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Climate Variation within the Range of Longleaf Pine Forests during the Past Century

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Abstract: Longleaf pine (*Pinus palustris* Mill.) forests are an important ecosystem in the southeastern United States, with high economic and ecological value. It is necessary to study the climate variation within its range in order to understand the effects of climate change on longleaf pine forests. In this study, past climate data at three sites within the longleaf pine range were used to detect climate variation. The results indicated no dramatic change in solar radiation at the three sites. There were high variations in annual air temperature at the three sites. The trend of annual air temperature change depended on the time scale and start/end time. The annual air temperature generally increased from the 1960s at three sites. However, from 1901 to 2020, the trend of increasing annual air temperature was not consistent. The annual precipitation and the standardized precipitation-evapotranspiration index were relatively stable, with variation at the three sites. The regimes of annual and monthly air temperature and precipitation were not shifted based on the analysis of multiscale entropy. The climate niche of longleaf pine forests based on long-term climate data was broader than previously found. These results may be helpful to understand the interactions of the atmosphere and growth of longleaf pine forest and develop relevant management strategies.

Keywords: air temperature; drought; multiscale; precipitation; regime shift; solar radiation

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1. Introduction

Global warming is estimated to increase air temperature by 1.2~3.0 °C around 2050 based on different greenhouse gas emission scenarios [1]. Since the climate is the primary limiting factor for species' range limits [2,3], global and regional climate change can affect plant growth and cause a shift in the growing region, especially for narrowly distributed plant species. Moreover, vegetation and the atmosphere interact with each other [4]. Vegetation can affect chemical composition (e.g., CO_2 emission) and physical properties (e.g., air temperature and humidity) of the atmosphere through physiological activities. In response to changing conditions, plants can migrate to new suitable habitats, adapt to the new climates, or disappear locally. However, due to the complicated interactions with local topography, soil types, and species' biological characteristics, some plant species, such as trees, have remained static for a long time [5], while others have moved in the opposite direction than expected (typically poleward/upslope) [6]. For example, the forests of northern Canada did not show boundary expansion from satellite images despite an increase of 0.6 °C in the regional air temperature [7]. Thus, it is essential to specifically evaluate regional climate change and species adaptation in each region, especially for those with a high economic value [8].

Longleaf pine (*Pinus palustris* Mill.) forest is an important ecosystem in the southeastern United States due to its economic (e.g., timber and related forest products) and ecological value (e.g., excellent wildlife habitat) [9,10]. Its understory is characterized by a high biodiversity with an abundance of endemic plant and animal species. The longleaf

pine ecosystem once covered a broad area of about 37 million ha along the coast from southeastern Virginia to eastern Texas across many diverse landscapes [11]. After European settlement, the area of longleaf pine forests declined dramatically. Following fire suppression, timber harvesting, and agricultural development, only about 1.02 million ha of longleaf pine forests remained in 1995 based on forest inventory and analysis data [12]. The remaining forests are fragmented, and the longleaf pine ecosystem is listed as an endangered ecosystem [13]. Government agencies and private landowners have renewed interest in restoring longleaf pine forests for their high-value wood products, pine straw production, wildlife and biodiversity benefits, and carbon sequestration. In addition, increasing the longleaf pine forest area has been proposed to mitigate climate change in southern forests [14].

There are close relationships between climate and factors of longleaf pine success. Many studies have indicated strong correlations between climate variables and longleaf pine growth, primarily based on tree ring growth data [15–17]. However, the limitation of this approach is that trees might have limited radial ring growth in order to achieve higher reproductive rates (e.g., great cone production). According to [18], longleaf pine trees grow in warm, wet temperate climates characterized by hot summers and mild winters. Their climate niche includes annual mean air temperatures ranging from 16 °C to 23 °C and annual precipitation from 1090 mm to 1750 mm. The physiological and reproductive activities of longleaf pine are also related to the climate, such as its temporal pattern of pollen shedding [19–21] and sporadic seed production [22–24]. Management practices for longleaf pine forests, such as prescribed fires, can change atmospheric composition (e.g., releasing aerosols, CO_2, and others) [25]. However, current studies with a regional focus on climate within the range of longleaf pine forests are lacking. There are many uncertainties in climate projections, such as errors and bias with global circulation models and different dynamics, physics, and simulation resolutions. These can cause the models' projected climate to vary significantly at regional scales [26]. Given that average air temperatures in this region are expected to increase by 3–5 °C by the end of the century [27], studies on the recent and previous climate variation in this region and possible longleaf pine adaptation abilities are needed.

This study aims to use long-term climate data to characterize climate variation within the range of longleaf pine forests. The climate variables include solar radiation, air temperature, precipitation, and drought. The specific objectives include (i) is there a general pattern of climate change in this region? (i.e., have air temperature, precipitation, or drought increased/decreased?); (ii) what are the climate thresholds that longleaf pine forests already experienced?; and (iii) has the climate regime in the range of longleaf pine been shifted? These results may provide a clear picture of regional climate change, the tolerance of longleaf pine forests, and implications for adaption strategies for the persistence and restoration of this endangered ecosystem.

2. Materials and Methods

2.1. Area and Sites

The historical range of longleaf pine is shown in Figure 1. However, the current distribution area is much smaller and more fragmented. We choose Bladen Lake State Forest (NC) as the northeastern point, Kisatchie National Forest (LA) as the western point, and Escambia Experimental Forest (AL) as the southern center, which is close to the northern boundary of the Gulf of Mexico. The map distances from Bladen Lake State Forest to Escambia Experimental Forest and Kisatchie National Forest are approximately 1000 km and 1330 km, respectively. We used the climate data of these three sites to represent the climate variation within the range of longleaf pine forests.

