2008-6-16**

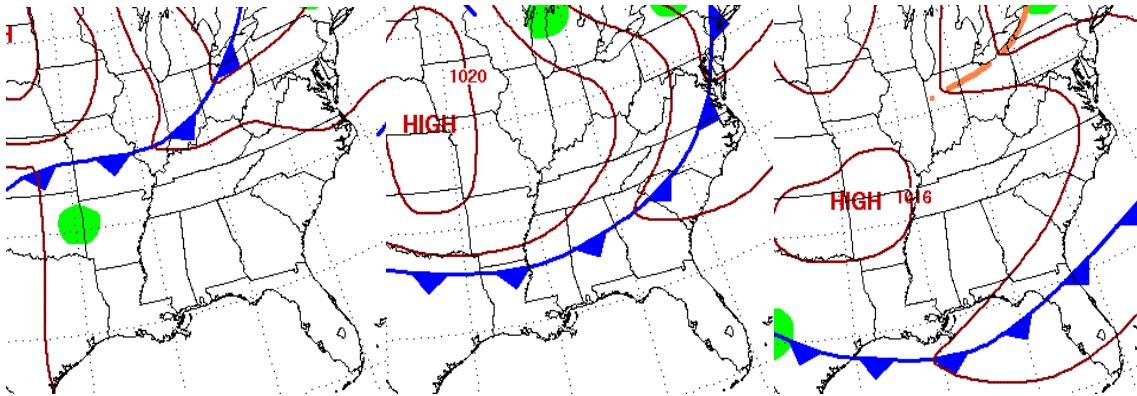
The study area was in a severe drought (PDSI -3.33). The synoptic classification for this day was node 10 (Figure 45H-I). Three days prior to the wildfire a high pressure system was over the region with a cold front advancing from the west (Figure 45A). The cold front passed through the study area two days prior to lightning ignition, after precipitating 59.2 mm, with another cold front a couple days behind it (Figures 45B-E). The day of lightning ignition a cold front moved through the area, precipitating 0.3 mm, with high pressure behind it (Figures 45D-E). Winds averaged between 0-6.4 kph with gusts up to 14.5 kph from the southeast (Table 5). The high pressure remained in the southeast for at least the three days following the lightning ignition (Figures 45E-G). A half-acre burned, while 0.6 mm of precipitation fell, extinguishing five days later (Table 5).



**Figure 45A.** 20080613

**Figure 45B.** 20080614

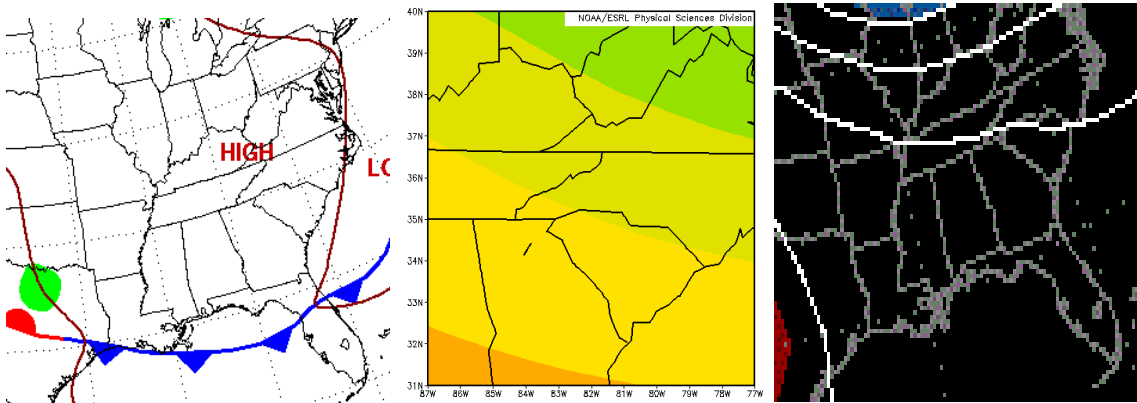
**Figure 45C.** 20080615



**Figure 45D.** 20080616

**Figure 45E.** 20080617

**Figure 45F.** 20080618



**Figure 45G.** 20080619

**Figure 45H.** Node 10

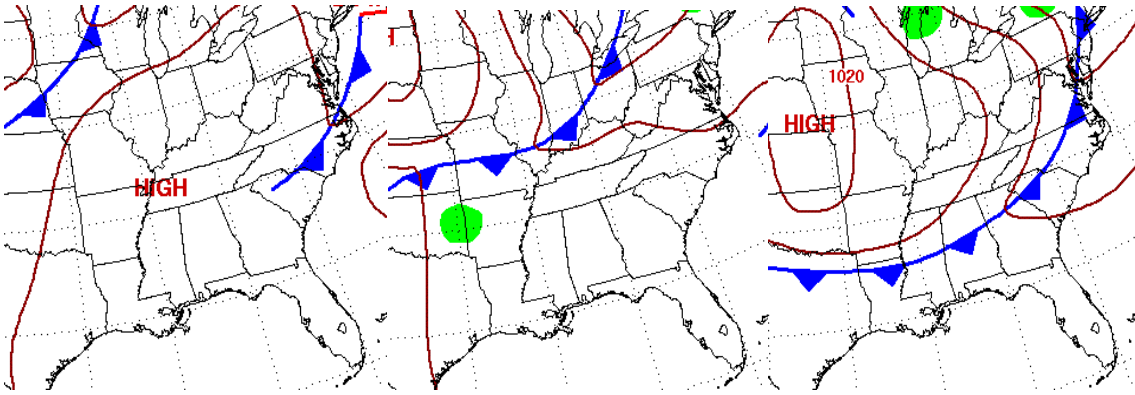
**Figure 45I.** 500mb 20080616

**Figures 45A-I.** NOAA WPC Surface Analysis maps for 2008-6-13 through 2008-6-19, SOM node associated with day of fire, and 500 mb geopotential height map of the event.

**Event 33: 2008-6-18**

The study area was in a severe drought (PDSI -3.33). Synoptic type 2 was associated with the cold air aloft (Figures 46H-I). Three days prior to lightning ignition a cold front had moved across western North Carolina and high pressure moved in as a second cold front moved into the region two days prior to the ignition with high pressure again moving in afterwards (Figures 46A-C). There was a total of 58.3 mm precipitated over the study region the week prior (Table 5). The high pressure stayed over the region the day of ignition and persisted throughout the following three days post ignition (Figures 46D-G). No precipitation fell the day of ignition as winds from the southeast averaged between 1.6-8 kph with gusts up to 19.3 kph (Table 5). The wildfire burned until July 3<sup>rd</sup> after consuming across thirty acres (Table 5). A total of 94.5 mm of precipitation fell on the wildfire before it extinguished (Table 5).

