Previous Atlantic Multidecadal Oscillation (AMO) modulates the lightning-ignited fire regime in the boreal forest of Northeast China

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Abstract
Lightning-ignited fire is sensitive to climatic change and responsible for large fires in boreal forests. In addition to global-warming caused fire increase, large-scale climate oscillations have significantly contributed to fire variability. However, the leading climate oscillation driving lightning-ignited fire and the mechanisms connecting regional and large-scale climate in the boreal forest of Northeast China, the most fire-prone biome of China, are still unclear. By compositing fire, climate, and atmospheric data, we found that the previous Atlantic Multidecadal Oscillation (AMO) was significantly coherent with the May to August temperature–evapotranspiration variability and lightning-ignited fire occurrence. These connections were valid at both the interannual and multidecadal time scales. Different from previous viewpoints, we found no connection of fire occurrence with the El Niño-Southern Oscillation and Pacific Decadal Oscillation. A warm AMO was followed by high sea level pressure and geopotential height over the study region. We assume these atmospheric anomalies are associated with descending atmospheric motion, producing adiabatic warming and less precipitation on the land surface, both of which favour high fuel aridity and lightning ignition. Therefore, we believe that the winter AMO could be a promising predictor for lightning-ignited fire occurrences in the following summer.

1. Introduction
Global warming has increased fuel aridity and snow-free days (Lyons et al. 1998, Flannigan et al. 2016, Gergel et al. 2017). Increased fuel aridity has led to higher fire frequency and intensity (Silva et al. 2018, Williams et al. 2019), and more snow-free days has been associated with advanced spring and delayed autumn phenology, which lengthens the fire season (Westerling et al. 2006, Flannigan et al. 2013). Both mechanisms have contributed to higher global fire risks (Flannigan et al. 2009) and have been responsible for the frequent large fires over North America and globe in the last decade (Pechony and Shindell 2010, Veraverbeke et al. 2017, Cattau et al. 2020).

The observed and Coupled Model Intercomparison Project 5 (CMIP5)-projected warming is faster at higher latitudes (Meehl et al. 2009, Screen and Simmonds 2010), e.g. the boreal forests have experienced more rapid temperature rises than the global mean level. Coupled with increased lightning strikes and heatwaves (Price and Rind 1994, Romps et al. 2014), boreal forests are prone to more frequent wildfires with greater severity (Hoy et al. 2016). Fire disturbance in boreal forests has released a large amount of carbon from soil organic matter and decreased the
surface albedo (Bond-Lamberty et al. 2007, Walker et al. 2019), both of which have in turn aggravated global warming and fire risks (Liu et al. 2014, Walker et al. 2019).

Superimposed on anthropogenic-warming caused fire risk increase, natural climate variabilities, such as the El Niño-Southern Oscillation (ENSO), have driven interannual summer monsoon precipitation in East Asia, Southeast Asia, and Australia (Mariani et al. 2016, Wu and Zhou 2016). A warm (or cold) ENSO could lead to a shortened (or prolonged) summer monsoon season (Goswami and Xavier 2005, Zhou and Chan 2007), with weakened (or strengthened) precipitation intensity (Kawamura 1998, Roy et al. 2017), leading to increased (or reduced) fuel aridity and more (or less) frequent wildfire occurrences in Asia and Australia. Another climate variability of the Pacific Ocean, e.g. the Pacific Decadal Oscillation (PDO), has modulated the effect of the ENSO through in-phase (overlapping) or out-of-phase (counteracting) with the ENSO (Krishnan and Sugi 2003, Krishnamurthy and Krishnamurthy 2014, Dong and Xue 2016, Wu and Mao 2016, 2019). Furthermore, the combined effect of the ENSO and PDO has largely contributed to the interannual to multidecadal wildfire regime shift in North America and the Amazon forests (Fauria and Johnson 2006, Yocom et al. 2010, Chen et al. 2017, Mason et al. 2017).

Furthermore, sea surface temperatures (SSTs) over the North Atlantic sector showed predominant variability with 50–70 year periodicity and spatially coherent anomalies (Schlesinger and Ramankutty 1994). This variability, termed the Atlantic Multidecadal Oscillation (AMO), was recognized as a major source of natural climate variability in the Northern Hemisphere (NH) (Delworth and Mann 2000, Sutton and Hodson 2005, Li et al. 2013, Delworth et al. 2016, Sun et al. 2017), particularly in changes in the NH temperature (Zhang et al. 2007, Li et al. 2013, Shi et al. 2019) and precipitation in some regions (Enfield et al. 2001, Lu et al. 2006, Kucharski et al. 2009). The warm phase of the AMO was associated with a warm and dry climate, resulting in synchronous wildfire occurrence with greater fire severity in the boreal forests of North America (Collins et al. 2006, Kitzberger et al. 2007, Le Goff et al. 2007, Ascoli et al. 2020).