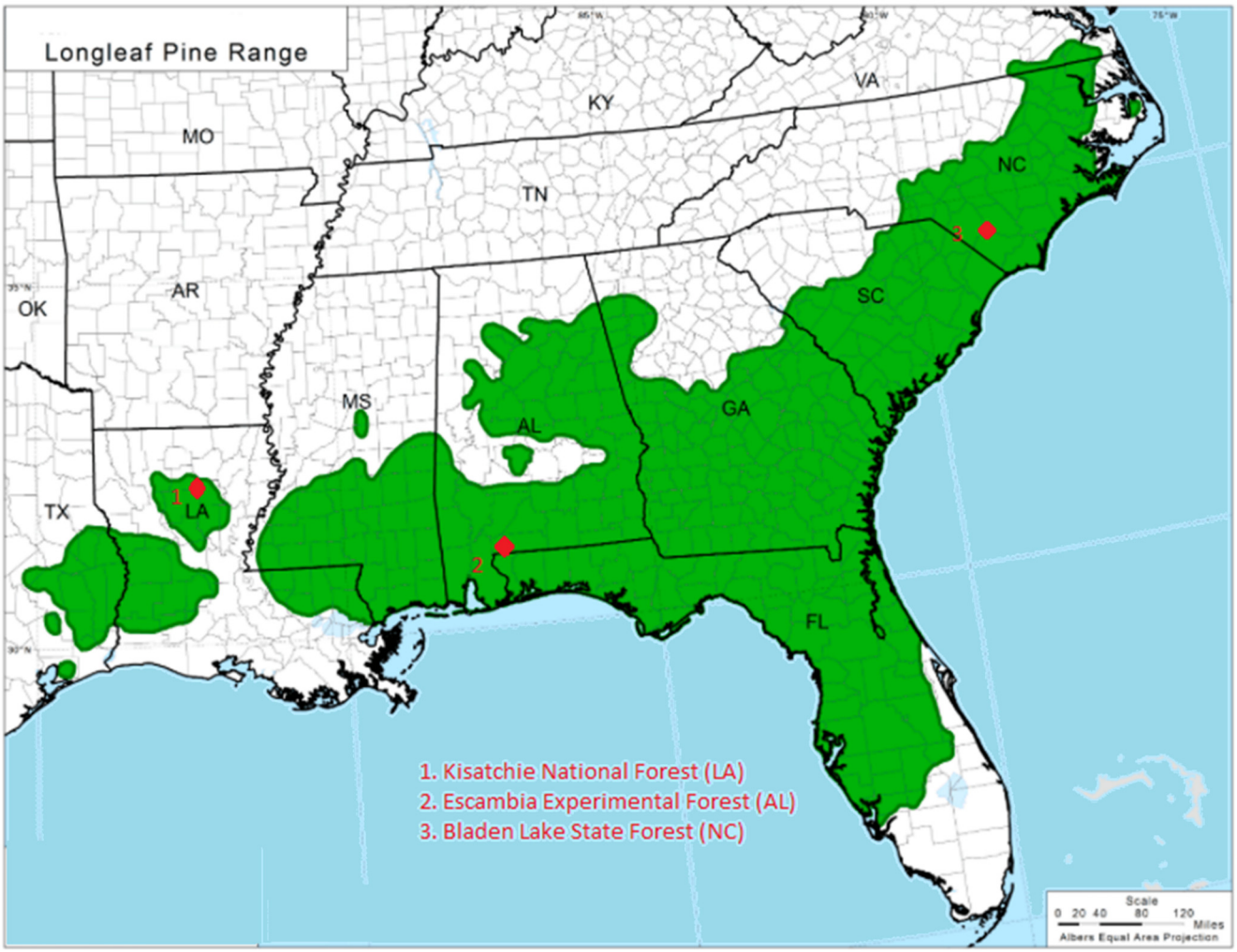

Figure 1. The historical range of longleaf pine forests and locations of three study sites (the original map is from USDA).

2.2. Climate Data

We obtained solar radiation information from 1998 to 2020 from the national solar radiation database (NSRDB). The NSRDB is a serially complete collection of half-hourly values of the three most common measurements of solar radiation—diffuse horizontal irradiance (DHI), direct normal irradiance (DNI), and global horizontal irradiance (GHI) (https://nsrdb.nrel.gov/, accessed on 12 March 2022). GHI and DHI are based on a plane horizontal to the ground, while DNI is for a plane perpendicular to direct sunlight. These indices can describe the amount of radiation received at the land surface per unit on direct and indirect paths from the Sun. The current NSRDB is modeled using multi-channel measurements from geostationary satellites. A sufficient number of locations and temporal and spatial scales were used to accurately represent regional solar radiation for each area of 4 km × 4 km. Using the NSRDB data, it is possible to estimate the amount of solar energy that has been historically available at a given time and location, as well as its trend.

Since the records of ground weather observation within the region of longleaf pine are usually short and incomplete (e.g., from mechanical failure), the climate data for these three sites were obtained from the Climate Research Unit (CRU) (University of East Anglia, Norwich, UK). High-resolution gridded (0.5° × 0.5°) data of monthly air temperature and precipitation from 1901 to 2020 were used in this study. The standardized precipitation–evapotranspiration index (SPEI, from 1901 to 2018) is designed to consider both precipitation and potential evapotranspiration in determining drought. These data

were drawn directly from the CRU Time Series (TS) 4.05 dataset [28]. Previous studies indicated that CRU TS data could represent local observation data [5]. In this study, we found that annual air temperature and precipitation from CRU TS were correlated with the data from the local weather station near Escambia Experimental Forest (Figure 2).

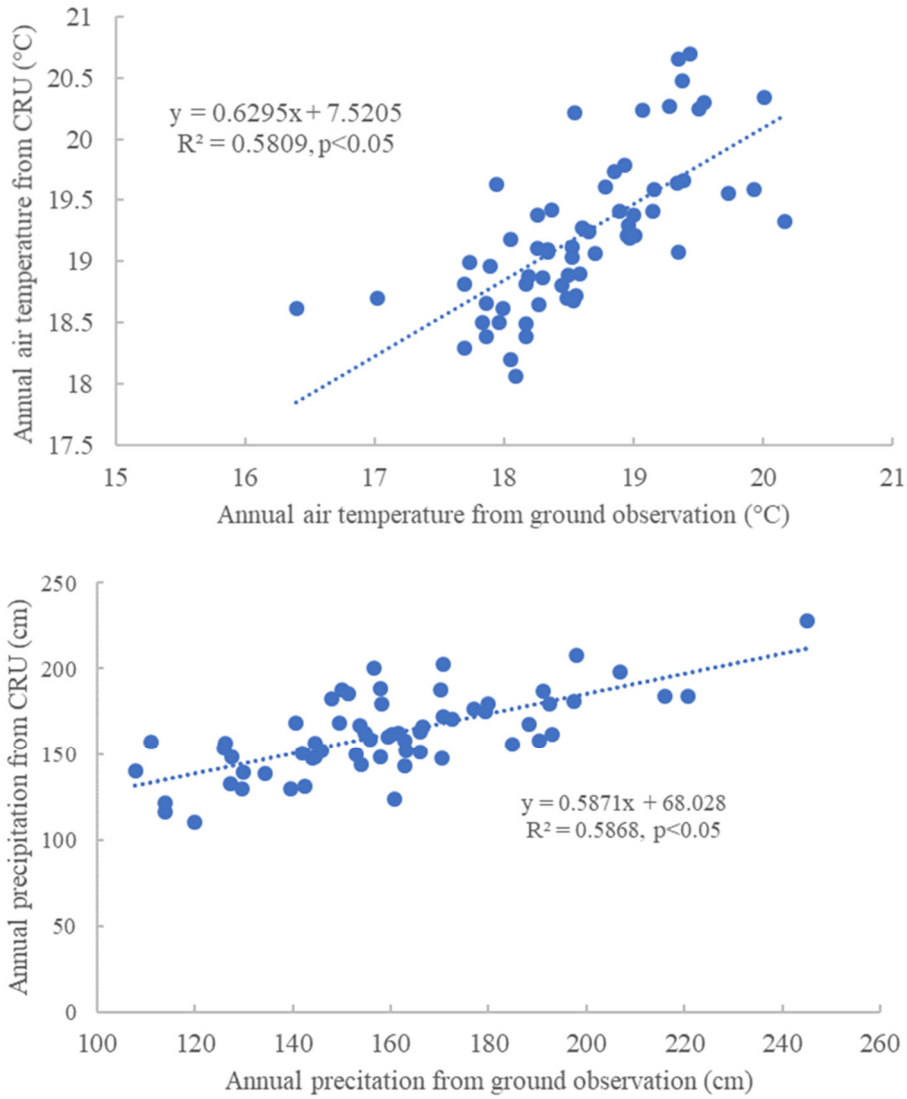

Figure 2. The correlations in the data from the local weather station at Escambia Experimental.

2.3. Methods of Data Analysis

The sliding window approach has been broadly applied in climate data analysis. Here, a continuous window with a fixed size of 10 years was used because trees usually have a long lifetime. The average climate variable (e.g., annual air temperature, precipitation, and SPEI) within the window was used to represent the climate during these 10 years. The sliding window was applied continuously from 1901 until 2011 (or 2009 for SPEI).

Multiscale entropy is a method for analyzing the complexity of nonlinear and non-stationary signals in finite-length time series. It consists of two portions: time scale and the entropy for each time scale. The varied time scales are similar to sliding windows. The entropy is defined as Shannon entropy:

$$H_\varepsilon\ (x) = -\Sigma p_\varepsilon(x)\log_{10}p_\varepsilon(x),$$

$$p_\varepsilon(x) = 100 \times x_i/\Sigma x_i$$

Here, $H_\varepsilon(x)$ represents the entropy of a climate variable (air temperature or precipitation) along the temporal length scale ε. Higher values of $H_\varepsilon(x)$ represent higher temporal heterogeneity of the climate variable at the time scale of ε years (or months). $p_\varepsilon(x)$ represents the percentage of a climate variable (x_i) at the ith year measured in the time scale of ε units. The details can be found in [22]. In this study, the entropy of air temperature or precipitation was estimated at different time scales, such as 1, 2, 3, 4, 5, 10, 20, 30, and 40 years and also in 1, 2, 3, and 6 months. This method was used to detect regime shifts in the climate variables [29].

Spearman correlation analysis between the time and climate variables (e.g., annual temperature and total precipitation) was conducted by SAS software (SAS Institute Inc., Cary, NC, USA). Statistical significance was considered at $p < 0.05$.

3. Results

3.1. Solar Radiation

There was no trend of increasing/decreasing radiation in the three indices (DHI, DNI, GHI) from 1998 to 2020 at the three sites (Figure 3). The solar radiation dynamics were very similar at these sites. DHI was stable around the average of 70 w/m^2 per half-hour. Although there were slight variations in DNI and GHI in 2010 and 2016, both were largely stable around the values of 212 and 196 w/m^2 per half-hour, respectively.

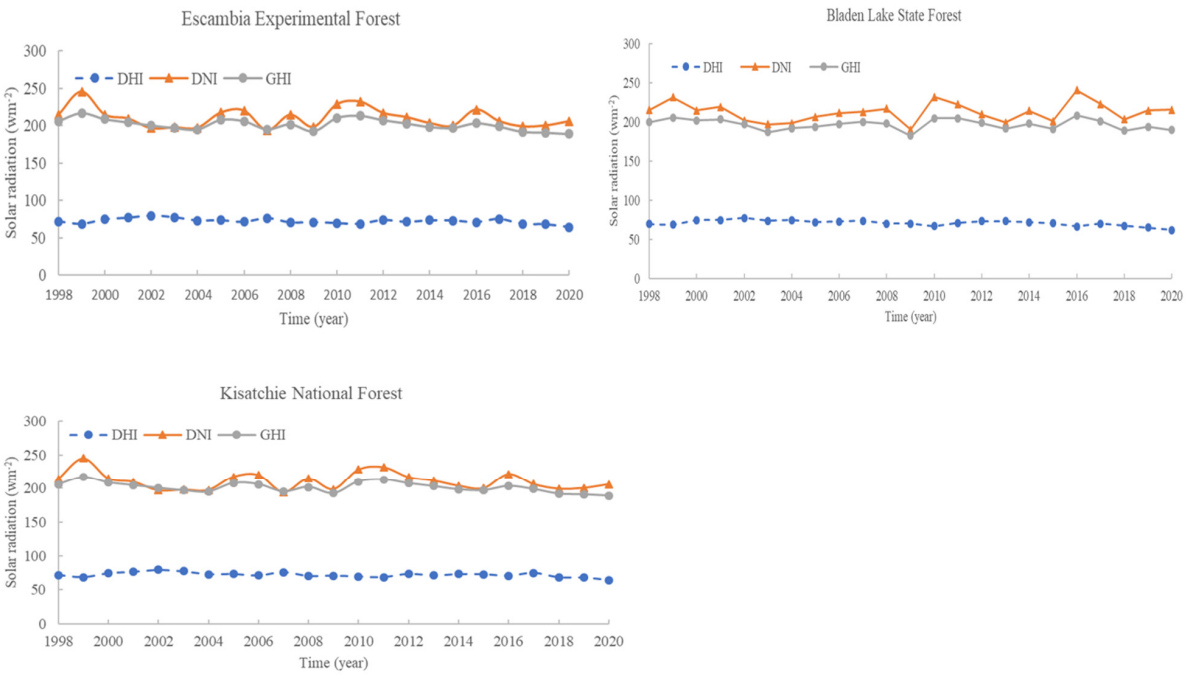

Figure 3. The solar radiation dynamics of the three indices (DHI, DNI, GHI) from 1998 to 2020 at the three sites.

3.2. Annual and Monthly Air Temperature

There were high variations in the annual air temperature at the three sites, and the trend was dependent on the time scale and start/end time (Figure 4). The annual air temperature increased from the 1960s at three sites. However, starting from 1901, this trend did not exist because high air temperatures also occurred around the 1920s. Based on the average annual air temperature of every 10 years, it was relatively warm during the 1920s, but the annual air temperature decreased rapidly in the 1950s. For Bladen Lake State Forest, the recent annual air temperatures were about 0.5 °C higher than in the 1920s. Kisatchie National Forest experienced the highest air temperatures among the three sites (Table 1), such as 21.2 °C for the annual air temperature in the year 2016 and 29.8 °C for the monthly air temperature in August 2011. Bladen Lake Forest experienced the lowest air

temperatures, such as 15.1 °C for the annual air temperature in the year 1904 and 0.2 °C for the monthly air temperature in January 1940.

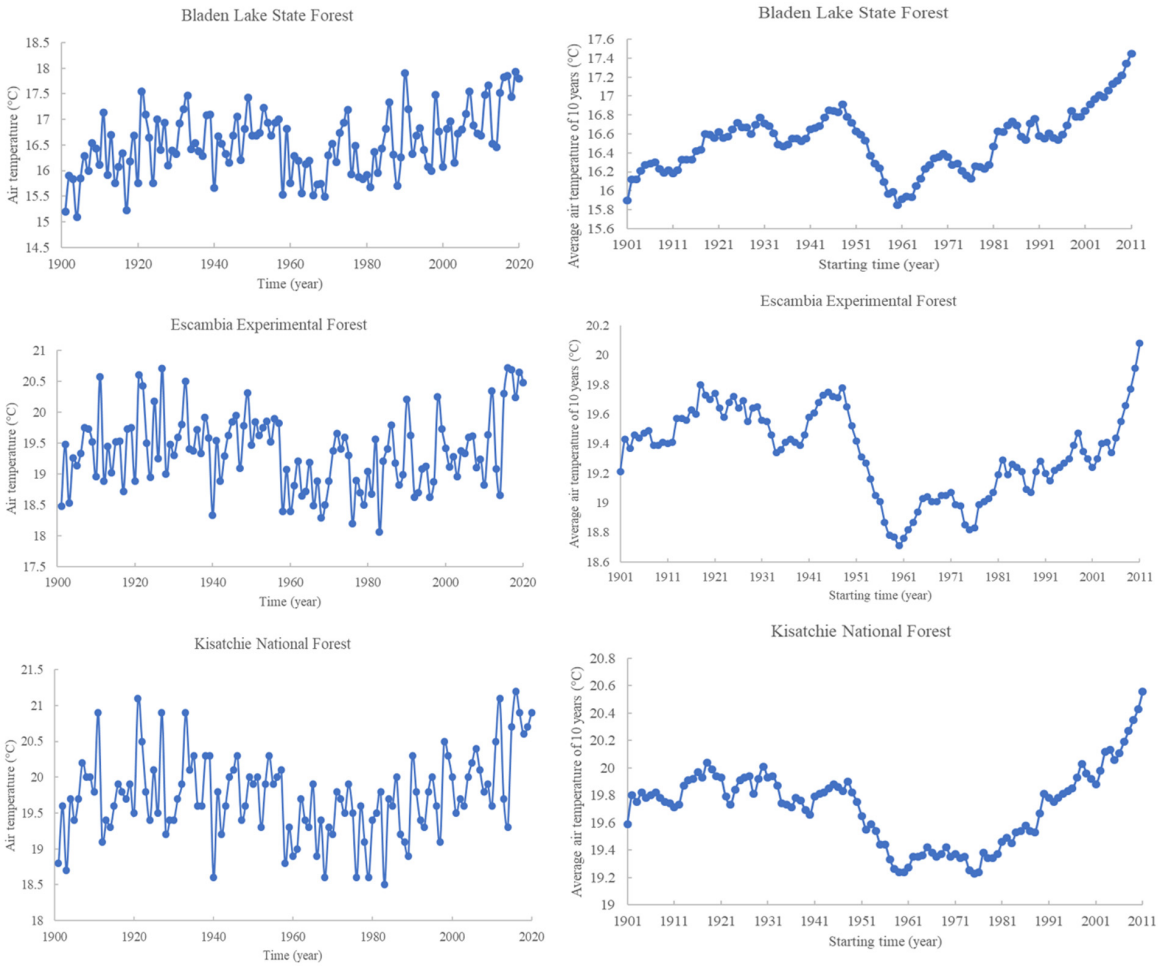

Figure 4. The variation in annual air temperature and the average of every 10 years at the 3 sites from 1901 to 2020.

Table 1. The maximum and minimum air temperatures and precipitations occurred at the three sites from 1901 to 2020.

	Bladen Lake State Forest	Escambia Experimental Forest	Kisatchie National Forest
Maximum annual air temperature (°C)	17.9	20.7	21.2
Minimum annual air temperature (°C)	15.1	18.1	18.5
Maximum monthly air temperature (°C)	29.1	29.3	29.8
Minimum monthly air temperature (°C)	0.2	3.3	4.0
Maximum annual precipitation (mm)	1591.6	2280	1942.8
Minimum annual precipitation (mm)	848.8	876	909.6
Maximum monthly precipitation (mm)	322.9	455.9	421.1
Minimum monthly precipitation (mm)	0	0.7	0.6

The entropy dynamics of the air temperature across multiple years were exactly the same at the three sites (Figure 5). The regime of annual air temperature was not shifted at the yearly scale. There existed a slight difference in the entropy at the multi-month scale (Table 2). This indicated variations in monthly air temperature at the three sites, but the regime of monthly air temperature dynamics did not change because their entropy dynamics were very similar.

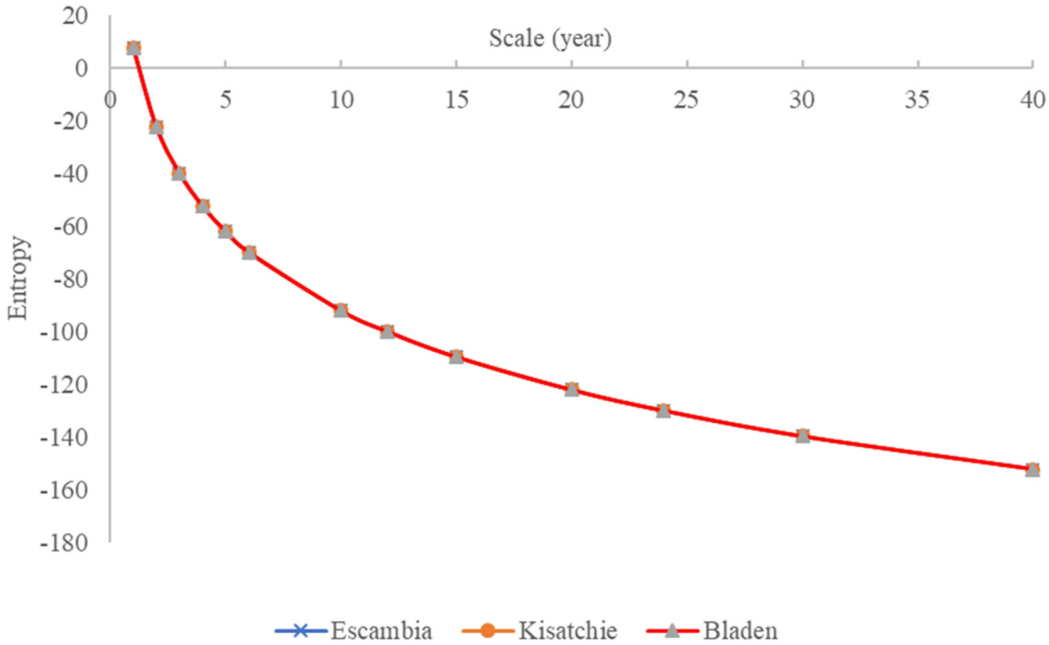

Figure 5. The entropy dynamics of air temperature at multi-year at the three sites.

Table 2. The entropy at the monthly scale for air temperature and precipitation from 1901 to 2020.

Scale (Month)		Bladen Lake State Forest	Escambia Experimental Forest	Kisatchie National Forest
Air temperature	1	110.8	113.1	113.3
	2	81.3	83.4	83.4
	3	64.3	66.1	66.4
	6	37.7	37.8	37.8
Precipitation	1	110.2	110.1	110.1
	2	82.6	82.6	82.6
	3	65.6	66.0	66.2
	6	37.3	37.1	37.0

3.3. Annual and Monthly Precipitation

The annual precipitation was relatively stable at the three sites (Figure 6). Based on the average precipitation of every 10 years, relatively high annual precipitation occurred in the 1920s, 1940s, and the 1960s, though there were slight differences among the three sites. The average annual precipitation was about 1200 mm at Bladen Lake State Forest, 1564.4 mm at Escambia Experimental Forest, and 1455.9 mm at Kisatchie National Forest. Escambia Experimental Forest had the highest annual and monthly precipitation (Table 1): 2280 mm in 1975 and 455.9 mm in June of 1916, respectively. Bladen Lake State Forest had the lowest precipitation value of 848.8 mm in the year 2007 (lowest annual) and 0 mm in October of 2000 (lowest monthly).

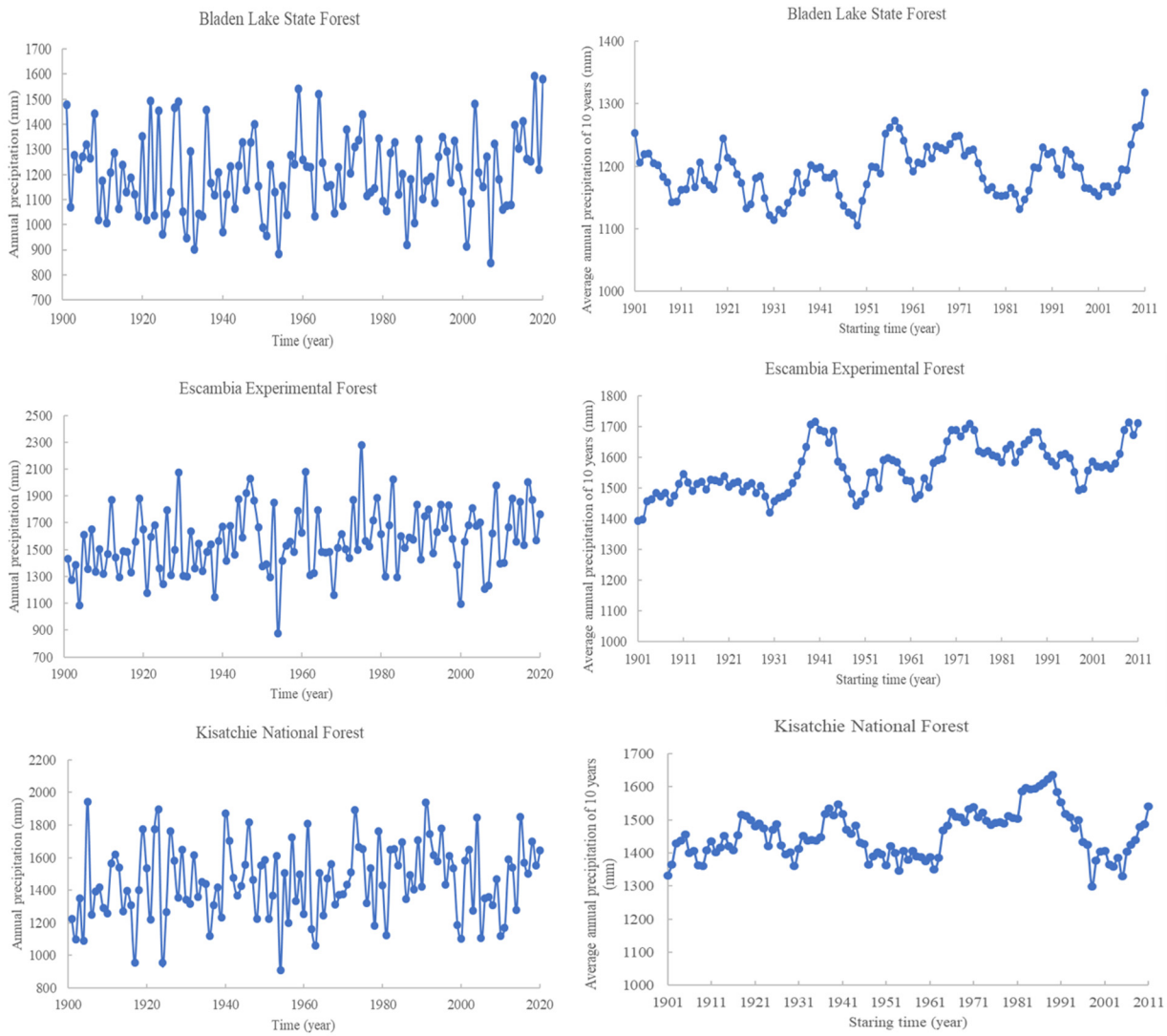

Figure 6. The dynamics of annual precipitation and the average of every 10 years at the 3 sites from 1901 to 2020.

The entropy dynamics of annual precipitation across multiple years were exactly the same at the three sites (Figure 7). The regime of yearly air temperature was not shifted at the yearly scale. There existed a slight difference in the entropy at the multiple-month scale (Table 2). Although the monthly precipitation was different among the three sites, the regime of monthly precipitation dynamics did not change because their entropy dynamics were very similar.

3.4. Drought

SPEI values fluctuated from 1901 to 2018, but overall, the average annual SPEI was close to 0 at each site (Figure 8). It was the same for the average monthly SPEI. There was no trend of increasing or decreasing SPEI at these sites during the past century. Based on the average SPEI of 10 years, there was a relatively dry time during 1920~1950 and a wet time during 1970~1990. The highest annual SPEI value was 0.7 at Escambia Experimental Forest (Table 3). The highest monthly SPEI was 2.7 at Kisatchie National Forest, while the lowest annual and monthly SPEI (−2.2 and −2.3) were at Bladen Lake State Forest.

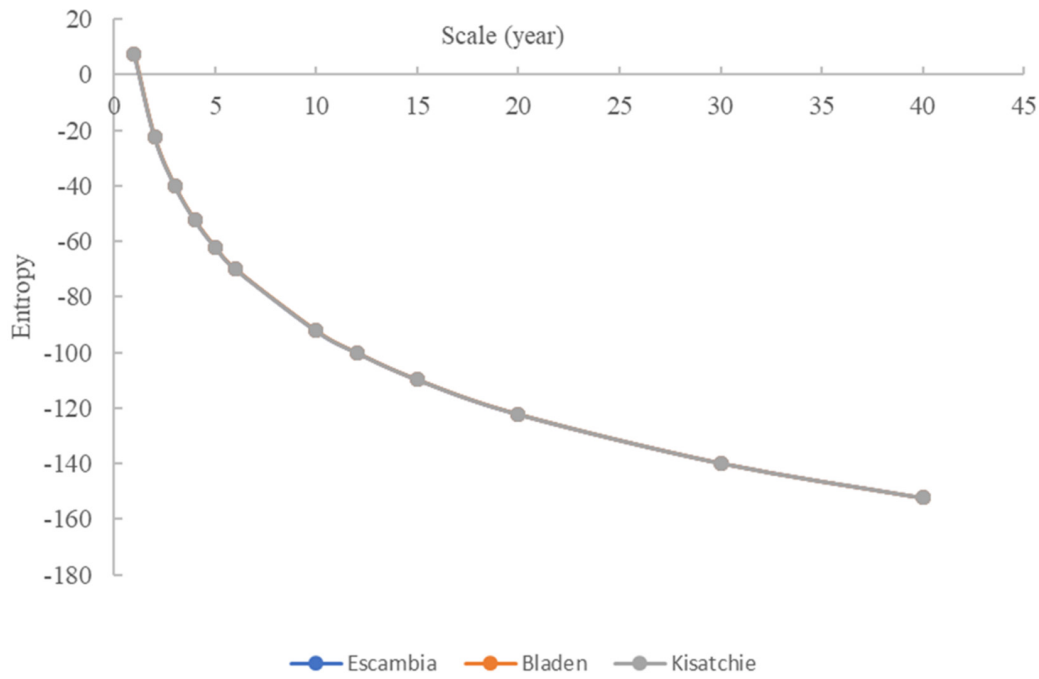

Figure 7. The entropy dynamics of annual precipitation at multi-year at the three sites.

Table 3. The maximum and minimum values of SPEI at three sites.

	Bladen Lake State Forest	Escambia Experimental Forest	Kisatchie National Forest
Maximum annual SPEI	0.6	0.9	0.8
Minimum annual SPEI	−2.2	−1.0	−0.8
Maximum monthly SPEI	2.5	2.6	2.7
Minimum monthly SPEI	−2.3	−2.4	−2.8

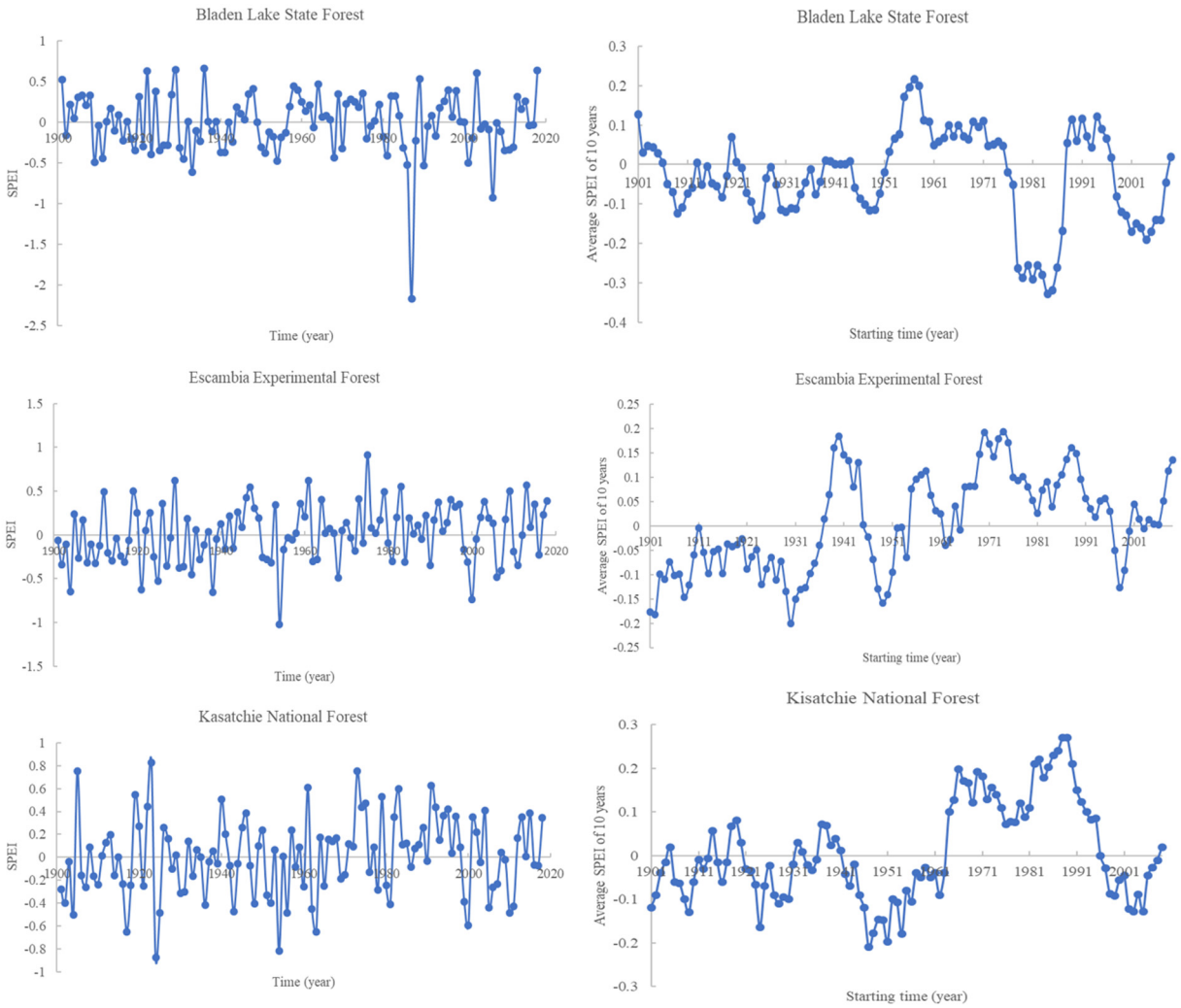

Figure 8. The dynamics of annual SPEI and the average of every 10 years at the 3 sites from 1901 to 2018.

4. Discussion

Longleaf pine forests are a critically important ecosystem in the southeastern USA. Most previous studies connecting climate to the longleaf pine forest emphasized the possible effect of assumed climate change [30]. Limited studies have been conducted on climate variation and regime shifts within the range of longleaf pine forests due to the short time series of climate data. We used long-term CRU data to analyze climate variation and regime shifts for important variables in the longleaf pine forests over the past century. Further considerations related to tree responses and management practices (e.g., prescribed fires) may provide implications for their climatic adaptation.

The total radiation at the unit surface was relatively stable with slight fluctuations. The fluctuations occurred at three sites in the same years (e.g., 1999, 2005, 2008, 2010, and 2016). These changes might be related to solar activity (e.g., the Sun's solar flares cycle of roughly 11 years). Overall, there was no trend of consistently increasing or decreasing solar radiation from 1998 to 2020. However, local land-use change might change the albedo and alter energy paths. Prescribed burning may also affect local albedo on a short time scale.

It appeared that the average air temperature increased from 1901 to 1960 and from the 1960s onwards at three sites. However, if we consider the entire time frame from 1901 to 2020, this trend is not apparent. Thus, if we extend the time scales slightly, the claimed trend may not exist. This follows the previous finding that different time scales may affect the patterns of annual air temperature [24]. The cooling in the mid-20th century

is considered from the effect of atmospheric aerosols due to anthropogenic emissions (primarily from the burning of fossil fuels). The aerosol emissions were later controlled by government intervention [31]. However, the specific mechanisms of increasing/decreasing air temperature might be quite different here. In longleaf pine forest management, for example, aerosol emissions from prescribed burning are unavoidable and could change the chemical composition of the local atmosphere [25].

Longleaf pine trees have endured annual air temperatures from 15.1 °C to 21.2 °C based on these three sites. However, if the monthly air temperature is considered, longleaf pines have endured 0.2 °C to 29.8 °C. Longleaf pine also tolerated annual precipitation from 849 mm to 2280 mm, and monthly precipitation from 0 mm to 455 mm. However, temperature and precipitation varied between sites, and it is not yet fully understood how genetic adaptability to climate extremes varies spatially across the longleaf pine range. This climate range is different from one study [18], which found that annual air temperature was from 16 °C to 23 °C and annual precipitation was from 1090 mm to 1750 mm. It is not clear how the range was estimated at that time. We did not include the possible sites in southern Florida in this study. For this reason, the upper limit of annual air temperature is likely low. Our analysis may produce different climate niches for longleaf pine trees than other methods because we have used climate data for over a hundred years.

High air temperatures affect plant growth because the plants need to produce heat-shock proteins to refold denatured proteins and remove unwanted denatured proteins [32,33]. Under high temperatures, the plants are forced to use more resources for homeostasis at an accelerated respiratory rate for repairing heat damage. Thus, less energy is available for plant growth [34]. One study found that older-aged trees can facilitate seedlings' survival and development by providing shelter from harsh climate [35]. At these sites, the annual precipitation was stable. Many studies indicate that precipitation is correlated with the growth of longleaf pine trees, although the amount of precipitation in each season may be different among sites [16,36].

The regime of annual and monthly air temperature and precipitation was not shifted. Still, there were variations in the monthly air temperature and precipitation, which means seasonal climate variation did occur. This is consistent with the fact that hurricanes occasionally bring heavy precipitation. The climate regime is highly correlated to the cone production of longleaf pine [22]. Therefore, this region can still serve as a suitable area for the longleaf pine forests, where prescribed burning is necessary. However, strategic foresight needs to be developed for the climate and prescribed burning based on climate-ecological research on longleaf pine [37].

Both temporally varied drought and flooding occurred at these sites, but there was no general trend of increase or decrease in drought and wet (e.g., flooding) conditions. Drought can be an essential climate factor not only because it affects soil and water but also because it links to the vapor pressure deficit in the atmosphere. It has been indicated that the percentage of areas in the southeastern USA experiencing drought has increased since the 1970s [38], but this may be partially attributed to more local water use for agricultural development. However, if the analysis started from 1901, this trend may not be found. Although drought may kill the seedlings of longleaf pine [18], mature trees can usually tolerate drought due to their extensive root systems [39]. Higher soil water, but not saturated soil water, can help longleaf pine growth after prescribed fires [36]. Prescribed burning with drought conditions may affect the development of longleaf pine trees because cambium necrosis is caused by heat conduction through the bark, and xylem cavitation can occur when the xylem water potential decreases when heat from fire decreases sap surface tension [40]. Hurricanes and tropical storms can bring significant precipitation and cause flooding in some areas, but in 14 Coupled Model Intercomparison Project phase 5 models, tropical storm activity found no robust changes [41].

5. Conclusions

Climate data from the past century are helpful to provide multiscale climate variation and regime information. It appears that the climate within the range of longleaf pine forests

has had no clear trend of change in the past century, though air temperature has been increasing since the 1960s, and precipitation and drought have variation at different periods. The climate niche of longleaf pine based on the long-term climate data is much broader than the previously reported. There are monthly and seasonal variations, but yearly and monthly climate regimes have not been shifted. It is not clear whether longleaf pine forests can stabilize climate within their range to some extent. Longleaf pine forests have high endurance and adaptation to local conditions given their wide climate gradient along the coastal plain. Managing longleaf pine forests may increase resiliency under the uncertainty of the future climate. Yet, prescribed burning in longleaf pine forest areas could affect atmospheric properties. Further research should be conducted to study the interactions between climate and longleaf pine forests in the southeastern region, such as on a daily scale. A similar approach can also be used to detect climate variation in other areas (e.g., cities and urbanization areas).

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