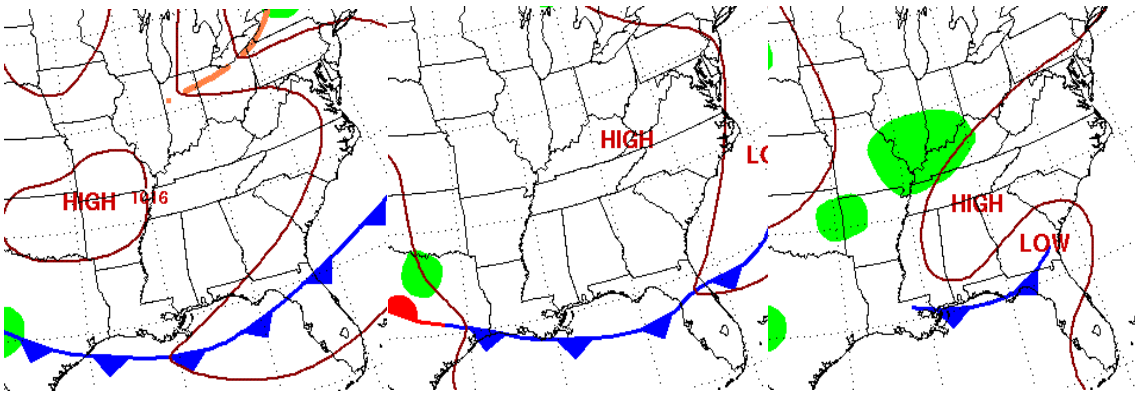




**Figure 46A.** 20080615

**Figure 46B.** 20080616

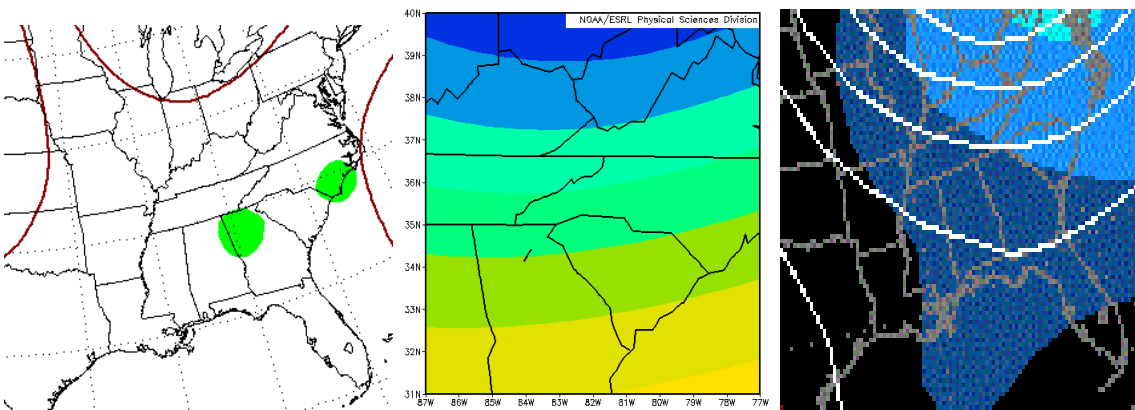
**Figure 46C.** 20080617



**Figure 46D.** 20080618

**Figure 46E.** 20080619

**Figure 46F.** 20080620



**Figure 46G.** 20080621

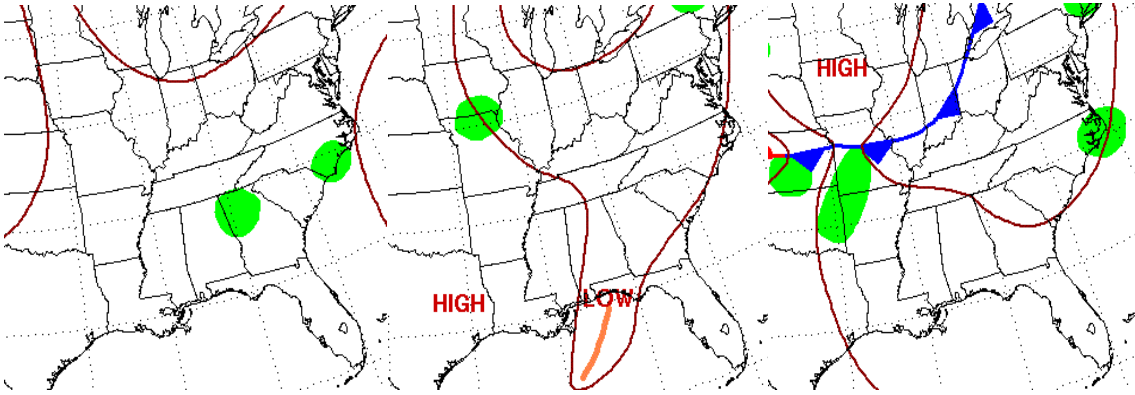
**Figure 46H.** Node 2

**Figure 46I.** 500mb 20080618

**Figures 46A-I.** NOAA WPC Surface Analysis maps for 2008-6-15 through 2007-6-21, SOM node associated with day of fire, and 500 mb geopotential height map of the event.

**Event 34: 2008-6-24**

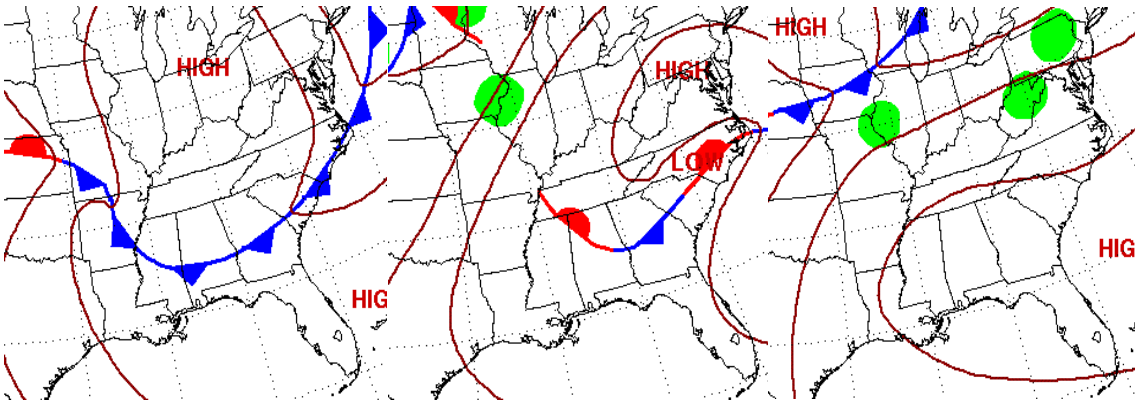
Severe drought gripped the study area (PDSI -3.33). Synoptic type 3 was associated with the air aloft (Figures 47H-I). Weak high pressure sat over the region until a cold front moved through the day before lightning ignition, producing 61 mm of precipitation (Figures 47A-C). High pressure moved in the day of fire after the cold front moved through, although the front stalled into a stationary front to the south and east of western North Carolina (Figure 47D-E). Winds blew on average of 0-6.4 kph, from the south, with gusts up to 16.1 kph as no precipitation occurred (Table 5). High pressure then returned for the remaining observed days after the ignition (Figures 47F-G). A total of 36.5 acres burned as 137.7 mm fell on the wildfire before it extinguished July 15<sup>th</sup> (Table 5).



**Figure 47A.** 20080621

**Figure 47B.** 20080622

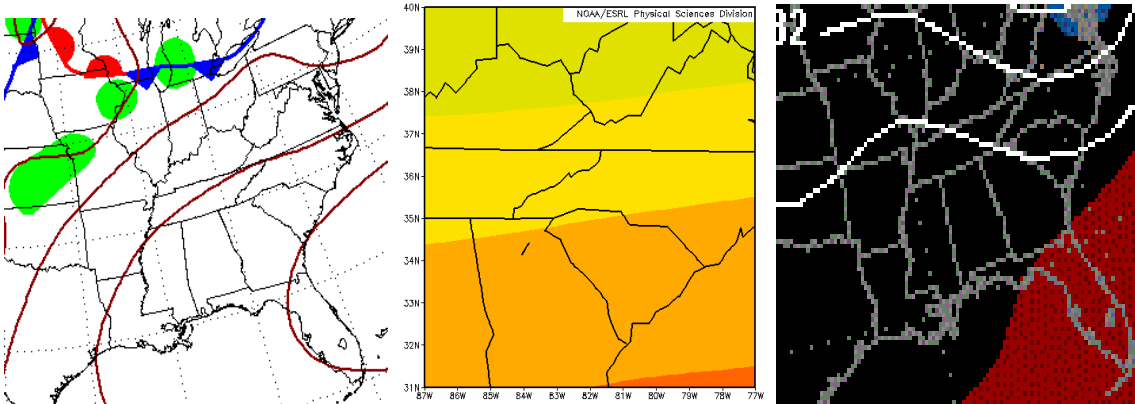
**Figure 47C.** 20080623



**Figure 47D.** 20080624

**Figure 47E.** 20080625

**Figure 47F.** 20080626



**Figure 47G.** 20080627

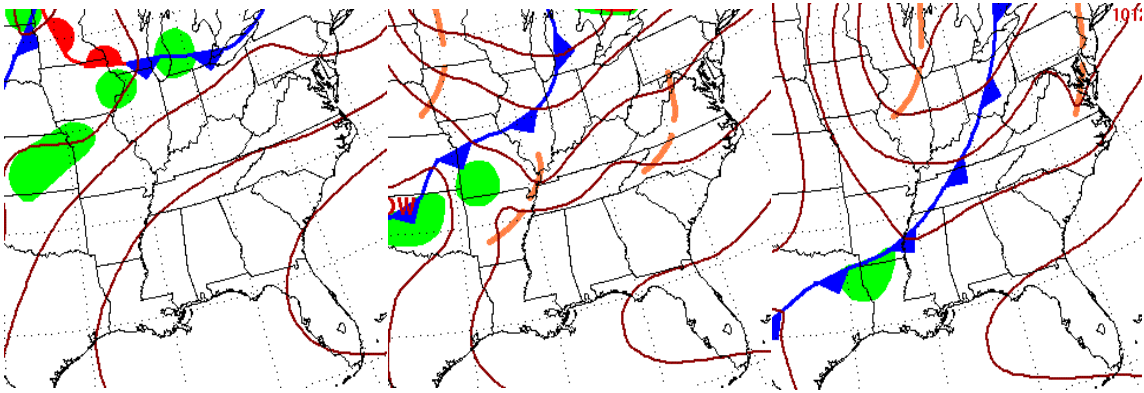
**Figure 47H.** Node 3

**Figure 47I.** 500mb 20080624

**Figures 47A-I.** NOAA WPC Surface Analysis maps for 2008-6-21 through 2007-6-27, SOM node associated with day of fire, and 500 mb geopotential height map of the event.

**Event 35: 2008-6-30**

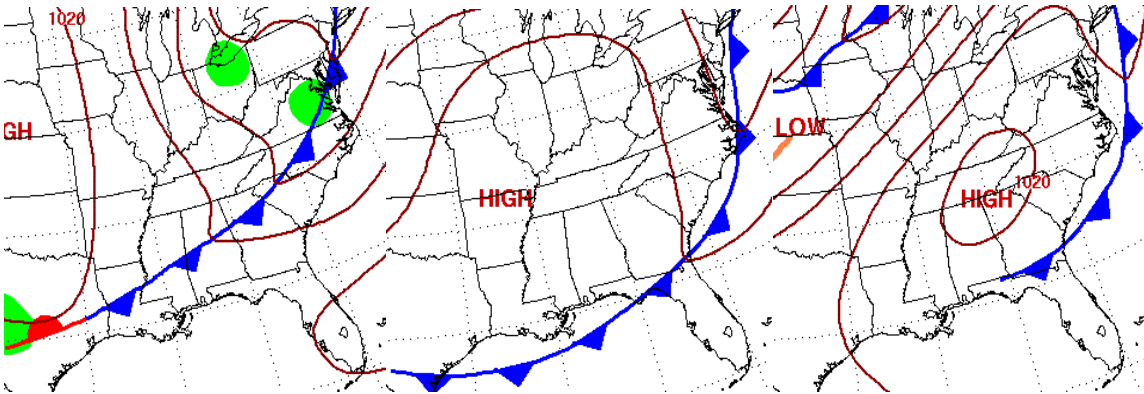
The last event in June, 2008 was under severe drought (PDSI -3.33). Synoptic type 6 associated with the air aloft (Figures 48H-I). High pressure exited the region as a cold front passed through precipitating 44.7 mm in the days preceding the wildfire (Figures 48A-C). A surface trough extended over western North Carolina two days prior to ignition and the cold front moved through the day before the fire (Figures 48B-C). Precipitation amounted 8.6mm and winds gusted up to 17.7 kph, averaging 0-6.4 kph from the north as high pressure followed the cold front and stayed over western North Carolina until three days post ignition (Figures 48D-G). The fire burned 95 acres, burning out July 11<sup>th</sup> after 92.5 mm precipitated on it (Table 5).



**Figure 48A.** 20080627

**Figure 48B.** 20080628

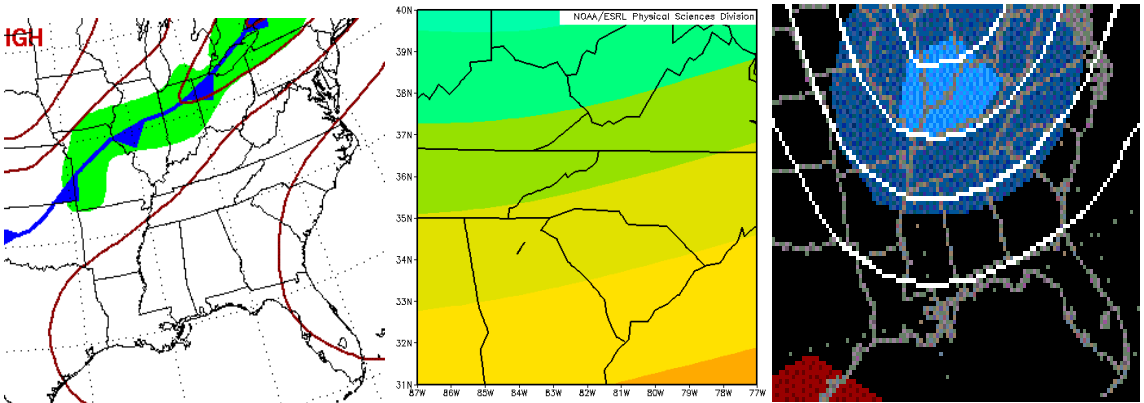
**Figure 48C.** 20080629



**Figure 48D.** 20080630

**Figure 48E.** 20080701

**Figure 48F.** 20080702



**Figure 48G.** 20080703

**Figure 48H.** Node 6

**Figure 48I.** 500mb 20080630

**Figures 48A-I.** NOAA WPC Surface Analysis maps for 2008-6-27 through 2008-7-3, SOM node associated with day of fire, and 500 mb geopotential height map of the event.