Boreal forest of Northeast China, which are the southern margin of the Siberian boreal forest, were ranked as the most fire-prone biome in China. Lightning-ignited fires there have exhibited large temporal variability and high sensitivity to climate dynamics (Liu et al. 2012). Using fire-scarred tree materials, Yao et al. (2017) concluded that fire regime shifts before the 1950s were closely related to SST anomalies of the Pacific and Atlantic Oceans. However, the leading climate oscillation driving wildfires, and the underlying mechanisms connecting large-scale climate oscillations and the regional climate of Northeast China are still not clear. In this study, we have collected lightning-fire records, climate data, and atmospheric circulation data, in order to explore how regional and large-scale climate driving local wildfire occurrence and the teleconnection of regional and large-scale climate oscillations.

2. Data and methods

2.1. Study area

The study area is the Greater Khingan forest of Heilongjiang Province, Northeast China (figure 1), which is the southern extension of the Russian Far East boreal forest into China, covering a rectangular area of 121°−127° E, 50°−53° N. Deciduous conifers of Larix gmelinii, Pinus sylvestris var. mongolica, and Pinus pumila are the dominant species. The terrain is high in the west and low in the east, north, and south. The mean elevation is 573 m above sea level (asl.), and the highest peak is 1528 m asl. 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 °C to −2 °C and 400–550 mm (figure 1(a)), respectively, with 90–110 frost-free days. Almost all lightning-ignited fires (96.8%) occurred between May and August (MJA) (figure 1(b)), which was defined as the lightning-ignited fire season.

2.2. Fire and climate data

Detailed information on historical wildfires, including the fire dates, coordinates, causes, and burned areas, was recorded by the local forest administrations. The lightning-ignited fire (here defined as fires that ignited by lightning) data were selected for this study. Since policy-related strict measures by Chinese government have been taken in recent decades, the risk of forest fire occurrence, including lightning-ignited fire, should have largely reduced. This would have caused potential data uncertainty. The 1968–2018 0.5° × 0.5° resolved monthly mean temperature (Temp) and precipitation (Pre) climate data were obtained from the Climatic Research Unit Timeseries (CRUTS) 4.03 (land) dataset and averaged over the area of 121°–127° E and 50°–53° N to estimate the mean climate conditions of the study region. The 1968–2010 ERA-20 C sea level pressure (SLP), and the 1968–2018 200 hPa geopotential height from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis dataset were obtained. The 1968–2017 CRU self-calibrating Palmer Drought Severity Index (scPDSI) and the 1979–2016 evapotranspiration (Eva) of the Common Land Model ERA-interim were extracted from the Koninklijk Nederlands Meteorologisch Instituut.
2.3. Analysis

Pearson correlation coefficients ($R$) (Pearson 1895) between the monthly AMO, PDO, Niño 3.4 index, and MJJA total fire frequency were calculated to determine the key season of large-scale climate oscillations modulating the fire occurrence. Pearson correlation analysis was also conducted to estimate the effect of regional climate on fire occurrence and the connections between AMO and regional climate variabilities. Fire and climate data were low-pass filtered by 10 year loess smoothing to detect potential regime shifts (Cleveland and Devlin 1988).

3. Results

3.1. Fire frequency and burned area

A total of 908 lightning-ignited fires occurred in the Greater Khingan forest from 1968 to 2018, accounting for 48% of the total fire occurrence, with a total burned area of 350 857 hm$^2$. The fire frequency significantly increased ($\text{slope} = 0.55 \pm 0.17 \text{ year}^{-1}$, $P < 0.01$, 1968–2018). The $R$ between fire frequency and the mean MJJA temperature reached 0.47 ($P < 0.01$), and the mean MJJA scPDSI reached $-0.44$ ($P < 0.01$), suggesting the connection between hot-drought severity and lightning-ignited fire occurrence.

3.2. Lightning-ignited fire frequency and climate variability

Figure 2(a) shows that the AMOs of the previous October and December and the current January are significantly ($P < 0.05$) and positively correlated with MJJA fire frequency. For convenience, we establish November of the previous year to January of the
current year as the AMO’s key season. Although nonsignificant for some months, the correlation coefficients were all positive from the previous July to the current September, implying a persistent tele-connection between the previous SST of the Atlantic Ocean and lightning-ignited fire occurrence in MJJA. In contrast, no significant correlation was found for fire occurrence with the PDO and ENSO (figure 2(b) and (c)).

To understand the mechanisms connecting the AMO, regional climate and fire occurrence, correlation analysis of the key-season AMO and MJJA climate parameters was conducted and is presented in figure 2(d). The results showed that both the mean temperature and evapotranspiration were significantly and positively correlated with fire frequency and the AMO index ($P < 0.01$); Both the precipitation and the scPDSI were significantly and negatively correlated with fire frequency ($P < 0.01$). All these results suggested that a previous Atlantic SST could affect temperature–evapotranspiration variability and then modulate lightning-ignited fire in the study region (figure 2(d)). Although insignificant, precipitation and the scPDSI showed negative correlations with the AMO ($R = -0.09$, $P = 0.54$; $R = -0.27$, $P = 0.06$, respectively) (figure 2(d)).

Figure 3 shows the temporal variation of the key-season AMO, fire frequency, mean temperature, and evapotranspiration in the fire season (MJJA, 1968–2018). The 10 year smoothing has identified consistent negative to positive regime shifts in approximately 1998 for the AMO, fire occurrence, temperature, and evapotranspiration. Moreover, decadal AMO variation explained 81% and 73% variabilities of smoothed summer temperature and evapotranspiration, respectively, and contributed up to 54% variation of summer lightning-ignited fire (table S1 (available online at stacks.iop.org/ERL/16/024054/mmedia)).

To examine the effects of the AMO on temperature and evapotranspiration within a broader area, the spatial correlations between the key-season AMO with MJJA temperature and evapotranspiration were calculated (figures 4(a) and (b), respectively). The results suggested that a warm AMO had significant and positive impacts on temperature over the study region and most of the Eurasian continent ($P < 0.05$) (figure 4(a)). The highest correlations were observed
in southern Europe, the Arabian Peninsula, and the central part of East Asia. Significant and positive correlation of the AMO and evapotranspiration were identified in western Europe, central Mongolia, and the area around the study region (figure 4(b)). We also calculated differences for the summer temperature and evapotranspiration between the intervals of AMO positive phase (1998–2018) and the negative phase (1968/1979–1997) (figure S1), the results exhibited a significant \( (P < 0.05) \) hotter climate with higher evapotranspiration when the AMO phase is positive.

The previous warm AMO was followed by a significantly \( (P < 0.05) \) higher MJJA SLP over Northeast to North China, including the study region (figure 5(a)). Correspondingly, a previous higher AMO had a significant \( (P < 0.05) \) positive effect on the geopotential height of a similar area (figure 5(b)).

4. Discussion

4.1. Regional climate variability and lightning-ignited fire

Lightning-ignited fire is more related to climate variation than human-caused fire (Hu and Zhou 2014) and is responsible for large fires in boreal forests (Veraverbeke et al 2017). The significant positive correlations with temperature and evapotranspiration and negative correlations with moisture indicators such as precipitation and the scPDSI suggest that warm and dry conditions could increase fuel aridity, which favours high fire occurrence. Moreover, climate warming could lead to increased lightning strikes (Romps et al 2014, Romps 2019) and prolonged fire seasons (Westerling et al 2006, Fill et al 2019), both of which further elevate the possibility of lightning ignition (Cattau et al 2020). Although great fire suppression actions were taken after the 1987 fire in the study
region, the frequency of lightning-ignited fire generally increased with the warming of the climate.

4.2. Coherence of the AMO, temperature, and fire occurrence
The AMO, a near-global scale climate pattern with alternating warm and cool phases (Knight et al 2006), has driven interannual to multidecadal climate variabilities in the Pacific Ocean (Levine et al 2017, 2018). Moreover, the AMO was proven to be a promising predictor of future NH temperature variation (Delworth and Mann 2000, Wang et al 2017, Xie et al 2019). An AMO phase change from negative to positive occurred in 1998, which has largely amplified the global warming rates in addition to anthropogenic forcing (Zhang et al 2007, Gastineau and Frankignoul 2015, Hong et al 2017, Shi et al 2019). Similarly, we found synchronous phase changes in the AMO and MJJA temperatures in the late 1990s (figure 3) and a significant correlation of the AMO and temperature in the study region and the Eurasian continent (figures 2 and 4(a)). These results suggest that the previous AMO statistically modulated summer temperature variation at both interannual and multidecadal timescales. MJJA temperature warming could increase evapotranspiration ($R = 0.74, P < 0.001, 1979–2016$), further led to high fuel aridity and more frequent fire occurrence in addition to warming itself.

4.3. Mechanisms connecting the AMO, regional climate, and fire occurrence
A warm winter AMO was observed prior to significantly higher SLP and geopotential height in the following summer (figures 5 and S1). We assume a high SLP and associated descending atmospheric motion could lead to adiabatic warming according to the adiabatic lapse rate (Betts 1973, Lalas and Einaudi 1974), probably favouring fewer clouds and precipitation because the water vapour is less saturated. Less cloud could lead to more incoming solar energy, further enhancing the warming rate. An AMO targeted simulation using the atmospheric general circulation model showed that a zonal SLP dipole structure across the Atlantic–Eurasia region played a key role in connecting the Atlantic SST anomaly with the land surface temperature and precipitation of East Asia. A warm AMO causes low SLP with an upward
motion and upper-level divergence on the Atlantic Ocean. The outflow moves eastward and converges over East Asia, which induces atmospheric subsidence with anomalous high SLP (Shi et al 2019).

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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Figure 5. Spatial correlation coefficients of the key-season AMO and (a) MSL from May to August in 1968–2010 and (b) 200 hPa geopotential height from May to August in 1968–2018. The black rectangles show the region of the study area. The results are only shown where P < 0.05.
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