Asymmetrical Lightning-ignited Fire Season Expansion in the Boreal Forest of Northeast China

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Key Points:

- Lightning fire season didn't advance in the early fire season, but largely extended into snowless late fire season since the late 1990s
- Stable snow melt dates and distinct climate trends in early and late fire seasons are responsible for the asymmetrical fire season expansion

Abstract

All-season warming is thought to advance snow melt and delay snow accumulation; coupled with warming-induced drought stress, this could extend both the beginning and end of the fire season. Using the updated fire data of 1967-2018, we found an asymmetrical expansion of the lightning-ignited fire season in the boreal forest of Northeast China. The lightning-ignited fires have not advanced into the early fire season (May-June) but have largely extended into the snowless late fire season since the late 1990s. The length of the lightning-ignited fire season increased by 10.9 days per decade from 1968-2018 ($P<0.01$), and the mean annual number of lightning-ignited fires has increased from 9.8 to 29.2 times/year since 1998. Despite significant warming, the Julian days of snow melt have changed little, which has prohibited the fire season from advancing into early spring. The expansion of lightning-ignited fires from July-September was associated with warming-induced evapotranspiration and the soil/fuel aridity increase.

Keywords: lightning-ignited fire, fire season, boreal forest, asymmetrical expansion

1 Introduction

In association with climate warming and frequent heatwaves, wildfire frequency, burned area, and duration have all increased (Shu & Tian 1999; Shu et al., 2003; Cary et al., 2006; Flannigan et al., 2009; Flannigan et al., 2013), leading to a great loss of human lives and property, disturbance of forest ecosystems, and damage to biodiversity (San-Miguel-Ayanz et al., 2013; Brando et al., 2014; Dennison et al., 2014; He et al., 2019; Boer et al., 2020). Wildfire is a key factor in transforming forest ecosystems from net carbon sinks to net sources (Kasischke et al., 1995; Walker et al., 2019) and has substantially contributed to greenhouse gas emissions (van der Werf et al., 2010), which in turn has exacerbated global warming and fire risks (Liu et al., 2014).

Warming rates are faster at high latitudes (Post et al., 2018) and therefore have caused greater drought stress, higher fuel aridity, and longer dry seasons in boreal forests (Lindner et al., 2010; Dai, 2011; Peng et al., 2011; Cattau et al., 2020). Lightning is the leading cause of fire ignition in boreal forests (Nash & Johnson, 1996; Hu & Zhou, 2014; Veraverbeke et al., 2017). Romps et al. (2014) predicted that lightning strikes would increase by 12±5%/°C with warming. The observed lightning increase, coupled with aggravated drought severity, is responsible for the increase in fires in boreal forests (Tian et al., 2009; Kharuk et al., 2016; Young et al., 2017; Hanes et al., 2019).

In addition to fire frequency increases, warming is supposed to expand the fire season by advancing the beginning and pushing back the end in North America, the Mediterranean, and Southwest China (Moriondo et al., 2006; Nitschke et al., 2008; Tian et al., 2014). The global wildfire season length has increased by 18.7% from 1979 to 2013 (Jolly et al., 2015), and the season expansion will be more pronounced in the northern high latitudes (Flannigan et al., 2013). Fire ignitions are highly dependent on fuel aridity, which is further modulated by precipitation, evapotranspiration, and interactions between snow cover and soil moisture conditions. Snow cover naturally prohibits fire occurrence, and strong spring-summer warming and earlier snow melt theoretically reduce soil and fuel moisture and therefore advance fire occurrence into early spring (Westerling et al., 2006; Westerling, 2016).

Greater Khingan forest, the only boreal forest in northeast China, has experienced a rapid warming rate and suffered from the largest number of lightning-ignited fires among all forests in China (Tian et al., 2009; Tian et al., 2016). An increased fire occurrence, burned areas and an elongated fire season were observed in this region over 1980-2005 (Fan et al, 2017). However, debates still remained about whether the seasonality has changed, especially for lightning-ignited fires (Hu et al, 2014), mainly due to distinct time intervals used for analysis, and old version of fire record ending around the 2000s. The frequency and severity of lightning-ignited fires were determined by moisture conditions, fuel stock and aridity (Liu et al, 2012; Wu et al, 2018; Ying et al, 2018). The potential mechanisms linking fire seasonality, snow cover, and soil moisture are still unclear for the boreal forest of Northeast China.

In this study, we have used the updated fire records, climate, soil moisture, and snow cover data for the Greater Khingan forest. The dynamics of the lightning-ignited fire seasonality, fire frequency, snow melt days, snow cover, and key climate factors over 1967-2018 were characterized. The connections of climate change, snow cover, moisture condition, and fire occurrence were explored.

2 Data and Methods

2.1 Study area

The study area is located in the Greater Khingan forest of Heilongjiang Province, China **(Fig. 1)**, which is the southern extension of the Russian Far East boreal forest into China, and covered a rectangle from 121°-127°E and 50°-53°N. The Greater Khingan forest is mainly dominated by deciduous conifers, including *Larix gmelinii, Pinus sylvestris* var. *mongolica,* and *Pinus pumila*. The terrain is high in the west and middle and low in the east, north, and south. The average elevation is 573 m a.s.l., and the highest peak is 1528 m a.s.l.

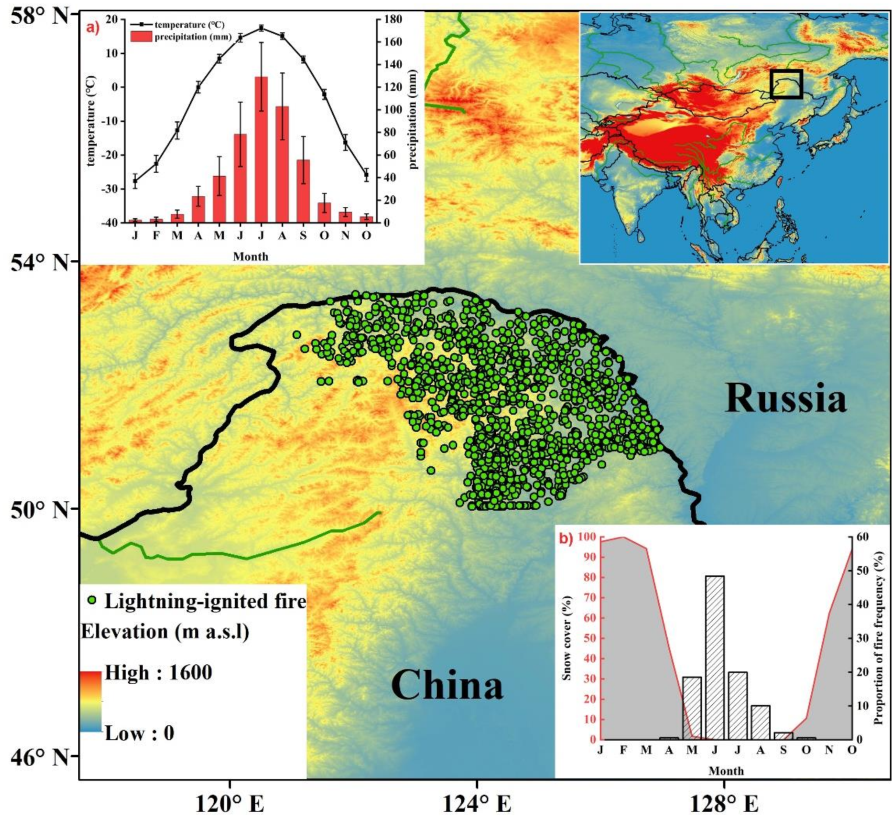

Figure 1. Locations of lightning-ignited fire from 1968 to 2018. The black rectangle at the top right indicates the boundary of the map. The top left insert shows the monthly mean temperature and precipitation of the study area (**a**, 121°-127°E and 50°-53°N). The bottom right insert shows the monthly mean snow cover and lightning fire ratio (**b**).

The Greater Khingan Mountains are located in the cold-temperate continental monsoonal climate region. The annual mean temperature and total precipitation of the study region range from -4 to -2℃ and 400 to 550 mm (**Fig. 1a**), respectively, with 90 to 110 frost-free days. Almost all lightning-ignited fires (98.7%) occurred between May and September (MJJAS) (**Fig. 1b**), which is here defined as the lightning-ignited fire season. The whole fire season was separated into the early and late fire seasons of May to June (MJ) and July to September (JAS), respectively.

2.2 Fire and climate data

Detailed information on historical wildfires was recorded by the local forest administrations, including the fire dates, coordinates, causes, burned areas. To examine the changes in fire season over time, we arranged the fire dates as Julian days (Hatcher, 1984). The data of the lightning-ignited fires were selected for further analysis. 0.5°×0.5° resolved monthly climate data including mean temperature (Temp), maximum temperature (Tmax), and precipitation (Pre) were obtained from the CRU TS 4.03 (land) dataset and averaged over a rectangle of 121°-127°E, 50°-53°N to estimate the mean climate condition of the Greater Khingan. Snow cover data were extracted from Rutgers University Global Snow Lab, the one-month standardized precipitation evapotranspiration index (SPEI) from Spanish National

Research Council (CSIC), 0-10 cm soil moisture (SM) and evapotranspiration (Eva) were downloaded from CLM ERA-interim. The daily snow cover data were available from the Rutgers GSL 1° database.

3 Results

3.1 Fire frequency and burned area

A total of 908 lightning-ignited fires occurred in the Greater Khingan forest from 1968-2018, accounting for 48% of the total fire occurrence, with a total burned area of 350,857 hm^2. The trend of change in MJ lightning-ignited fires frequency was insignificant (**Fig. 2a**), while the trends for JAS and MJJAS showed significant increases from 1968-2018 (P<0.01, **Fig. 2b** and **2c**). The number of JAS lightning-ignited fires has largely increased since the late 1990s.

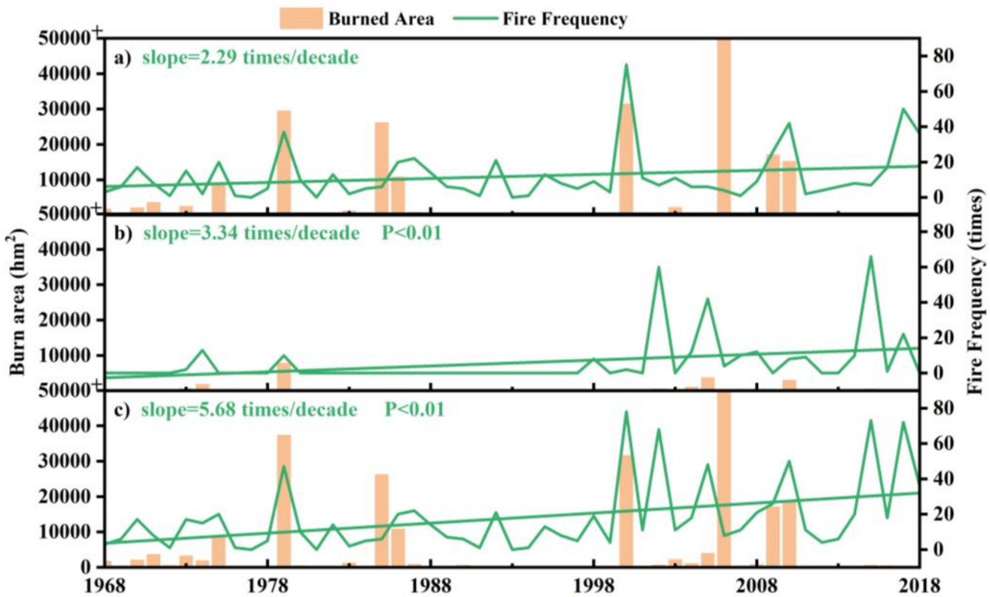

Figure 2. The lightning-ignited fire frequency and burned area in MJ (**a**), JAS (**b**) and MJJAS (**c**). Green lines indicate the trends of fire frequency.

3.2 Lightning fire season and snow cover

Figure 3 shows that the snow melting and snow accumulation days were within the intervals from 82-131 and 280-360 Julian day, respectively. None of the trends were significant. The lightning-ignited fires only occurred on snow-free days. The linear trend of lightning fire start date was insignificant from 1968-2018, while the end date was significantly delayed by 10.9 days/decade (P<0.01). Before 1998, 90.5% of the lightning-ignited fires occurred in MJ, and only 8.5% were found in JAS. From 1998 onwards, the proportion of JAS lightning fires increased to 43.4%, and the mean length of the lightning-ignited fire season increased from 22 days to 80 days, with fires occurring from 9.8 to 29.2 times/year.

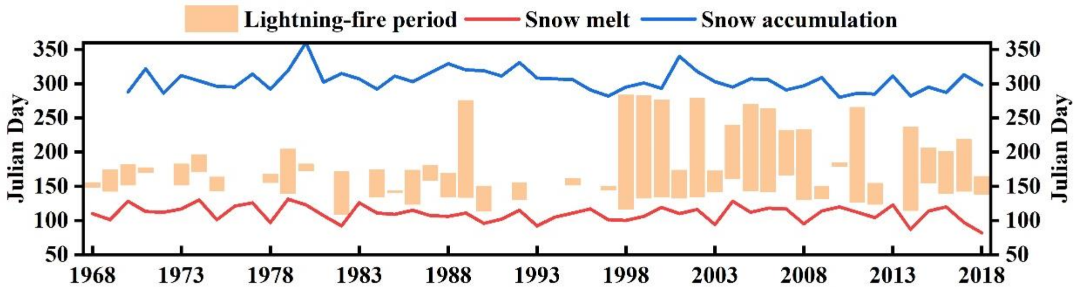

Figure 3. The Julian days of lightning-ignited fires occurrence, snow melt, and snow accumulation; the daily snow cover data are from Rutgers GSL 1°.

3.3 Lightning-ignited fire frequency and climate variability

The correlation coefficients of the climate parameters and lightning-ignited fires frequency within the early, late, and whole fire seasons are presented in **Figure 4**. The mean temperature, maximum temperature and evapotranspiration were significantly and positively correlated with lightning-ignited fires frequency in all fire seasons (MJ, JAS, and MJJAS); precipitation, SPEI, and soil moisture were significantly and negatively correlated with lightning-ignited fires occurrence **(Fig. 4)**.

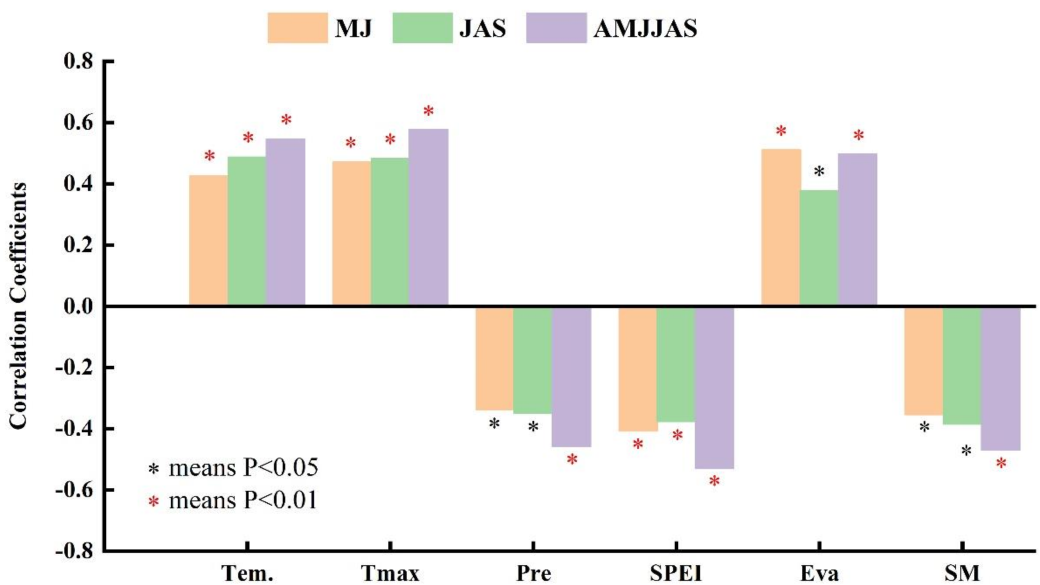

Figure 4. The correlation coefficients of the annual climate parameters and lightning-ignited fire frequency in MJ, JAS, and MJJAS. The black and red stars indicate significance levels above 95% and 99%, respectively.

Trend analysis of the climate parameters showed that the mean and maximum temperatures in MJ, JAS, and MJJAS were all rising significantly **(Fig. 5a** and **5b)**. The moisture trends of MJ and JAS were the opposite: although statistically insignificant, both precipitation and SPEI increased for MJ and decreased for JAS **(Fig. 5c** and **5d)**. In association with the significant warming trends, a significant increase in evapotranspiration was observed for JAS

(**Fig. 5e,** P<0.01), and the surface soil moisture significantly decreased in the late fire season (**Fig. 5f,** P<0.05).

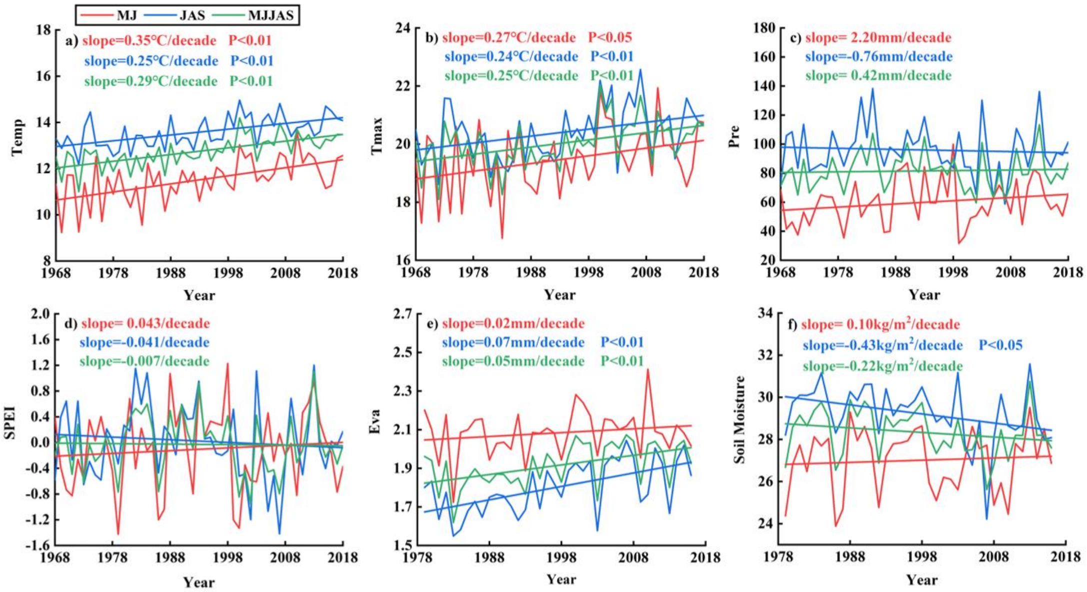

Figure 5. The linear trends of mean temperature (Temp), maximum temperature (Tmax), precipitation (Pre), SPEI, evapotranspiration (Eva), and soil moisture (SM) from 1968-2018.

4 Conclusions and discussion

4.1 Fire season expansion

The existence of snow cover naturally prohibits wildfire occurrence. Climate warming has increased drought severity and snow-free days in early spring and late autumn (Balch et al., 2017; Williams et al., 2019), both of which favor symmetric fire season expansion towards the beginning and end (Cattau et al., 2020; Dupuy et al., 2020). However, we observed an asymmetric extension in the Greater Khingan forest: lightning-ignited fire did not advance in spring but significantly expanded from July-September.

The Greater Khingan forest is located above the permafrost of Northeast China (Ran et al., 2012, Cong et al., 2020), where the warming-associated acceleration of snow melting and surface-thawing water tends to be maintained in shallow soil (Fu et al., 2015). The mean April snow cover remained at a high level of 45.1% from 1968-2018 **(Fig. 1b)**, and the snow melt date changed little **(Fig. 3)**; both effectively prevented fire from advancing into early spring. The JAS soil moisture had been significantly decreasing **(Fig. 5f)**, mainly due to the significantly increased JAS evapotranspiration **(Fig. 5e)** in association with warming **(Fig. 5a and 5b)** and the increased lightning strikes throughout the Greater Khingan Mountains (Tian et al., 2009), which could contribute to the extension of wildfire into the snowless late fire season of JAS.

4.2 Fire frequency and climate variability

A warmer climate increases fuel aridity (Turco et al., 2017), leading to more frequent fire occurrences, burn areas (Portier et al., 2016; Gonzalez et al., 2018), and extreme wildfire episodes (Ruffault et al., 2018). The significant positive correlations of JAS fire frequency with temperature, drought severity (SPEI) and soil moisture coincided with this assumption (**Fig. 4)**. The significant warming and evapotranspiration increase (P<0.01, **Fig. 5a**, **5b** and **5e**) led to aggravated soil and air aridity (**Fig. 5f**) and therefore a significantly increased lightning fire occurrence in JAS (**Fig. 2b**). In contrast, the trends of MJ soil moisture and evapotranspiration were insignificant (**Fig. 5e** and **5f**), which was consistent with the ambiguous fire frequency trend (**Fig. 2a**).

4.3 Comparison with previous studies

Hu et al (2014) reported that the lightning-ignited fires were advancing over 1967-2006. While using the updated fire record of 1967-2018, we found the trend is insignificant, and highlighted the much more significant delaying in summer and fall since the late 1990s. These results coincided with the satellite-derived pattern of total fire (both lightning-ignited and human-caused) seasonality within 1980-2005 (Fan et al. 2017). The connections of total fire frequency and severity with temperature and precipitation (Tian et al., 2009; Liu et al. 2012; Fan et al, 2017), fuel moisture conditions (Wu et al., 2018; Ying et al., 2018) and topography (Shu et al., 2003) were wildly reported. However, the underlying mechanisms for seasonality of lightning-ignited fires were seldomly explored in previous studies. Lightning-ignited fires were much more sensitive to climatic changes (Hu et al, 2014). In this study, we interpreted seasonality of lightning-ignited fire of Northeast China boreal forests in terms of snow cover, and linking the prolonged fire period to a warming and drying climate trend in JAS.

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