**Event 36: 2008-7-16**

The severe drought persisted over Grandfather Ranger District (PDSI -3.37). Synoptic type 7 was associated with the day of the wildfire (Figures 49H-I). Light rain extended over much of Tennessee into western North Carolina before a cold front moved through three days prior to ignition, precipitating 84.3 mm (Figure 49A). The day of ignition had winds averaged between 0-8 kph, gusting up to 16.1 kph, and no precipitation (Table 5). High pressure then moved into the region two days prior to ignition and persisted until at least three days post ignition (Figures 49B-G). Only an acre and a half burned, with 4 mm of precipitation falling on the fire before it extinguished July 22<sup>nd</sup> (Table 5).

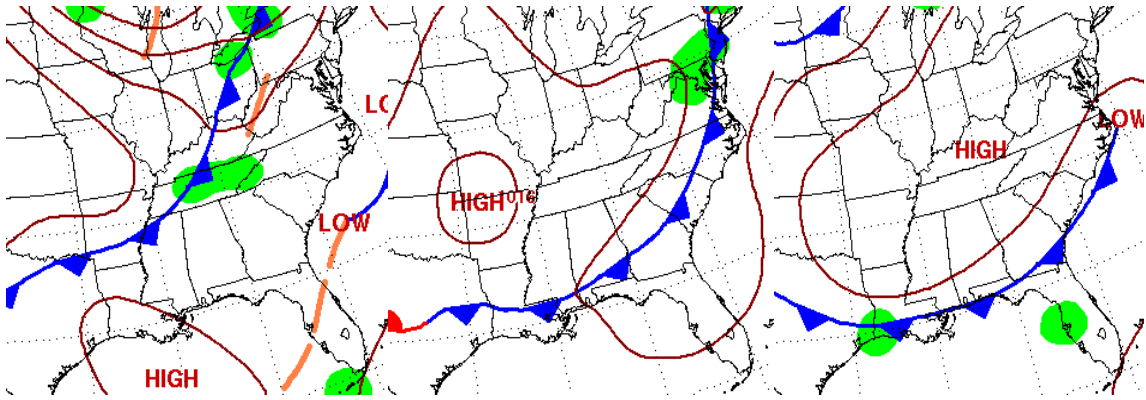


Figure 49A. 20080713

Figure 49B. 20080714

Figure 49C. 20080715

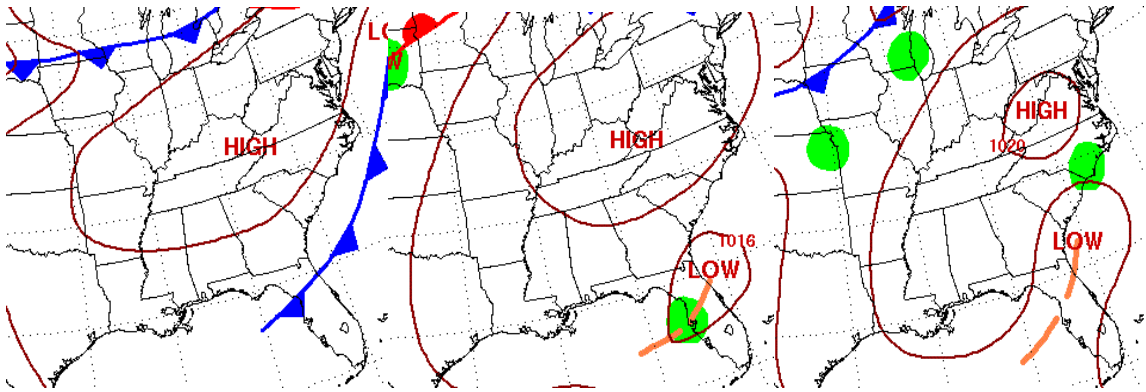


Figure 49D. 20080716

Figure 49E. 20080717

Figure 49F. 20080718

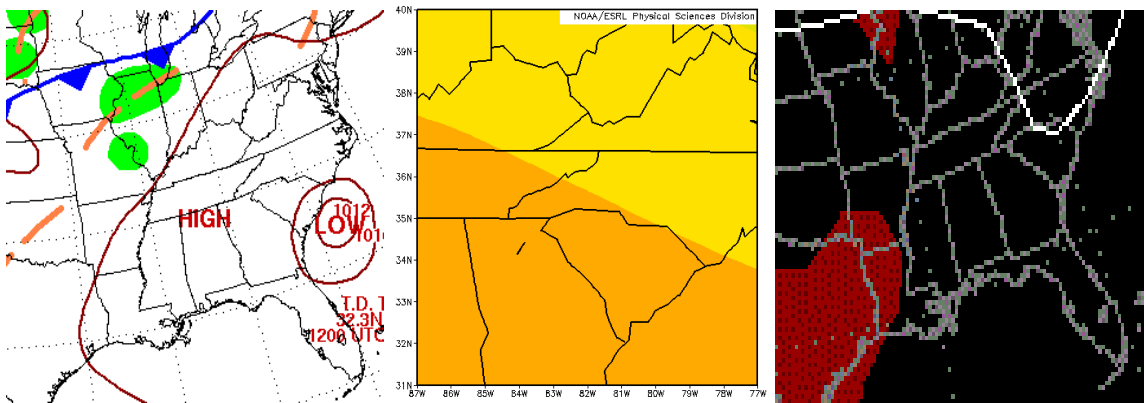


Figure 49G. 20080719

Figure 49H. Node 7

Figure 49I. 500mb 20080716

Figures 49A-I. NOAA WPC Surface Analysis maps for 2008-7-13 through 2008-7-19, SOM node associated with day of fire, and 500 mb geopotential height map of the event.

**Event 37, and 38: 2009-4-24**

The study area was near normal for drought conditions (PDSI -1.48). Synoptic type 8 was associated with the warm air aloft (Figures 50H-I). High pressure moved into the southwest after a cold front moved across western North Carolina three days prior to ignition, depositing 32.8 mm of precipitation (Figure 50A-C). A stationary front associated with an occluded front spanning from the Great Lakes moved through western North Carolina the day of lightning ignition (Figure 50D). There was no precipitation as winds averaged 1.6-8 kph from the south-southwest gusting up to 22.5 kph (Table 5). High pressure remained over much of the southeast for the three days post lightning ignition. Two lightning ignited fires occurred, with event 37 burning 17 acres and event 38 burning 2 acres, both extinguishing three days later on April 27<sup>th</sup> after 12.7 mm of precipitation fell on the wildfires (Table 5).



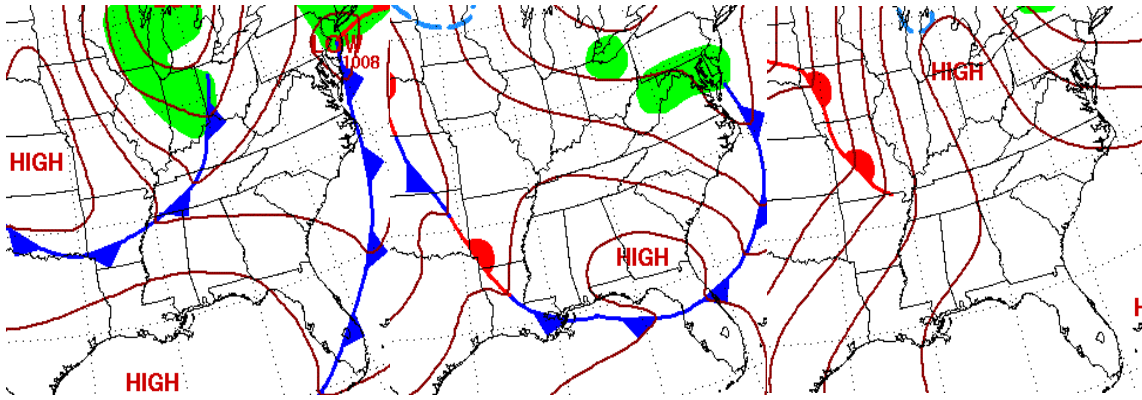


Figure 50A. 20090421

Figure 50B. 20090422

Figure 50C. 20090423

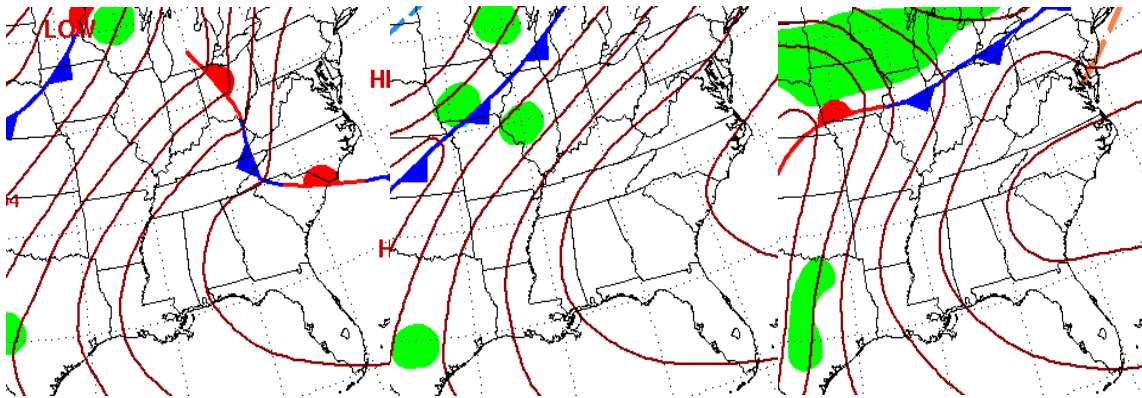


Figure 50D. 20090424

Figure 50E. 20090425

Figure 50F. 20090426

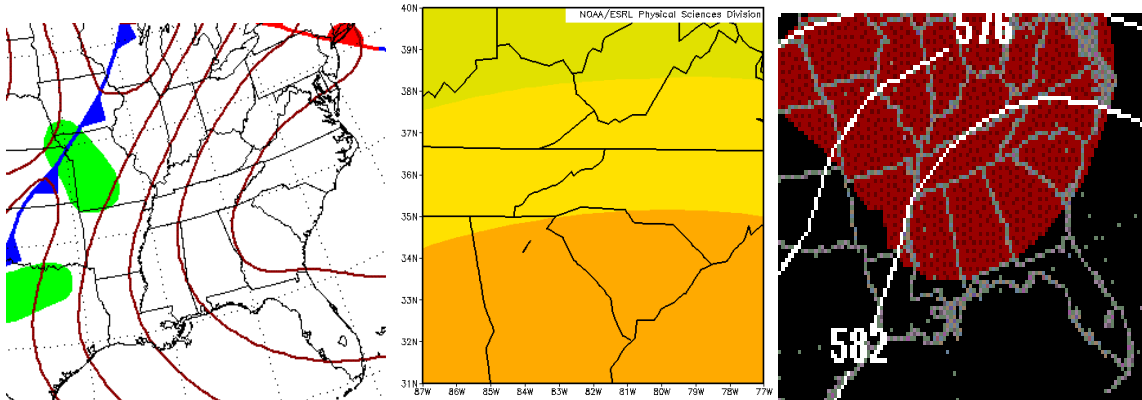


Figure 50G. 20090427

Figure 50H. Node 8

Figure 50I. 500mb 20090424

Figures 50A-I. NOAA WPC Surface Analysis maps for 2009-4-21 through 2009-4-27, SOM node associated with day of fire, and 500 mb geopotential height map of the event.

**Event 39: 2009-9-14**

Grandfather Ranger District was encountering an unusually moist spell (PDSI 2.35). Synoptic type 7 was associated with the day of ignition (Figures 51H-I). There was 16.3 mm of precipitation in the week leading up to ignition (Table 5). A high pressure system extended over western North Carolina over the days preceding and after ignition (Figures 51A-D). No precipitation occurred with winds averaged between 1.6-4.8 kph, gusting up to 12.9 kph, from the southeast (Table 5). Low pressure from the Gulf of Mexico moved up through Texas and Louisiana disrupting the high pressure in the days after ignition (Figures 51B-G). The wildfire burned an acre, extinguishing five days later after 41.2 mm of precipitation fell on it (Table 5).

