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Fire in the Earth System

Key Points:
- Four climatic stages identified between 6.2 and 1.3 cal kyr BP based on pollen and charcoal concentrations
- Climatic changes were linked to changes in East Asia Summer Monsoon intensity, which is mainly controlled by solar radiation
- The Toushe Basin experienced drought conditions and frequent paleowildfires during the El Niño years

Supporting Information:
- Supporting Information S1
- Data Set S1

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Abstract
We identified four climatic stages between 6.2 and 1.3 cal kyr before present (BP) based on pollen and charcoal concentrations by high-resolution Accelerated mass spectrometer (AMS) 14C-dated sediment profile from Taiwan’s Toushe Basin. From 6.2 to 4.6 cal kyr BP, the region was warm-wet with infrequent wildfires and dominant subtropical evergreen broad-leaved forests. The climate was cooler-drier from 4.6 to 3.0 cal kyr BP, with a decline in forest and increased fire frequency. From 3.0 to 2.1 cal kyr BP, climate further cooled and dried, with the development of alpine meadows and higher fire frequency. The region became warmer and wetter from 2.1 to 1.3 cal kyr BP, accompanied by forest recovery. Climatic changes were linked to changes in East Asia Summer Monsoon intensity, which is mainly controlled by solar radiation. Wildfires were likely controlled by precipitation variability that is influenced by East Asia Summer Monsoon and El Niño–Southern Oscillation. Toushe Basin experienced drought conditions and frequent wildfires during the El Niño years.

Plain Language Summary
The purpose of our study is to reveal the relationship between paleoclimate, vegetation, and wildfire. The study area is located in the Toushe Basin, central Taiwan. Through palynological and charcoal analysis, the vegetation, climate, and wildfire history of the past 6,000 to 1,000 years in the study area were reconstructed. The study found that after 4,600 years, the East Asian summer monsoon continued to weaken until approximately 2,000 years ago, during which time the climate was dry and cool, and wildfires were frequent. In addition, it is found that the climate in this region is mainly controlled by the changes in solar radiation. The cycle of climate change coincides with that of solar activity. In El Niño years, the Toushe Basin was dry and frequent wildfires occurred.

1. Introduction
Forest fires can significantly impact the regional environment. Wildfire records are important ecological indicators for paleoclimate and paleovegetation reconstructions (Bird, 1998; Harrison et al., 2010; Westerling et al., 2006). Several studies have investigated the history of forest fires around the world, including in Europe (Carrión et al., 2003; Finsinger et al., 2017; Vannière et al., 2012), North America (Brunelle et al., 2016; Filion, 1984; Lynch & Hu, 2004), South America (Bush et al., 2007; Pesenda et al., 2004; Whitlock et al., 2007), and Oceania (Edwards et al., 2008; Kershaw et al., 2002; Murphy et al., 2013). In contrast, paleofire research in Asia (Huang et al., 2006; Liu et al., 2010; Werf et al., 2008) and Africa (Ivory & Russell, 2016; Roberts & Wooster, 2008; Seydack et al., 2007) is relatively limited, particularly in tropical and subtropical regions. What is encouraging is that in recent years, fire events in the East Asian monsoon region have attracted more and more attention (Ma et al., 2018; Xue et al., 2018).

Research on forest fires has predominantly focused on the links between wildfire occurrence with climate change, vegetation, and human activity. For example, studies have found that increased fire activity is both a result and a cause of changing climate (Feurdean et al., 2017; Lee et al., 2015; Liu, Goodrick, & Heliman, 2014). Others studies have demonstrated that forest fires play a key role in vegetation succession (Finsinger et al., 2017; Gilromera, 2010; Stahle et al., 2017), and human activity has been found to strongly influence the occurrence of past wildfires, particularly after the mid-Holocene (Alizadeh et al., 2015; Kaal et al., 2011; Wang et al., 2013). Additionally, a number of studies have applied fire-climate models to reconstruct paleofires and to predict fire activity (Gerstner & Brette, 2009; Higuera et al., 2007).
Tree ring records in Northern China inferred a significant correlation between regional precipitation and the intensity of both the East Asia Summer Monsoon (EASM) and El Niño–Southern Oscillation (ENSO) (Gao et al., 2013). Compared to La Niña events, Chen et al. (2014, 2017) conclude that reduced precipitation and terrestrial water storage during and following El Niño events from 1997 to 2016 increased fire emissions in pantropical equatorial forests by 133%. In agreement a modeling study identified a strong correlation between massive wildfires in lowland Borneo and strong El Niño events during the past two decades (Taufik et al., 2017). Likewise, satellite data and statistical modeling research showed that ENSO-driven precipitation changes had increased forest fire activity by 51% in southern Africa from 2001 to 2012 (Andela & van der Werf, 2014). In South America, Chen et al. (2011) identified a correlation between the Oceanic Niño Index and the interannual fire activity in the eastern Amazon, whereas the Atlantic Multidecadal Oscillation index was more closely linked to the occurrence of forest fires in the south and southwest Amazon. A decadal-resolution Holocene pollen record from northeast China revealed synchronous ~500-year quasi-periodic changes of the EASM over the last 8,000 years, which was linked to ENSO (Xu et al., 2019). Along Track Scanning Radiometer data from July 1996 to December 2001 in Indonesia inferred a strong correlation between forest fires and the Southern Oscillation Index \( r = -0.75 \) and the Niño 3.4 index \( r = 0.72 \) in forested regions of the equatorial belt (5.5°S–5.5°N) (Fuller & Murphy, 2006).

Our study focused on the Toushe Basin located in a subtropical monsoonal region of Taiwan, which is very sensitive to the EASM. The Toushe Basin consists of 80 m thick lacustrine sediments, which formed before the last glacial period. The lake became a swamp in the early part of the last glacial period and dried up \(~1.7 \text{ kyr before present (BP)} \) (Liew, Huang, et al., 2006). The primary sediments in the basin are a muddy layer, a sand layer, and peat from lacustrine and swamp facies (Kuo & Liew, 2001). Previous studies have inferred a relatively warm and humid climate in the basin after 6.2 kyr BP, with a dominance of subtropical forests that later degenerated into subalpine meadow during the late Holocene (Li et al., 2013; Liew, Lee, et al., 2006; Tsukada, 1967). A study in Liyu Lake (Wang et al., 2020) near the Toushe Basin found similar results, and the authors suggested that there was significant agricultural activity between 2.7 and 2.4 and 1.5 cal kyr BP to the present.

Previous paleo-studies in the Toushe Basin have predominantly focused on the Pleistocene, while current Holocene studies, particularly during the middle and late Holocene, are relatively limited and low in temporal resolution. Moreover, current studies have predominantly focused on the relationship between vegetation and climate, while investigations into fire activity are still limited. Hence, it is of great significance to study the high temporal resolution climate of the middle and late Holocene in the Toushe Basin. Our study is focused on high resolution fire events, vegetation, and climate in the middle and late Holocene to (1) reconstruct the history of high-resolution fire activity in the study area from the middle and late Holocene, (2) reconstruct high-resolution vegetation succession from the middle and late Holocene, and (3) explore the relationship between fire events, vegetation, and climate in the study area.

### 2. Regional Setting

The Toushe Basin (23°49′N, 120°53′E) is located in the East Asian subtropical monsoon region (Figure 1a). The region’s climate is thus sensitive to variability in the EASM, where weaker summer monsoons result in annual drought conditions in Taiwan (Selvaraj et al., 2012). The Sun-Moon Lake Station (1,014 m) located 6-km north of the study area records an average annual precipitation of 2,341 mm, evaporation of 1,098 mm, and temperature of 19.2°C. The coldest monthly average temperature is 13.9°C, and the hottest monthly average temperature is 23.6°C. According to the lapse rate (5.4°C/1,000 m), the estimated annual average temperature in the Toushe Basin is 21.2°C (Liew, Huang, et al., 2006). The study area has an altitude of 640–650 m, and the elevation of the surrounding mountains is 900–1,000 m (Figure 1b). The study site lies within a relatively closed intermountain basin and is therefore less affected by human activity. The modern vegetation of the Toushe Basin (Figure 1c) is subtropical evergreen broad-leaved forest dominated by Fagaceae and Lauraceae, with species belonging to the following primary genera: *Machilus*, *Bellschmiedia*, *Phoebe*, *Sapium*, *Glochidion*, *Michelia*, *Cyclobalanopsis*, *Lithocarpus*, *Castanopsis*, *Quercus*, *Ardisia*, *Zelkova*, *Engelhardtia*, *Trema*, *Liquidambar*, *Rhus*, *Schefflera*, *Fraxinus*, *Lagerstroemia*, *Symplocos*, and *Sapindus* (Lin et al., 1968).
3. Materials and Methods

A sediment profile (280 cm; 120.90°E, 23.83°N; Figure 1) was obtained from Toushe Basin, which was dated via AMS-14C dating, after removing 34 cm of surface cultivated soil at 2-cm intervals (124 samples in total) for charcoal and palynology analyses. The plant functional type, defined by Liew (Liew, Huang, et al., 2006), was used to assign arboreal pollen into four groups: evergreen coniferous forest, evergreen broadleaf forest, deciduous broadleaf forest, and shrubs. Herbaceous pollen types were grouped as terrestrial taxa (nonarboreal pollen) or wetland taxa (aquatic and hygrophytes) according to their habitat preference. We also used 37 μm as a separation criterion between cultivated and wild Poaceae (Maloney et al., 1989). The ratio of microcharcoal and pollen was used to identify “false peaks” from the core record (Swain, 1973). In addition, we measured the magnetic susceptibility of all the samples. A detailed description of methodological procedures is provided in supporting information Text S1.

Figure 1. Map compilation of the study site, including (a) location map of the Toushe Basin and sites of nearby palaeoenvironmental records (1: Sanbao Cave, 2: Huguangyan maar lake, 3: YJ core, 4: Chitsai Lake, 5: Liyu Lake, 6: Dongyuan bog, 7: Retreat Lake, and 8: Daiyunshan); (b) digital elevation map of the study area; and (c) modern vegetation map of the study area.
4. Results

The sampling section was stable, mainly composed of 11 layers of interaction between clay and peat (Figure S2). The magnetic susceptibility of all 124 samples ranged from $-10.79$ to $22.79$ (SI, Système International), with lower magnetic susceptibility of the peat layer relative to the clay layer. A detailed description of the lithology and magnetic susceptibility is provided in supporting information Text S3.

Bottom (124 cm) age of core is 6.2 kyr BP and top (34 cm) age of core is 1.3 kyr BP. The deposition of the core can be divided into three stages. A detailed description of the age model is provided in supporting information Text S2.

We observed similar trends for the different macrocharcoal types, inferring the impact of wildfires on all vegetation types, and make no distinction between different vegetation types (Figure 2a). Moreover, the variabilities of macrocharcoal and microcharcoal were consistent, indicating consistency in the occurrence of fire events at regional and local scales. However, differences in these trends were also observed during a number of time periods. We identified six charcoal peaks indicative of high fire activity and frequency: Peak1 (6.2–6.0 cal kyr BP), Peak2 (5.3–5.1 cal kyr BP), Peak3 (4.5–4.1 cal kyr BP), Peak4 (2.4–2.2 cal kyr BP), Peak5 (1.9–1.6 cal kyr BP), and Peak6 (1.5–1.3 cal kyr BP).

A total of 95 taxa were identified, including 53 arboreal, 24 herbaceous, 8 aquatic, and 10 fern taxa (except at 256, 258, 260, 270, 274, 276, and 278 cm, due to the poor preservation of pollen grains), and the primary taxa were subtropical. The main results of the pollen analysis are shown in Figures 2b and 2c. We identified five prominent pollen zones based on pollen cluster analysis and sediment lithology. A detailed discussion on the pollen is provided in supporting information Text S4.

5. