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Analysis of forest fire patterns and their relationship with climate variables in Alberta's natural subregions

Hatef Dastour [a], M. Razu Ahmed [b], Quazi K. Hassan [a,*]

[a] Department of Geomatics Engineering, University of Calgary, 2500 University Drive NW, Calgary, AB T2N 1N4, Canada
[b] Western Arctic Centre for Geomatics, Government of Northwest Territories, Inuvik, NT X0E 0T0, Canada

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ABSTRACT

Forest fires are significant ecological and environmental phenomena that can be influenced by various climatic factors. This study used fire point records from the Canadian National Fire Database (CNFDB) and interpolated climate data, which include the minimum and maximum air temperature, the average relative humidity, and the precipitation for each subregion of Alberta, Canada, to analyze the patterns and relationships of forest fires and climate variables using trend analysis and anomaly detection methods. The trend analysis was based on the Mann-Kendall test and Sen's slope, which were used to detect the presence and magnitude of monotonic trends in the monthly aggregated data from 1955 to 2022. The anomaly detection is based on the RobustSTL method, which was used to decompose the monthly aggregated data into seasonal, trend, and remainder components, and to identify the periods of significantly high or low values for each component. Most subregions showed a significant increase in temperature and a decrease in humidity, indicating a warming and drying trend due to climate change. Precipitation change was variable across subregions. Human-caused or prescribed forest fires increased significantly in Central Mixedwood, Dry Mixedwood, Lower Foothills, Montane, and Upper Foothills, while lightning-caused forest fires had mixed trends in Dry Mixedwood, Upper Foothills, Central Mixedwood, and Lower Boreal Highlands. The fire occurrence and source were affected by the climate variables in different ways across subregions. The fire occurrence in the Athabasca Plain subregion changed with the air temperature. It was low when the temperature was significantly low, and it was high due to lightning when the temperature was significantly high. The Central Mixedwood subregion had three peaks of lightning-induced fires when the relative humidity was significantly low, and several peaks of fires from human activities and lightning when the air temperature was significantly high. The study also revealed some other interesting patterns and relationships between the climate and fire variables and the forest fire distribution in different subregions, which may help to understand and manage the climate and fire interactions and their implications for forest fire understanding and management in the context of climate change.

1. Introduction

Forest fires are crucial ecological phenomena that are influenced by various climatic factors such as temperature, humidity, and wind speed (Coogan et al., 2020; Flannigan et al., 2000; Hanes et al., 2019). Climate change, especially pervasive warming, and increased human activities in forests can alter fire weather conditions, fostering higher fire instances and prolonged seasons (Coogan et al., 2020; Flannigan et al., 2006). These changes pose substantial challenges to fire management agencies, requiring resources based on established knowledge and historical patterns (Flannigan et al., 2009b; Thompson and Calkin, 2011; Tymstra et al., 2020). Even a slight increase in fires beyond norms or a longer fire season can overwhelm existing resources, resulting in uncontrolled fires and greater damage (Bowman et al., 2020; Tedim et al., 2018; Vadrevu et al., 2023). Using trend analysis and anomaly detection methods, this study aims to analyze the patterns and relationships between forest fires and climate variables in different natural subregions of Alberta, Canada, and to identify the most vulnerable areas to forest fires and provide insights into the relationship between climate variables and forest fires in Alberta.

Canada is facing an increase in the frequency and extent of forest fires in recent decades, as well as significant changes in the timing and

* Corresponding author.
E-mail addresses: hatef.dastour@ucalgary.ca (H. Dastour), Razu_Ahmed@gov.nt.ca (M.R. Ahmed), qhassan@ucalgary.ca (Q.K. Hassan).

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duration of fire activity, due to climate change, human activities, and forest conditions (Ahmed and Hassan, 2023; Coogan et al., 2019; Drobyshev et al., 2017; Flannigan et al., 2009a, 2013; Hanes et al., 2019; Tymstra et al., 2020). These trends have implications for both forest ecosystems and human well-being and safety (Ahmed and Hassan, 2023). Fire weather is a pivotal determinant of forest fires within these ecosystems, whereby fuel moisture, a fundamental component, assumes a critical role (Abatzoglou and Kolden, 2013; Flannigan and Wotton, 2001; Jain et al., 2017; Littell et al., 2009). The moisture content of fuel varies across diverse ecoregions and subregions, influenced by factors such as forest type and corresponding climate conditions (Ahmed and Hassan, 2023; Hassan et al., 2021a; Podur and Martell, 2009; Schneider, 2013). An intricate interplay exists between forest ecosystems and climate change, with changes in climate exerting direct or indirect impacts on forest growth and productivity (Groffman et al., 2014). This phenomenon profoundly shapes tree species distribution, growth rates, and overall forest structure by influencing tree growth, reproduction, and mortality (Gebeyehu and Hirpo, 2019). In turn, local climate and weather patterns are reciprocally influenced by forests, contributing to atmospheric carbon dynamics, solar radiation interactions, ground cooling through evapotranspiration, and aerosol production affecting cloud formation (Arneth et al., 2010; Pielke Sr et al., 2011). This situation carries challenges for the allocation of fire suppression resources by fire management agencies, which may not be enough to cope with the increased fire activity and variability (Maike et al., 2023; Schneider, 2005; Stocks et al., 1989). Despite enhanced fire suppression strategies and resources, Canada has experienced larger areas being burned and more uncontrolled fires (Ahmed et al., 2020; Ahmed and Hassan, 2023; Hassan et al., 2021b). These trends are projected to extend throughout the country, with projections indicating warmer and drier spring and summer conditions, and shorter and milder winters (Flannigan et al., 2006; Tymstra et al., 2020).

Fire management agencies face significant challenges in allocating fire suppression resources due to the changing trends in forest fires (Maike et al., 2023; Schneider, 2005). These trends are driven by climate change, which affects fire weather patterns and increases the frequency and duration of fire seasons (Abram et al., 2021; Drobyshev et al., 2017; Duane et al., 2021; Mateus and Fernandes, 2014; Tymstra et al., 2020), and by human activities in forested areas (Flannigan et al., 2009a; Maike et al., 2023). The existing resource capacities, based on historical fire data and seasonal patterns, may be inadequate when the number of fires exceeds expectations or when the fire season extends beyond its usual timeframe in certain regions (Coogan et al., 2020; Stocks et al., 1989). This could result in a higher incidence of uncontrolled fires and potentially larger burned areas (Ahmed et al., 2020; Ahmed and Hassan, 2023; Hassan et al., 2021b).

Forest compositions, fire behaviors, and local warming characteristics vary across distinct subregions (Fons, 1946; Hassan et al., 2021a; Kitzberger et al., 2012; Lawes et al., 2011; Osunkoya et al., 2007; Sedano and Randerson, 2014; Stevens et al., 2020). These factors influence the initial ignition and fire propagation stages of forest fires (Fons, 1946; Kitzberger et al., 2012; Sedano and Randerson, 2014). Many forest fire-related studies in the literature focus on ecoregional or subregional characteristics, as they reflect the diversity of fire patterns and impacts. For example, some studies reported that western ecozones in Canada had the highest forest fire densities and the longest fire seasons during 1959–2018 (Ahmed and Hassan, 2023; Coogan et al., 2020), and that spatial metrics of fire size, shape, clustering, and orientation differed among Canadian ecozones (Parisien et al., 2006). Another study found variable rates of land surface temperature change within Alberta's subregions, which could affect the incidence, extent, and seasonality of forest fires (Hassan et al., 2021a).

The relationship between climate and forest fires is a complex and dynamic one that varies across different subregions of the world. Various studies have explored how climate variables such as temperature, precipitation, and wind speed affect the patterns, causes, impacts, and management of forest fires using different methods and data sources. For instance, (Lopes and Tenreiro Machado (2014) used a spatiotemporal data mining and geographic information system method to analyze the forest fire data of Alberta from 2006 to 2010 and to identify the spatiotemporal distribution patterns, hotspots, and clusters of forest fires. They also examined the relationship between forest fires and climate variables in different subregions of Alberta. Hessburg et al. (2019) reviewed the properties of forests that enhanced resilience and resistance in fire-maintained forests in 15 ecoregions, from Canada to Mexico. They discussed how climate change, land use, and fire suppression have altered the historical fire regimes and reduced the resilience of these forests. They also suggested recommendations for restoring and maintaining forest resilience in the face of global change. Murphy (2020) investigated the trends in fire activity at the national and provincial levels in Canada over six decades. They showed that the destruction caused by forest fires increased sharply in the first half of this period and declined in the second half. They also ranked the years according to area burned and found that the six worst years all occurred before the year 2000. Singh (2022) provided a comprehensive analysis of the factors driving forest fires and their relationship with biodiversity, land degradation, and climate change. They highlighted the role of forest fire emissions in global climate change and discussed the mitigation strategies and policy implications. Ahmed and Hassan (2023) analyzed the distribution and number of forest fire occurrences, burned areas, and seasonality, and their trends of human- and lightning-caused small ($<$200 ha) and large ($\geq$200 ha) fires from 1959 to 2022 in the forested 14 subregions of Alberta, based on the Canadian National Fire Database. They applied a non-parametric statistical test, i.e., Mann–Kendall and Sen's slope estimator, to examine the patterns and magnitudes of the trends. They found that all subregions experienced significantly increasing trends of fire occurrences, either monthly or yearly, except the Alpine subregion.

The relationship between forest fire trends and climate is pivotal in understanding the evolving dynamics of fire occurrences (Jones et al., 2022). Analyzing trends and anomalies in climate variables such as temperature, precipitation, and relative humidity provides valuable insights into the factors influencing the frequency and behavior of forest fires (Jain et al., 2022; Littell et al., 2016). Systematic examination of these connections through robust trend analysis and anomaly detection methodologies enhances our ability to predict and respond to changing fire patterns (Grotjahn et al., 2016). Recognizing and interpreting anomalies in climate conditions further enables proactive measures to address potential shifts in forest fire dynamics (Celis et al., 2023). This comprehensive understanding is crucial for the development of effective strategies in forest fire management and mitigation within the context of a changing climate (Hessburg et al., 2021).

This study aims to enhance the understanding of the intricate attributes of forest fires across various natural subregions of Alberta, Canada, and their correlation with climate variables. The specific objectives are:

- Utilizing fire point records from the Canadian National Fire Database and interpolated climate data to conduct statistical analyses of forest fire trends and anomalies, as well as climate variables, across Alberta's different natural subregions.
- Identifying patterns and relationships between the climate and the temporal distribution of forest fires for each of these subregions.

This research can provide valuable insights for fire managers and agencies to make informed and prudent decisions for protecting human lives and assets in Alberta, within the context and limitations discussed in the previous section.

2. Materials and methods

2.1. Study region

The study focuses on the province of Alberta, Canada, spanning an extensive geographic expanse of 438,063 km^2, positioned between 55 and 60 degrees north latitude (Stralberg et al., 2018). Fig. 1 provides a graphical depiction of the region of interest, featuring 21 subregions distributed across the six natural regions within the Alberta province.

2.2. Data

The climate data used in this study were sourced from the Township Data Viewer website of the Agriculture and Irrigation Department (Goverment of Alberta, 2020), which provided interpolated values for Relative Humidity Average (%), Precipitation (mm), Air Temperature Minimum (°C), and Air Temperature Maximum (°C) for each township within the province of Alberta for the period 1955 to 2022. In the mountainous regions located southwest of the province, the reliability of climate data is generally less reliable. This is attributed to several factors including a sparse observation network, the complexity of the topography, and the impact of orographic effects (Eum and Gupta, 2019).

The study incorporated fire point data from the National Fire Database of the Canadian National Fire Database (CNFDB), which is a collection of forest fire data from various sources, including fire locations (point data) and fire perimeters (polygon data) as provided by Canadian fire management agencies (provinces, territories, and Parks Canada). The dataset includes information from 1959 up to September 01, 2021, and is obtained from the fire history records of Natural Resources Canada, Government of Canada (Natural Resources Canada, 2023). The database only encompasses data contributed by various agencies and the completeness and quality of this data can differ among agencies and across different years (Natural Resources Canada, 2023).

Following a thorough dataset examination, it was determined that the focus of this study would concentrate on 12 out of the 21 subregions, selected based on the frequency of forest fires over the study period. These regions include Athabasca Plain (AP), Boreal Subarctic (BSR), Central Mixedwood (CM), Dry Mixedwood (DMW), Kazan Uplands (KU), Lower Boreal Highlands (LBH), Lower Foothills (LF), Montane (M), Northern Mixedwood (NM), Subalpine (SA), Upper Boreal Highlands (UB), and Upper Foothills (UF).

2.3. Methods

2.3.1. Data preparation

In this study, daily climate variable datasets were used to calculate the average values of Relative Humidity Average (%), Precipitation (mm), Air Temperature Minimum (°C), and Air Temperature Maximum (°C) for each of the 12 subregions, using the coordinates of township centers. Furthermore, the total monthly Precipitation was calculated for each of these 12 subregions. Similarly, the monthly averages of Relative Humidity Average (%), Air Temperature Minimum (°C), and Air Temperature Maximum (°C) were determined for all 12 subregions in Alberta.

2.3.2. Anomaly and trend analyses

In 1990, Cleveland et al. (1990) introduced the Seasonal and Trend decomposition using LOESS (STL) statistical methodology. STL is primarily designed for the decomposition of time series data into three essential constituents: trend, seasonality, and residuals. The trend component characterizes the overall trajectory of the data's temporal evolution, while the seasonal component captures recurrent cyclic patterns. In contrast, the residual component accounts for the unexplained variance in the data, not accommodated by the trend or seasonal elements. Mathematically, the decomposition of a time series denoted as Y_t into its seasonality (S_t), trend (T_t), and residual (R_t) components using STL is succinctly expressed by the following equation (Wen et al., 2019, 2020):

$$Y_t = T_t + S_t + R_t. \tag{1}$$

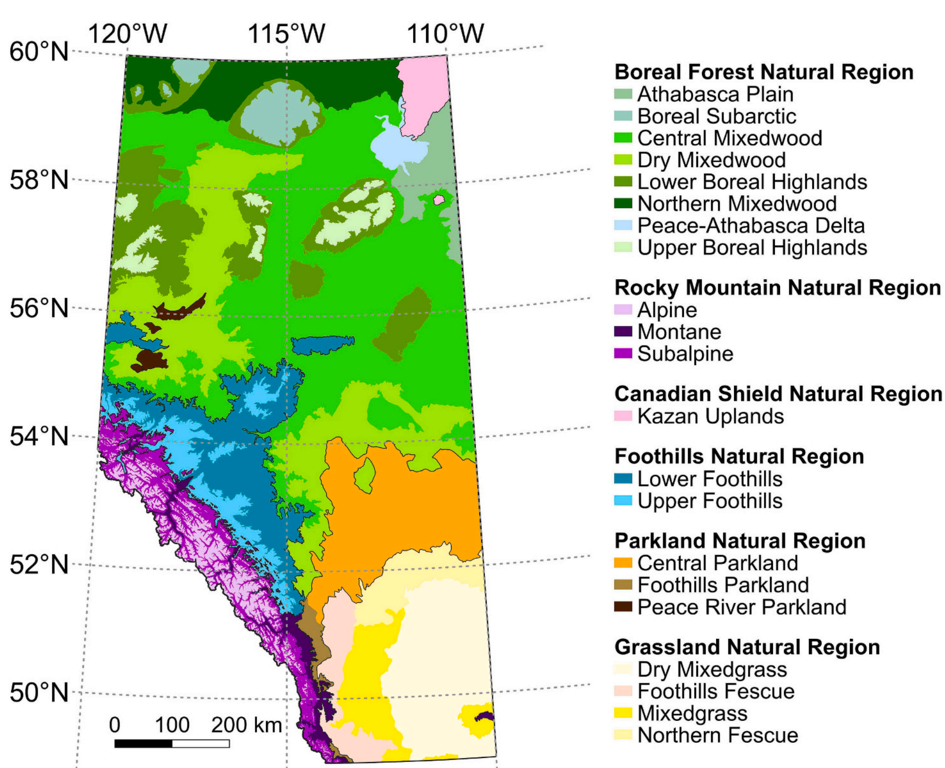

Fig. 1. The 21 subregions of Alberta, Canada. The colors used here are selected to align with the colormap employed in (Government of Alberta, 2020) for consistency.

Wen et al. (2019) introduced RobustSTL as an advanced iteration of the STL methodology. RobustSTL demonstrates proficiency in addressing the challenges posed by noise, outliers, and the fluctuating nature of seasonality within time series data. The operational framework of this algorithm encompasses four pivotal steps: denoising the time series, extracting the underlying trend, calculating the seasonality component, and adjusting the extracted components. These steps are applied iteratively until convergence is achieved, culminating in a robust and precise decomposition of the time series data (Wen et al., 2019, 2020).

In time series analysis, the identification of anomalous periods is of utmost importance, as it enables a deeper understanding of patterns or events that deviate significantly from the expected data behavior (Aggarwal and Aggarwal, 2017; Keogh et al., 2002; Santer et al., 2000). A method for detecting such periods involves the application of Z-score analysis to the trend component T_t derived from RobustSTL. Z-score analysis is a statistical technique that standardizes the data by subtracting the mean and dividing by the standard deviation (Aggarwal et al., 2019; Crosby, 1994). This standardization produces a score that quantifies how many standard deviations a particular data point deviates from the mean. In the context of time series analysis, employing Z-score analysis on the trend component T_t helps identify periods that exhibit noteworthy deviations from the expected trend behavior. Moreover, this approach is valuable for recognizing potential outliers, which, in turn, provides critical insights into the underlying data-generating processes (Boschetti et al., 2013; Jamshidi et al., 2022; Soriano-Vargas et al., 2021).

Initiating the process of pinpointing unusual periods within a time series Y_t involves the initial step of decomposing the series into its fundamental components—namely, S_t, T_t, and R_t—utilizing the RobustSTL algorithm. After this decomposition, the trend component T_t undergoes an independent evaluation, and instances that meet the specified condition are then identified (Chakrabarti et al., 2008). The condition for identifying significantly high or low values of the trend component T_t is expressed as follows:

$$\begin{cases} \dfrac{T_t-\mu_t}{\sigma_t} \geq Z_{\alpha/2}, & \text{Indicating Significantly High}, \\ \dfrac{T_t-\mu_t}{\sigma_t} \leq -Z_{\alpha/2}, & \text{Indicating Significantly Low}, \end{cases} \tag{2}$$

where μ_t and σ_t represent the mean and standard deviation of T_t respectively, while $Z_{\alpha/2}$ corresponds to the Z-score associated with the significance level α. For instance, when $\alpha = 0.05$, $Z_{\alpha/2}$ aligns with the 95th percentile of the standard normal distribution, providing a confidence level of 95% for identifying these periods as anomalies.

Furthermore, two non-parametric statistical techniques, specifically the Mann-Kendall (MK) test (Mann, 1945) and Sen's Slope Estimator (SSE) (Sen, 1968), were applied for data analysis. The MK test was employed to scrutinize the signs of differences between observations, allowing for the detection of trends within the data. Meanwhile, SSE was utilized to evaluate the magnitude and direction of these trends, indicating whether they represented increasing or decreasing trends (Ahmed and Hassan, 2023; Shawky et al., 2023).

The MK test was employed to ascertain the significance of trends at both the 95% and 99% confidence levels, providing a means to gauge the reliability of the results. These methods, which don't require assumptions about the data's underlying distribution, are valuable tools for identifying and evaluating trends in the dataset, as documented in the references (Ahmed and Hassan, 2023; Shawky et al., 2023).

The MK test statistic S can be computed for a time series $x_1, x_2, \ldots, x_n$ of length n using the following equation (Ahmed and Hassan, 2023; Shawky et al., 2023):

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn\left(x_i - x_j\right), \tag{3}$$

where $sgn\left(x_i - x_j\right)$ is the sign function defined as:

$$sgn\left(x_i - x_j\right) = \begin{cases} +1, & x_i - x_j > 0, \\ 0, & x_i - x_j = 0, \\ -1, & x_i - x_j < 0. \end{cases} \tag{4}$$

The sign function is employed to determine whether the difference between the values of the time series at two distinct time points, i and j, is positive, negative, or zero.

Note that the mean of variable S is zero, and the variance of S can be determined as follows:

$$VAR(S) = \frac{1}{18}\left(n(n-1)(2n+5) - \sum_{k=1}^{p} t_k(t_k-1)(2t_k+5)\right), \tag{5}$$

Here, p signifies the total number of tie groups in the dataset, and t_k denotes the number of data points within the k-th tie group.

When $n \geq 10$, the standard normal test statistic Z is calculated based on the following conditions:

$$Z = \begin{cases} \dfrac{S-1}{\sqrt{VAR(S)}}, & S > 0, \\ 0, & S = 0, \\ \dfrac{S+1}{\sqrt{VAR(S)}}, & S < 0. \end{cases} \tag{6}$$

The sign of Z, whether positive or negative, serves as an indicator of an increasing or decreasing trend, respectively.

The magnitude of trends was estimated using SSE, denoted by β, which is calculated using the following equation (Ahmed and Hassan, 2023; Shawky et al., 2023):

$$\beta = \text{Median}\left(\frac{x_j - x_i}{j - i}\right), j > i, \tag{7}$$

where x_i and x_j represent the i-th and j-th ordered observations, and i and j are indices such that $i < j$. When the value of β is positive, it implies an upward trend during the period of interest, whereas a negative value of β indicates a downward trend (Ahmed and Hassan, 2023; Shawky et al., 2023).

3. Results

3.1. Anomaly and trend analyses

Fig. 2 summarizes the anomaly analysis conducted on the monthly climate dataset. The figure shows the periods identified as anomalous based on the Z-score analysis of the trend component T_t obtained from RobustSTL. Each line segment represents an anomaly period between 1955 and 2022. Additionally, Fig. 3 illustrates the temporal distribution of forest fires throughout the study period. These figures exclusively encompass subregions characterized by a considerable frequency of forest fires.

Fig. 2 and Fig. 3 exhibit that during most of 1974 (February till November), both air temperature minimum (°C) and air temperature maximum (°C) were significantly low, and the forest fire distributions were low as well. In contrast, the air temperature values from October 2005 to October 2006 were significantly high, and during this period, fire caused by lightning was significantly high as well (16 counts in July 2026). After 1998, the Athabasca Plain sub-region witnessed more frequent and severe high-temperature anomalies. Meanwhile, the relative humidity average (%) was significantly low, and the air temperature maximum (°C) was significantly high towards the end of 2021. In the Boreal Subarctic subregion, the air temperature maximum and minimum remained significantly high for a duration exceeding two years, spanning from May 2015 to July 2017. Notably, in July 2015, there were 12 forest fires caused by lightning, and in January 2016, there were 11

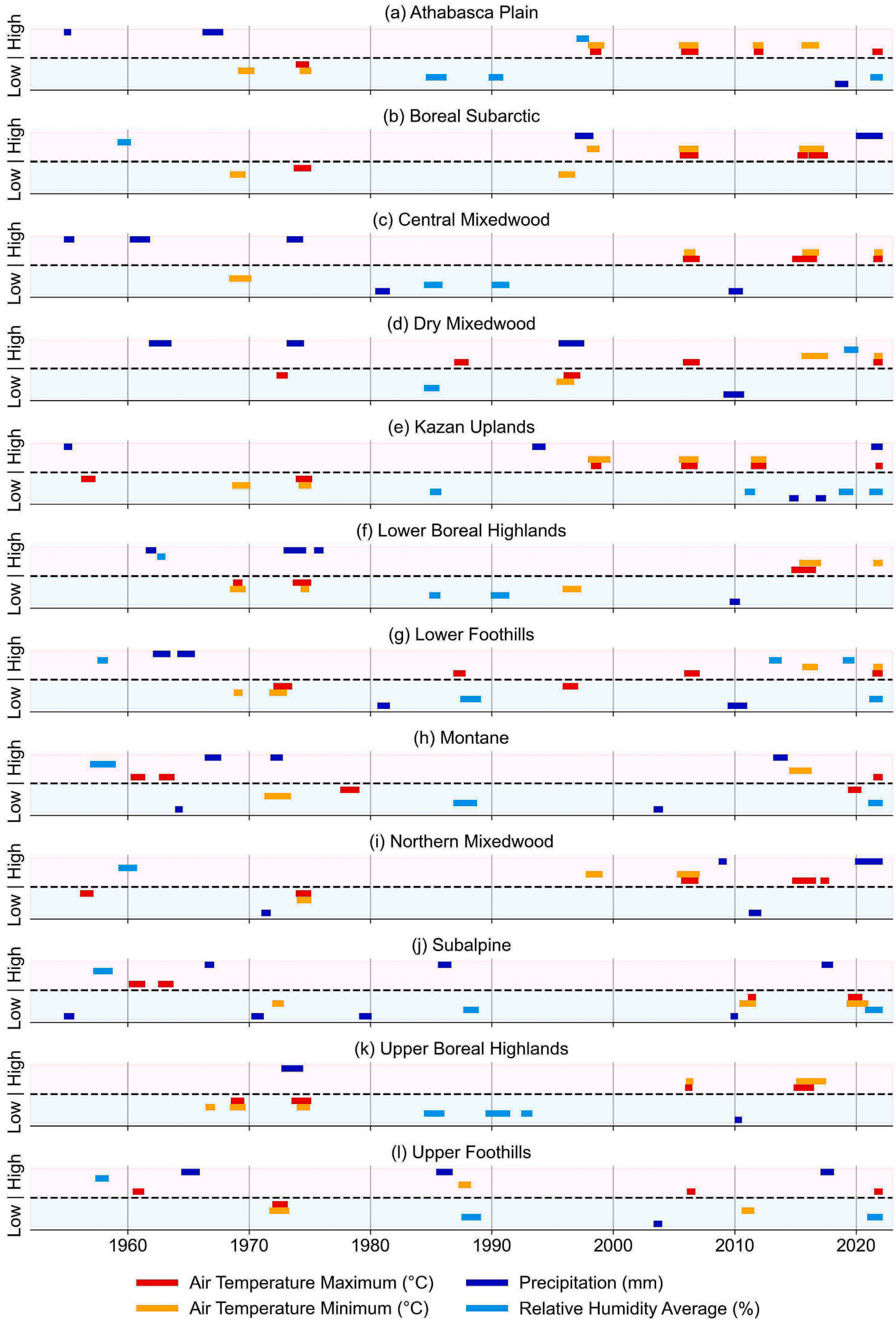

Fig. 2. Anomaly periods within each time series were detected by applying Z-score analysis to the trend component, denoted as T_t, obtained through RobustSTL. A significance level of $\alpha = 0.05$ was employed for this analysis. Across all panels, the x-axis encompasses the years from 1955 to 2022, with horizontal lines indicating anomalous periods. As per Eq. (2), periods exhibiting significantly high values are highlighted in pink at the upper portion of each panel, whereas those with significantly low values are shaded in blue at the lower section. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

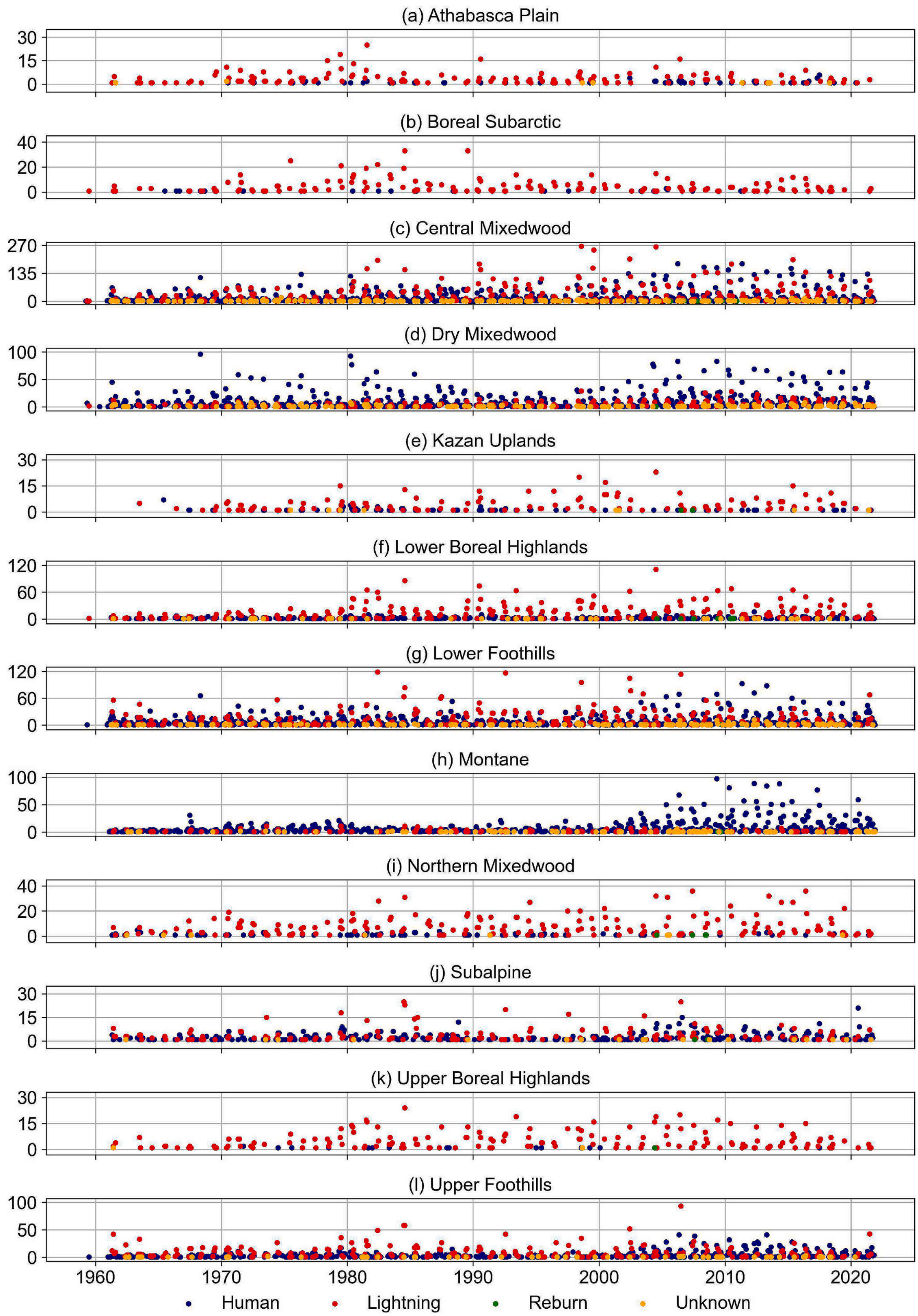

Fig. 3. Temporal and Subregional Distribution of forest fires by Cause. Forest fire causes in this figure: Human (H and H-PB), Prescribed Burn (Human Caused) (H-PB), Lightning (L), Reburn (RE), and Unknown (U). Two causes, Human and Prescribed Burn (Human Caused) were combined.

forest fires of similar origin. Both occurrences of lightning-induced forest fires during these periods were significantly high. In the Central Mixedwood subregion, the average relative humidity (%) experienced a period of significantly low values from April 1990 to March 1991. Within this timeframe, there were 85 forest fires caused by lightning in June 1990, 181 in July 1990, and 154 in August 1990. Furthermore, spanning from January 2006 to November 2006, January 2015 to July 2016, and September 2021 to December 2021, the maximum air temperatures (°C) exhibited significantly high values. Throughout these intervals, there were 182 forest fires caused by Human (H and H-PB) in March 2006, 159 human-caused forest fires in March 2015, 132 human-caused forest fires in May 2015, 201 lightning-induced forest fires in June 2015, 119 human-caused forest fires (H and H-PB) in April 2016, and 141 lightning-induced forest fires in June 2016. In the Dry Mixedwood subregion, significantly high air temperature minimum and maximum were consistently observed between January 2006 and 2022, coupled with significantly low precipitation values in 2009 and 2010. This climatic context contributed to a high occurrence of forest fires, particularly those initiated by re-ignition, since 2006. Between 1998 and the end of the period, the natural subregion of Kazan Uplands witnessed more significantly high air temperature minimum and maximum values. However, for this region, since 1998, lightning was the primary source of forest fires. Especially during those periods when the air temperature values were significantly high, the total number of forest fires was higher. Between December 2014 and November 2016, the Lower Boreal Highlands subregion experienced a notable occurrence of significantly high air temperature minimum and maximum values. This temporal pattern coincided with the outbreak of 65 forest fires triggered by lightning in June 2015 and 50 in June 2016. Between February 2006 and November 2006, the Lower Foothills subregion experienced a period of significantly high air temperature maximum. During this period, there was a noticeable increase in the maximum air temperature values in the Lower Foothills subregion. This period coincided with the outbreak of 114 forest fires induced by lightning in July 2006, along with 69 forest fires caused by human activities (H and H-PB) in May 2006. Since 2006, human activities (H and H-PB) have caused more forest fires in the Montane subregion. The minimum air temperature experienced a significantly high period from October 2010 to February 2016, while the maximum air temperature had a very high period from September 2021 to December 2021. Similar patterns were also observed in the Northern Mixedwood, Subalpine, Upper Boreal Highlands, and Upper Foothills subregions.

Table 1 shows Sen's slope values for the trend component (T_t) of various time series, obtained through RobustSTL, for different subregions and variables. The Sen's slope is a measure of the magnitude and direction of the trend. A positive slope indicates an increasing trend, while a negative slope indicates a decreasing trend. A slope of zero indicates a constant trend. The significance of the slope is indicated by the symbols (* for 99%, † for 95%).

Table 1 shows that most of the subregions had a positive and significant trend in the minimum and maximum air temperature, except for Subalpine (SA), where a negative and significant trend was found. This indicates that the air temperature was generally increasing over time, except for SA, where it was decreasing. The observed trends could be related to the effects of climate change, which could cause different responses in different regions. A negative and significant trend in the relative humidity for most of the subregions was also observed, except for the Boreal Subarctic (BSR) and Upper Boreal Highlands (UB), where no significant trend was detected. This indicated that the relative humidity was generally decreasing over time, except for BSR and UB, where it was constant. This could be related to the effects of evaporation and transpiration, which may have varied depending on the vegetation and soil moisture conditions. A negative and significant trend in the precipitation for some of the subregions, such as Athabasca Plain (AP), Central Mixedwood (CM), Dry Mixedwood (DMW), Lower Boreal Highlands (LBH), and Upper Boreal Highlands (UB), was observed, while a positive and significant trend for Boreal Subarctic (BSR) and Northern Mixedwood (NM), and no significant trend for the rest of the subregions was detected. This indicated that the precipitation was generally decreasing over time for some regions, increasing for others, and constant for the rest. This may have been related to the effects of atmospheric circulation and precipitation patterns, which may have changed due to climate change. It was observed that there is a positive and significant trend in forest fires caused by humans in some subregions such as Central Mixedwood (CM), Dry Mixedwood (DMW), Lower Foothills (LF), Montane (M), and Upper Foothills (UF). This indicated that the forest fires caused by humans are generally increasing over time for some regions and constant for the rest. The increase may be related to human activities such as land use change, recreation, and arson, which may have increased the risk of ignition and fire spread. Similarly, a positive and significant trend in forest fires caused by lightning was observed for some subregions such as Central Mixedwood (CM), Dry Mixedwood (DMW), and Lower Boreal Highlands (LBH). However, a negative and significant trend was observed for Upper Foothills (UF), and no significant trend was detected for the rest of the subregions. This indicates that the forest fire caused by lightning is generally increasing over time for some regions, decreasing for one region, and constant for the rest. The increase or decrease may be related to thunderstorm activity, which may have increased or decreased depending on the temperature, humidity, and wind conditions. Finally, a positive and significant trend in the total forest fire was observed for some subregions such as Central Mixedwood (CM), Dry Mixedwood (DMW), Lower Foothills (LF), Montane (M), and Upper Foothills (UF). However, a negative and significant trend was observed for Subalpine (SA), and no significant trend was detected for the rest of the subregions. This indicates that the total forest fire is generally increasing over time for some regions, decreasing for one region, and constant for the rest. The increase or decrease may be related to the combined effects of climate and human factors, which may influence the frequency, intensity, and duration of forest fires.

Table 1
Mann-Kendall test and Sen's Slope were used to analyze trend component (T_t) of various time series, obtained through RobustSTL, with significant slopes shown at 90% confidence level or higher (* for 99%, † for 95%). Subregion abbreviations: Athabasca Plain (AP), Boreal Subarctic (BSR), Central Mixedwood (CM), Dry Mixedwood (DMW), Kazan Uplands (KU), Lower Boreal Highlands (LBH), Lower Foothills (LF), Montane (M), Northern Mixedwood (NM), Subalpine (SA), Upper Boreal Highlands (UB), and Upper Foothills (UF).

Subregion	Air Temp. Min(°C)	Air Temp. Max (°C)	Rel.Humidity Average (%)	Precip (mm)	Human (H and H-PB)	Lightning	Total
AP	+2.09E-03*	+2.30E-03*	−2.03E-03*	−9.89E-03*			
BSR	+1.57E-03*	+1.40E-03*		+7.51E-03*	0.00E+00		
CM	+1.67E-03*	+2.24E-03*	−7.53E-04*	−8.72E-03*	+8.43E-03*	+2.22E-02†	+1.55E-02*
DMW	+1.63E-03*	+1.84E-03*	−1.07E-03*	−4.43E-03*	+8.44E-03*	+1.06E-02*	+1.35E-02*
KU	+2.87E-03*	+2.82E-03*	−8.25E-04*	−4.72E-03*	+0.00E+00†	+0.00E+00†	
LBH	+1.62E-03*	+1.76E-03*	−7.46E-04†	−5.60E-03*	+0.00E+00†	+2.68E-02*	+0.00E+00*
LF	+1.83E-03*	+1.35E-03*	−2.38E-03*	−3.22E-03*	+5.21E-03*		+7.58E-03*
M	+5.70E-04*		−1.80E-03*	+2.59E-03*	+8.50E-03*		+9.68E-03*
NM	+1.75E-03*	+2.64E-03*	−1.61E-03*	+2.93E-03*			+0.00E+00†
SA	−9.61E-04*	−6.19E-04*	−3.18E-03*	−4.55E-03*	+0.00E+00*		0.00E+00
UB	+1.56E-03*	+1.97E-03*		−6.45E-03*			
UF	+6.42E-04*	+8.51E-04*	−3.10E-03*		+3.40E-03*	−6.33E-03†	+2.55E-03*

4. Discussion

The implications of the trends and anomalies of climate and fire variables across different subregions of Alberta are discussed in this section. The results are also used to inform and improve the understanding and management of forest fires in a changing climate.

4.1. Examining the possible relationship between climate change and Forest fire trends

Based on the Mann-Kendall test and Sen's slope, a significant increase in the minimum and maximum air temperature over time was experienced by most of the subregions, except for Subalpine (SA), where a significant decrease was observed. Some other studies also reported a general warming trend in Alberta, with spatial and temporal variations (Hassan et al., 2021a; Landhäusser et al., 2010; Zhang et al., 2000). Climate change impacts, which can trigger varied responses in different regions based on local factors like elevation, topography, and vegetation, could be linked to the rise in air temperature (Estevo et al., 2022; Flannigan et al., 2009b). The feedback processes involving snow and ice, capable of reflecting more solar radiation and cooling the surface, might account for the reduction in air temperature in SA (Dewan and Corner, 2012; Flanner et al., 2011; Rasouli et al., 2022).

A significant decrease in the relative humidity over time was experienced by most of the subregions, except for the Boreal Subarctic (BSR) and Upper Boreal Highlands (UB), where no significant trend was detected, as revealed by the trend analysis. A general drying trend in Alberta, with some regional exceptions, was reported by other researchers as well (Beltaos, 2023; Elmes and Price, 2019; Hanesiak et al., 2011). Fluctuations in evaporation and transpiration, contingent on vegetation and soil moisture conditions, could be linked to a decline in relative humidity (Dai, 2011; Keshta et al., 2012). The preservation of moisture balance, due to higher precipitation and lower temperatures in these regions, could explain the absence of notable trends in BSR and UB (Milly et al., 2005).

As revealed by the trend analysis, a significant decrease in the precipitation over time was experienced by some of the subregions, such as Athabasca Plain (AP), Central Mixedwood (CM), Dry Mixedwood (DMW), Lower Boreal Highlands (LBH), and Upper Boreal Highlands (UB), while a significant increase was experienced by some, such as Boreal Subarctic (BSR) and Northern Mixedwood (NM), and no significant trend was shown by the rest. A complex pattern of precipitation change in Alberta, with spatial and temporal heterogeneity was also reported by other studies (Mekis and Vincent, 2011; Mwale et al., 2009). Changes in atmospheric circulation and precipitation patterns, potentially influenced by climate change, could be associated with a reduction in rainfall (Trenberth, 2005; Trenberth et al., 2003). Conversely, the intensification of rainfall in certain areas could be attributed to the impacts of orographic uplift and convective storms (Groisman et al., 2005; Houze Jr, 2012).

Some of the subregions, such as Central Mixedwood (CM), Dry Mixedwood (DMW), Lower Foothills (LF), Montane (M), and Upper Foothills (UF), showed a significant increase in the forest fire caused by human over time, as revealed by the trend analysis, while no significant trend was detected for the rest of the subregions. A general increase in human-caused fire in Alberta, with spatial variations was also reported by other studies (Ahmed and Hassan, 2023; Parisien et al., 2011; Wang and Anderson, 2010). The effects of human activities, such as land use change, recreation, and arson, which may increase the risk of ignition and fire spread, may be related to the increase in human-caused fire (Balch et al., 2017; Leone et al., 2009).

A significant increase in the forest fire caused by lightning over time occurred in some of the subregions, such as Central Mixedwood (CM), Dry Mixedwood (DMW), and Lower Boreal Highlands (LBH), while a significant decrease occurred in Upper Foothills (UF), and no significant trend was detected for the rest of the subregions. A mixed pattern of lightning-caused fire in Alberta, with spatial and temporal variability was also reported by other studies (Ahmed and Hassan, 2023; Veraverbeke et al., 2017; Wang and Anderson, 2010). The influence of thunderstorm activity, which can fluctuate based on temperature, humidity, and wind conditions, might be associated with the rise in fires ignited by lightning (Peterson et al., 2010; Romps et al., 2014). The impact of fire suppression and fuel management strategies, which can potentially lower the frequency and intensity of fires, could explain the reduction in fires caused by lightning in UF (Bowman et al., 2011; Hirsch et al., 2001).

A significant increase in the total forest fire over time for some of the subregions, such as Central Mixedwood (CM), Dry Mixedwood (DMW), Lower Foothills (LF), Montane (M), and Upper Foothills (UF), while a significant decrease was indicated for Subalpine (SA), and no significant trend was detected for the rest of the subregions. The combined effects of climate and human factors, which may influence the frequency, intensity, and duration of forest fires, may be related to the increase in total fire (Flannigan et al., 2006; Moritz et al., 2012). The effects of snow cover and fuel moisture, which may limit the fire season and spread, may account for the decrease in total fire in SA (Kasischke and Turetsky, 2006).

4.2. Exploring the potential relationship between climate change and Forest fire anomalies

The anomaly analysis revealed a period of significantly low air temperature minimum and maximum from February to November 1974, which corresponded to a low forest fire distribution in the Athabasca Plain subregion. Conversely, a relatively high fire occurrence caused by lightning, with 16 counts in July 2006, was aligned with a period of significantly high air temperature minimum and maximum from October 2005 to October 2006, as demonstrated by the fire distribution. These results suggested that the air temperature may have had an impact on the fire occurrence and source in this subregion, with higher temperatures promoting more lightning-induced fire. Other studies also reported a positive correlation between air temperature and fire frequency, area burned, and lightning-caused fires in boreal regions (Abatzoglou et al., 2016; Peterson et al., 2010; Veraverbeke et al., 2017). Higher air temperature could enhance the evaporation and drying of fuels, as well as the convective activity and thunderstorm development, which were the main sources of natural ignitions in boreal ecosystems (Giorgis et al., 2021; Hessilt et al., 2022). Therefore, the Athabasca Plain subregion, which was situated in the boreal forest zone of Canada, may have experienced more frequent and severe forest fires, especially those ignited by lightning (Hessilt et al., 2022; Veraverbeke et al., 2017).

A long period of significantly high air temperature minimum and maximum from May 2015 to July 2017 coincided with two peaks of fire occurrence caused by lightning in the Boreal Subarctic subregion, as shown by the anomaly detection and the fire distribution. There were 12 counts in July 2015 and 11 counts in January 2016. This indicated that the air temperature, with higher temperatures favoring more lightning-induced fire, may have influenced the fire occurrence and source in this subregion. Air temperature was suggested to be an important driver of fire activity and ignition source in this subregion, which was dominated by coniferous forests and peatlands. Some other studies also found a positive correlation between air temperature and fire frequency, area burned, and lightning-caused fires in boreal regions (Christianson et al., 2022; Peterson et al., 2010; Veraverbeke et al., 2017). Higher air temperature could have increased the evaporation and drying of fuels, as well as the convective activity and thunderstorm development, which were the main sources of natural ignitions in boreal ecosystems (Giorgis et al., 2021; Halofsky et al., 2018). Therefore, under a warming climate, the Boreal Subarctic subregion may have faced more frequent and intense forest fires, especially those ignited by lightning.

Three peaks of fire occurrence caused by lightning in the Central Mixedwood subregion were detected by the anomaly detection and fire distribution, coinciding with a period of significantly low relative humidity average from April 1990 to March 1991. There were 85 counts in June 1990, 181 counts in July 1990, and 154 counts in August 1990. This indicated that the relative humidity, with lower humidity favoring more lightning-induced fire, may have influenced the fire occurrence and source in this subregion. Moreover, several peaks of fire occurrence caused by human activities and lightning were detected by the anomaly detection and the fire distribution, coinciding with three periods of significantly high air temperature maximum from January 2006 to November 2006, January 2015 to July 2016, and September 2021 to December 2021. This indicated that the air temperature, with higher temperature favoring more fire from both sources, may have influenced the fire occurrence and source in this subregion. Relative humidity and air temperature were suggested to be important factors affecting the fire activity and ignition source in this subregion, which was located in the boreal forest zone of Canada and was characterized by a mosaic of coniferous and deciduous trees. A negative relationship between relative humidity and fire occurrence, area burned, and lightning-caused fires in boreal regions was also reported by other studies (Krawchuk et al., 2009a; Mohammadi et al., 2021; Peterson et al., 2010; Veraverbeke et al., 2017). Lower relative humidity could have reduced the moisture content and increased the flammability of fuels, as well as enhanced the convective activity and thunderstorm development, which were the main sources of natural ignitions in boreal ecosystems (Halofsky et al., 2020; Hessilt et al., 2022). Higher air temperature could increase the evaporation and drying of fuels, as well as the frequency and intensity of lightning strikes (Dowdy and Mills, 2012; Pineda and Rigo, 2017). Moreover, higher air temperature could increase the human presence and activity in the forest, which could increase the risk of accidental or intentional ignitions (Curt et al., 2016; Ren et al., 2023). Therefore, under a changing climate, the Central Mixedwood subregion may have faced more frequent and severe forest fires, especially those caused by lightning and human activities.

A high occurrence of fire, particularly those initiated by re-ignition, in the Dry Mixedwood subregion was detected by the fire distribution, coinciding with a consistent period of significantly high air temperature minimum and maximum since January 2006 and a period of significantly low precipitation from January 2009 to December 2010, as shown by the anomaly detection. This indicated that the air temperature and precipitation, with higher temperature and lower precipitation favoring more re-ignition fire, may have influenced the fire occurrence and source in this subregion. Air temperature and precipitation were suggested to be important factors affecting the fire activity and ignition source in this subregion, which was located in the boreal forest zone of Canada and was characterized by a mixture of coniferous and deciduous trees. An increase in air temperature might have amplified the evaporation and drying of fuels, thereby enhancing the chances of smoldering combustion and re-ignition of areas previously affected by fire (Krawchuk et al., 2009b; Randerson et al., 2006; Rein, 2016). Reduced precipitation could have led to a decrease in moisture content, thereby increasing fuel flammability and reducing the efficacy of fire suppression efforts. Consequently, in a climate that's changing, the Dry Mixedwood subregion could have encountered more frequent and intense forest fires, particularly those triggered by re-ignition.

Higher fire occurrence and lightning as the primary source of fire in the Kazan Uplands subregion were detected by the fire distribution, coinciding with more periods of significantly high air temperature minimum and maximum since 1998, as shown by the anomaly detection. This indicated that the air temperature, with higher temperatures favoring more lightning-induced fire, may have influenced the fire occurrence and source in this subregion. Air temperature was suggested to be an important driver of fire activity and ignition source in this subregion, which was located in the boreal forest zone of Canada and was characterized by a mosaic of coniferous and deciduous trees, shrubs, and grasslands. Higher air temperature could have increased the evaporation and drying of fuels, as well as the convective activity and thunderstorm development, which were the main sources of natural ignitions in boreal ecosystems (Duane et al., 2021; Halofsky et al., 2018; Hessilt et al., 2022). Therefore, under a changing climate, the Kazan Uplands subregion may have faced more frequent and severe forest fires, especially those ignited by lightning.

Two peaks of fire occurrence caused by lightning in the Lower Boreal Highlands subregion were detected by anomaly detection and fire distribution, coinciding with a period of significantly high air temperature minimum and maximum from December 2014 to November 2016. There were 65 counts in June 2015 and 50 counts in June 2016. This indicated that the air temperature, with higher temperatures favoring more lightning-induced fire, may have influenced the fire occurrence and source in this subregion. Air temperature was suggested to be an important driver of fire activity and ignition source in this subregion, which was located in the boreal forest zone of Canada and was characterized by a mixture of coniferous and deciduous trees, shrubs, and grasslands. This was consistent with previous studies that had found a positive correlation between air temperature and fire frequency, area burned, and lightning-caused fires in boreal regions (Peterson et al., 2010; Veraverbeke et al., 2017). Higher air temperature could have increased the evaporation and drying of fuels, as well as the convective activity and thunderstorm development, which were the main sources of natural ignitions in boreal ecosystems (Duane et al., 2021; Hessilt et al., 2022). Therefore, under a changing climate, the Lower Boreal Highlands subregion may have faced more frequent and severe forest fires, especially those ignited by lightning.

In the Lower Boreal Highlands subregion, the anomaly detection and the fire distribution revealed that a period of significantly high air temperature minimum and maximum from December 2014 to November 2016 was associated with two peaks of fire occurrence caused by lightning. There were 65 counts in June 2015 and 50 counts in June 2016. This suggested that the fire occurrence and source in this subregion might have been influenced by the air temperature, with higher temperatures favoring more lightning-induced fire. This subregion, which was located in the boreal forest zone of Canada and was characterized by a mixture of coniferous and deciduous trees, shrubs, and grasslands, was found to have air temperature as an important driver of fire activity and ignition source. Higher air temperature could have increased the evaporation and drying of fuels, as well as the convective activity and thunderstorm development, which were the main sources of natural ignitions in boreal ecosystems (Duane et al., 2021; Hessilt et al., 2022). Therefore, under a changing climate, the Lower Boreal Highlands subregion may have faced more frequent and severe forest fires, especially those ignited by lightning.

4.3. Ecological significance

This study explored the interactions between climatic variables and fire regimes of 21 natural subregions in Alberta. These subregions are, in fact, the subdivisions of six ecoregions that are defined as a function of climatic parameters (temperature and precipitation), bedrock (soil types), topography, and vegetation types (Downing and Pettapiece, 2006). The subregion-scale analyses over 12 natural subregions that exhibit forest cover in the scope of this study would, therefore, be critical in understanding the ecological regimes in Alberta. However, we emphasize that other disturbances, including insect infestation (Wright and Heinselman, 2014) and anthropogenic activities might be worthwhile for further comprehension. For instance, a significant amount of forest removal activities occurred in the northeastern part of the study area in relation to the oil and gas extraction activities (Afrin et al., 2019).

A baseline of forest fire regimes in Alberta was defined in this study, which would be critical to support and modify the forest management strategies (Burton et al., 2003). A significant increase in temperature and a decrease in humidity observed in the natural subregions of Alberta, indicating a warming and drying trend due to climate change, would further accelerate the occurrences of forest fires. In addition, the findings would be effective in understanding the ecological role of forest fire in conifer-dominant northern and western North America (Wright and Heinselman, 2014), such as (i) influence of the physical-chemical environment, (ii) control and manage the loading of dry fuels/materials, (iii) govern the plant species and surrounding communities, (iv) factors influence the distributions of forest fire habitat, (v) govern fungi, parasites, and insects, and (vi) regulate the structure, function, and biodiversity of the ecosystem (Manzello, 2019).

Another issue, i.e., communities and/or industries situated in the vicinity of the forested area have experienced enormous adverse impacts due to forest fire occurrences (Ahmed et al., 2018; Dastour and Hassan, 2024). For instance, the 2016 Horse River Fire in Fort McMurray, and the 2011 Flat Top Complex Fire in Lesser Slave Lake not only impacted the ecosystem but also cost millions of dollars to rebuild them (Ahmed et al., 2018). Thus, this study would be a useful tool in formulating policies and strategies to combat the adverse effects on ecology and human beings due to forest fires.

5. Conclusion

This study used the Mann-Kendall test, Sen's slope, and RobustSTL methods to conduct trend analysis and anomaly detection of climate and fire variables in different subregions of Alberta, Canada, and to explore the possible relationships and implications of these results for the understanding and management of forest fires in the context of climate change.

The study examined the temporal patterns and trends of climate and fire variables in different natural subregions of Alberta from 1955 to 2022. The Subalpine subregion was the only one where no significant temperature change was detected, while a significant increase in the minimum and maximum air temperature was observed in the rest of the subregions. Most of the subregions experienced a significant decrease in relative humidity, indicating a drying trend due to climate change. The only exceptions were the Boreal Subarctic and Upper Boreal Highlands subregions, which did not show a significant humidity change. The subregions showed a complex pattern of precipitation change, indicating a variable response to climate change. The Boreal Subarctic, Montane, Northern Mixedwood, and Upper Foothills subregions did not show a significant precipitation change, while the rest of the subregions showed a significant decrease in precipitation. Human-caused or prescribed forest fires showed significant increasing trends in five ecoregions: Central Mixedwood, Dry Mixedwood, Lower Foothills, Montane, and Upper Foothills. On the other hand, lightning-caused forest fires had significant decreasing trends in Dry Mixedwood and Upper Foothills, and significant increasing trends in Central Mixedwood and Lower Boreal Highlands. Overall, forest fires of any cause increased significantly in Central Mixedwood, Dry Mixedwood, Lower Foothills, Montane, and Upper Foothills.

The anomaly detection and the fire distribution revealed some interesting patterns and relationships between the climate and fire variables and the forest fire occurrence and source in different subregions, as discussed in the previous section. For instance, the Athabasca Plain subregion had a low forest fire distribution during a period of anomalously low air temperature, and a relatively high lightning-induced fire occurrence during a period of anomalously high air temperature. This suggested that the air temperature may affect the fire occurrence and source in this subregion, with warmer conditions leading to more fire from lightning. Likewise, the Central Mixedwood subregion had three peaks of lightning-induced fire occurrence during a period of anomalously low relative humidity, and several peaks of fire occurrence from both human activities and lightning during three periods of anomalously high air temperature. This suggested that the relative humidity and the air temperature may affect the fire occurrence and source in this subregion, with drier and warmer conditions leading to more fire from both sources. These are some examples of the patterns and relationships that were found by the anomaly detection and the fire distribution. The other subregions also had some interesting patterns and relationships, which are explained in detail in the previous section. These patterns and relationships may help to understand and manage the climate and fire interactions in different subregions of Alberta, Canada, in the context of climate change.

Future research endeavors present several intriguing opportunities. A comparative study could be undertaken to analyze the climate and fire trends across the 21 subregions of Alberta. This would explain the commonalities and disparities among these subregions and identify the factors underpinning regional variations. Beyond the scope of the current study, which focused on air temperature, relative humidity, and precipitation, future investigations could incorporate additional climate variables that potentially influence fire activity. These variables might include wind speed, solar radiation, and drought index. Moreover, a quantification of the ecological impacts of fire trends would significantly augment our understanding of these phenomena. This could entail an assessment of the repercussions of fire on diverse ecological components such as vegetation, soil, wildlife, and the carbon cycle. A combination of remote sensing, field surveys, and modeling techniques could be employed for this purpose.

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CRediT authorship contribution statement

Hatef Dastour: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **M. Razu Ahmed:** Writing – review & editing, Validation, Resources, Investigation. **Quazi K. Hassan:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Investigation, Funding acquisition.

Declaration of competing interest

The authors declare that they have no competing interests.

Data availability

The data used in this research are available in the public domain.

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