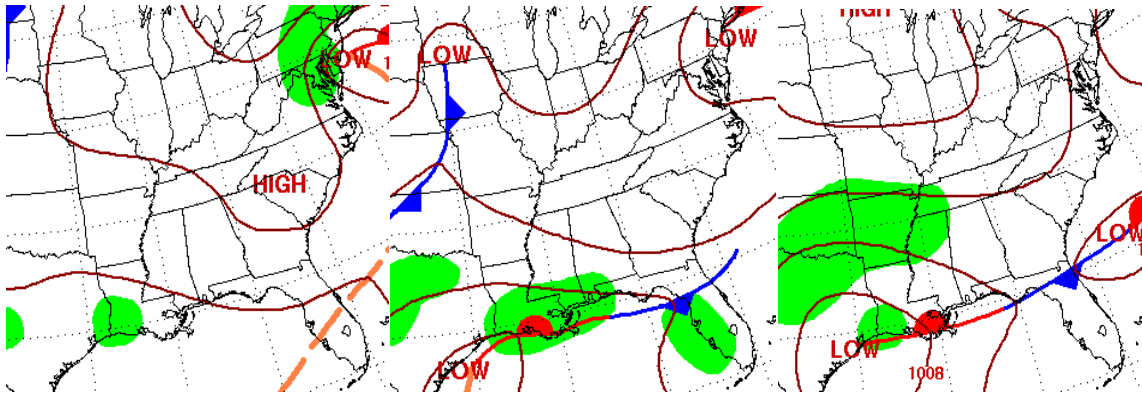


Figure 51A. 20090911

Figure 51B. 20090912

Figure 51C. 20090913

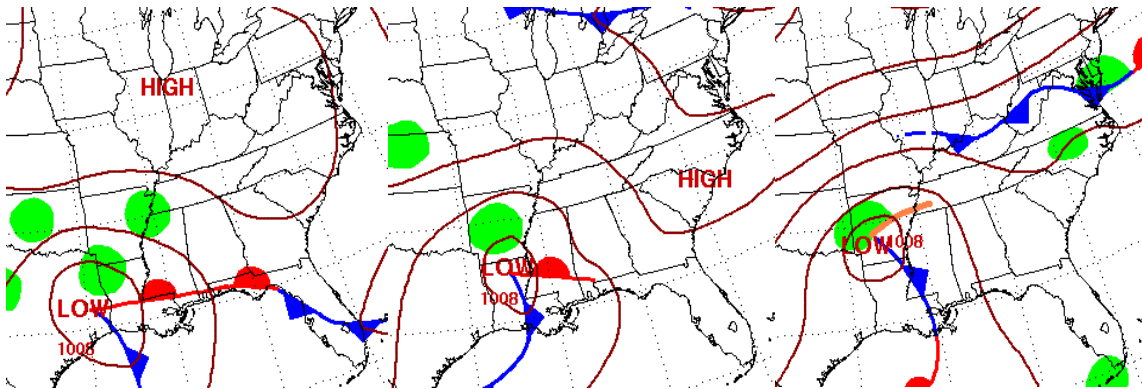


Figure 51D. 20090914

Figure 51E. 20090915

Figure 51F. 20090916

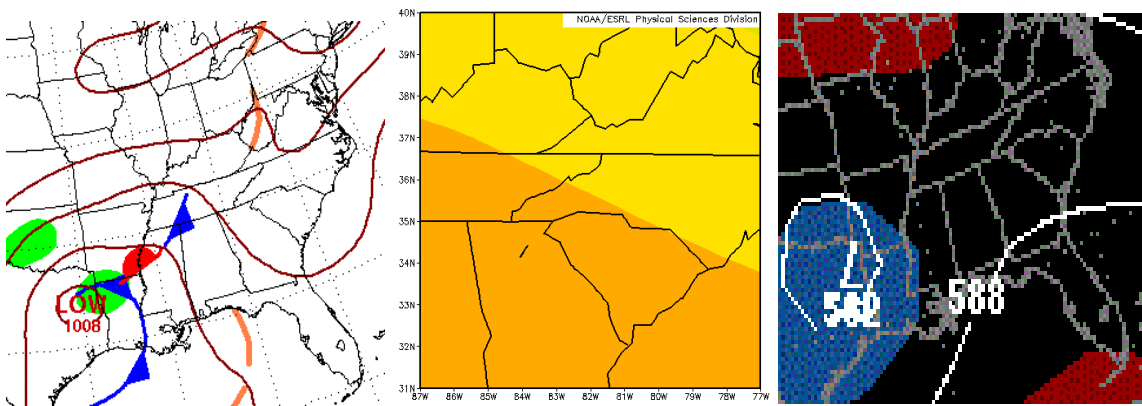


Figure 51G. 20090917

Figure 51H. Node 7

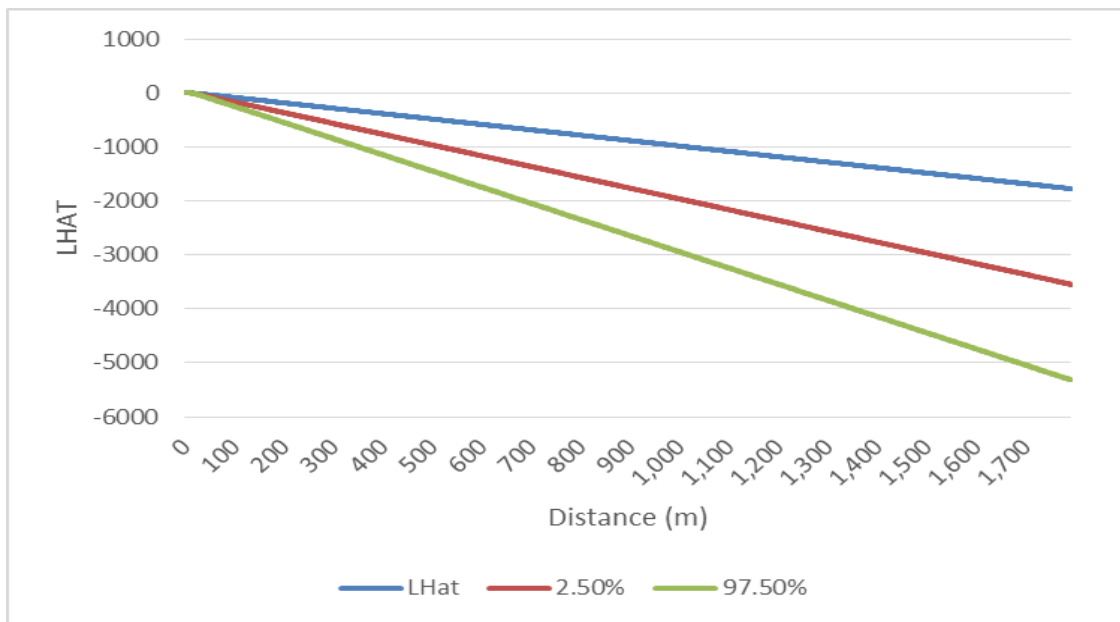
Figure 51I. 500mb 20090914

Figures 51A-I. NOAA WPC Surface Analysis maps for 2009-9-11 through 2009-9-17, SOM node associated with day of fire, and 500 mb geopotential height map of the event.

## 4.4 Objective 4 results

### 4.4.1 Point pattern analysis

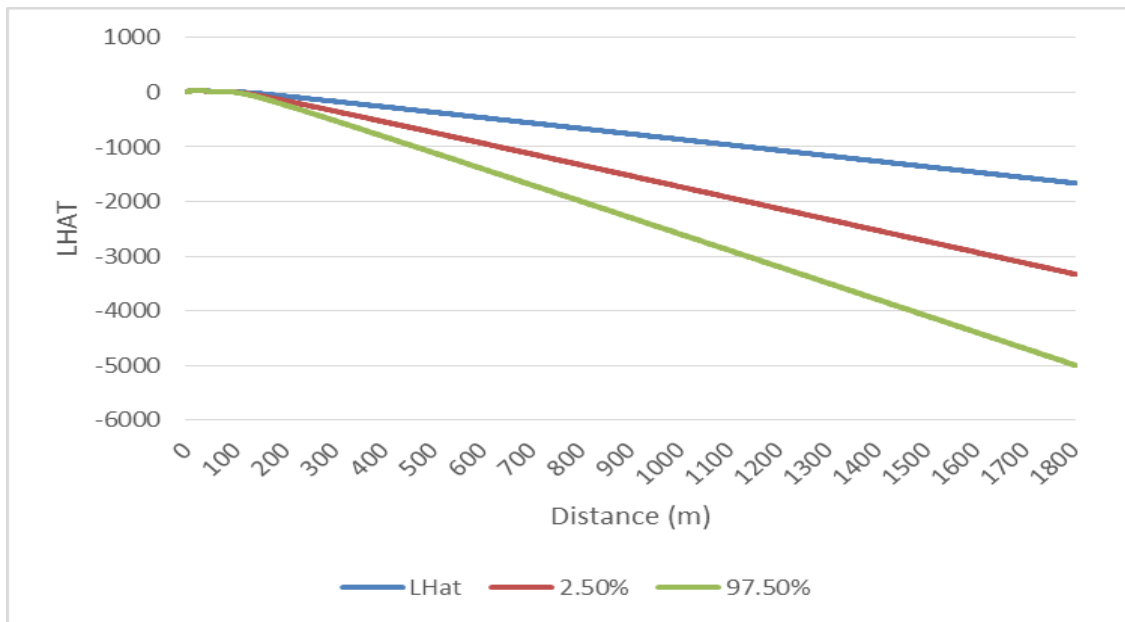
*Hudsonia montana* is spatially aggregated across the landscape in the Grandfather Ranger District (Figure 52). The endemic shrub is found to be clumped at scales is higher than one hundred meters. Due to the small population recorded for *Hudsonia montana* there may be error in the results at large scales however, the shrub is aggregated at small and intermediate scales.



**Figure 52.** Ripley K analysis of *Hudsonia montana* across Grandfather Ranger District, in meters.

Lightning ignited fires are also aggregated at intermediate and large scales. (Figure 53). At small scales, less than 200 meters, lightning ignitions are randomly located. The

record of lightning ignitions are also small suggesting large scale predictions of aggregation may not reflect the actual spatial configuration. However, small scales, below 200 meters, reflect random distributions of lightning ignitions; while intermediate scales and higher reflect an aggregation of lightning ignitions in the study area.

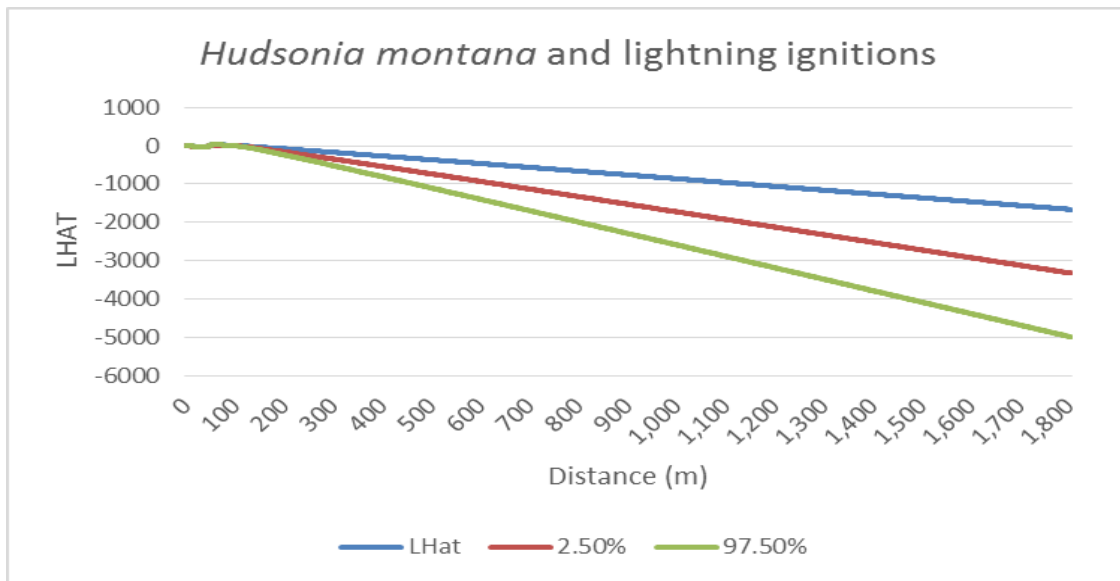


**Figure 53.** Ripley K analysis of lightning ignited fires in the Grandfather Ranger District, in meters.

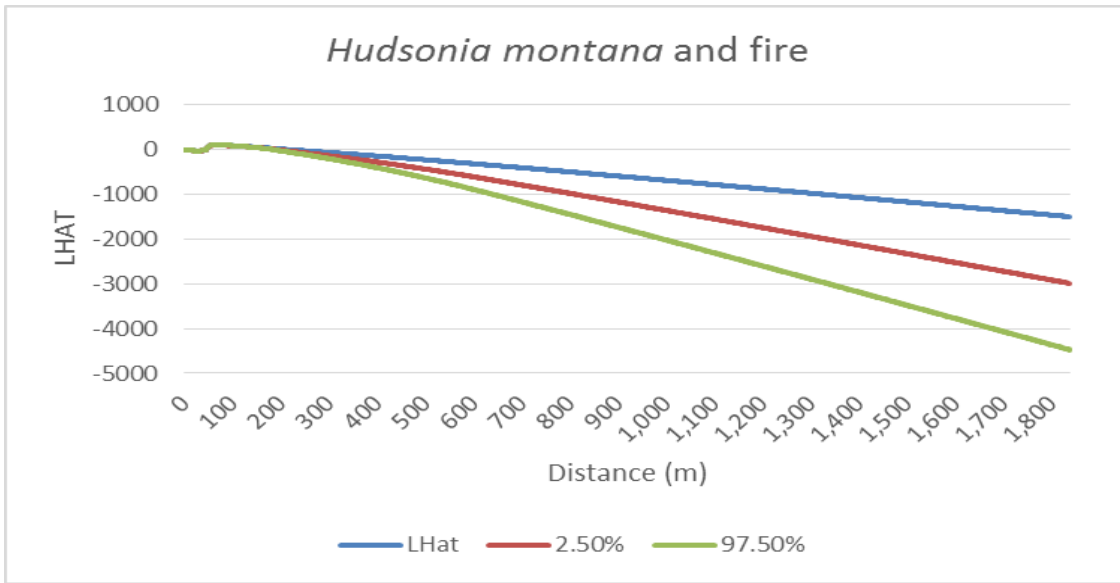
#### 4.4.2 Second order analysis

Bivariate analysis was completed on both lightning ignited fire locations and *Hudsonia montana* locations, as well as all fire types and *Hudsonia montana* locations. Bivariate analysis on all ignitions and *Hudsonia montana* showed random association at scales below 300 meters (Figure 54). However, at scales over 300 meters the shrub is

aggregated with fire (Figure 54). Second order analysis on lightning ignitions only and *Hudsonia montana* were different from the locations of the shrub and all fires. Lightning-ignited fires and the shrubs are aggregated at scales above 200 meters, and had associations spatially random below 200 meters (Figure 55).



**Figure 54.** Second order analysis on fire and *Hudsonia montana* locations.



**Figure 55.** Second order analysis on lightning-ignited fires and *Hudsonia montana* locations.

## 5. DISCUSSION AND CONCLUSIONS

Lightning-ignitions are paramount to consider when assessing vegetation distributions of fire dependent species (Hoss et al. 2008). While all fires impact vegetation, a species life traits that may associate it with fire would not have the time required to have developed in response to anthropogenic ignitions (Frost 1998; Noss 2013). Therefore, the existence of fire-adapted plant species in the Grandfather Ranger District suggests a long history of lightning-ignited fires. Recent wildfire statistics found a tendency to a large number of lightning-ignitions and large areas burned in the Grandfather Ranger District, when compared to other parts of the southern Blue Ridge Mountains (Baker 2009).

The majority of lightning-ignited fires occurred after a high pressure system had dominated the region, followed by a cold front passing through in the days prior to ignition and then a high pressure system moving in after ignition. Of the 35 days from 1989 to 2009 that had lightning ignitions, high pressure before lightning ignitions occurred 23 times, during the day of ignition 18 times and post ignition 25 times. Frontal movement through the study area occurred 24 times in days before ignition and 6 times on the day of ignition. These cold fronts brought little precipitation but apparently generated small thunderstorm cells that produced lightning. For lightning-ignitions that were not associated with these dry cold fronts, small convective storms were likely generated through heating of the mountain slopes on days dominated by high pressure.

Synoptic classification illustrated the importance of warm air aloft, as a ridge centered over the Gulf of Mexico extended up into western North Carolina. While lightning



ignitions do not occur often, the majority of them occur during the summer with ridging from the south. Forest managers should be aware of the possibility of lightning ignition when warm air aloft is ridging into the region and is coupled with a dry cold front or isolated thunderstorms during periods of high pressure.

Lightning ignitions generally occurred under moderate drought. However, when I aggregated the six months prior to each lightning-ignition, the majority of lightning-ignitions occurred in near-normal moisture conditions. This finding suggests that shorter temporal scale drought variability influenced lightning ignitions more than the longer temporal scale drought variability. This contrasts with temporal-scale variability found in other moist environments, e.g., the Florida Everglades (Beckage and Platt 2003), and suggests that fuels in the Appalachians do not need to dry for a year before lightning ignition is viable as reported by Mitchener and Parker (2005).

Slightly more acres burned under near-normal conditions than under severe drought. When the region falls into severe drought, few storms occur and thus few sources exist for lightning-ignition. Near-normal conditions have moister fuels, and with more ignitions those fuels are more likely to be ignited and smolder under incomplete combustion (Pyne, Andrews, and Laven 1996). When circumstances then enable the fuels to dry sufficiently, a fire may grow to large size, as seen during the summer of 2007, when lightning-ignited fires burned 2,361.34 hectares in the Grandfather Ranger District under moderate drought conditions.

The peak in lightning-ignitions in June from 1989-2009, not in May as suggested by Frost (1998) may be attributed to the fact that June had some 40,000 more lightning strikes

than May. Additionally, daily temperatures were warmer allowing for faster drying of fuels. However July witnessed an additional 40,000 more lightning strikes than June and had less lightning ignitions, perhaps reflecting to the humidity and closed forest canopy of summer. Additionally, synoptic type 11 occurred the least often in July, and was the most associated with lightning-ignition. Although July received the most lightning strikes, June had the most lightning ignitions. This disparity suggests the conditions that favor ignition, rather than the increase in ignition source, are more important when a certain threshold of ignition are available.

Ridging aloft and frontal movement through the study area prior to ignition occurred on June 8, 2007. That day two lightning-ignitions occurred. These ignitions led to the largest lightning-ignited fires during the study time period. The study area was experiencing moderate drought conditions. Little rain fell during the week before ignition. The day of ignition, winds were light and temperatures were moderate; this fits the example we see for most events of lightning-ignited fires.

The two synoptic types found to favor lightning ignition occurred in every month throughout the year. Synoptic type 11 occurred most often in September and October accounting for 18% of the days in those months. It was also dominant in April, May, and June accounted for 14-15% of the days, respectfully. Synoptic type 4 had less variability in its monthly frequency occurring 14% of the days in summer months and dipping to 9% of the days in February. The synoptic types that occurred the least often and had low or no occurrences during June were not associated with any lightning-ignitions. This included synoptic types reflecting troughs and one with ridging. Although synoptic type 12 represents

a ridge of warm area extending into the region centered over the Gulf of Mexico, it primarily occurs in December, February, and March when fuels may be covered with snow and lightning strikes are few.

*Hudsonia montana* populations exist in this moist environment with few lightning-ignitions over the past 20 years. Their decline is partly a consequence of fire suppression and trampling (Gross et al. 1998). Gross et al. (1998) recommended burning on a 6-8 year cycle which corresponds with the 5-10 year lightning-ignition cycle that has been suggested to characterize *Hudsonia montana* habitats (Frantz and Sutter, 1987). However, using the twenty year record of lightning-ignitions and *Hudsonia montana*, I found that not all locations were burned during the time frame, indicating that lightning-ignited fires do not currently occur at the intervals needed to maintain a viable population of *Hudsonia montana*. Most fires are burn relatively small areas and are probably the main reason why lightning-ignitions did not affect all populations of *Hudsonia montana*, and are so infrequently associated with those populations. The shrub were aggregated across all scales across the Grandfather Ranger District. Although lightning-ignition locations did not burn many *Hudsonia montana* locations this does not change the importance of lightning-ignitions for this plant. Likely, landscape fragmentation and fire suppression halt the spread of fire preventing the fire from lightning-ignitions from reaching the plants. Additionally, changes in fuel conditions are different from the past. Historical conditions in the southern Appalachians included open-canopy woodlands and prairies with herbaceous understories (Harrod et al. 2000; Ware et al. 1993). This may have fostered conditions allowing for fires to ignite easier with faster spread allowing for larger sized fires (Barden and Woods, 1973;

Harmon et al. 1983; Harrod et al. 2000). Thus allowing for infrequent lightning-ignitions to burn across the area and affect *Hudsonia montana* populations.

In conclusion, a twenty year sample of the synoptic conditions for the Grandfather Ranger District provided insights into the lightning-ignitions and atmospheric circulation patterns. High pressure occurred before, during, and after most of the events. Frontal movement through the area before ignition also preceded the majority of events. Lightning-ignition caused fires to burn on almost a yearly basis. There were only a few gaps in the temporal scale in which lightning-ignitions did not occur every year. This is below the suggested fire return interval, however, most of the lightning-ignited fires burned small amounts of land. Large lightning-ignited fires (>100 acres) occurred in 1998, 1999, and 2007. These large fires fall under the 6-8 year fire cycle that Gross et al. (1998) suggested is needed for *Hudsonia montana* to survive with population growth, however lightning ignitions burned in multiple locations with some not impacting *Hudsonia montana* populations. Managers will have to utilize prescribed burning in order to ensure *Hudsonia montana* populations are burned as frequently as ecologically required.

## 5.1 Limitations

Limitations to this study include the sample size and temporal scale. Lightning-ignited fires only totaled 39 events over the twenty year period. More events would allow for a more robust analysis. Additionally the limitation of twenty years does not allow for an in-depth analysis of the natural fire regime. Environmental variables used in the study also

presented limitations. Three different weather stations were required to factor in the wind and humidity for the study area. RAWS data was only available for after 2003.

Accuracy of recorded time and location are assumptions in this study. NIFMID fire ignitions are listed by degree, minute, second giving them roughly 10m accuracy. The data were recorded by forest rangers and human error is present. Ignition day and observed date of ignition were often very different, sometimes off by months. I utilized the observed time as it more accurately aligned with the extinction of the wildfires.

NLDN data is precise only to 0.5km so to minimize the error associated with NLDN mean detection errors, a 1km buffer was added to the park boundary. NARR data are only accurate to 32km. This is the best precision available for 500mb data. Thus limited assumptions are available at suggesting a change in the fire regime. While these limitations are present, this project will still provide information on lightning-ignited fires in the Grandfather Ranger District.

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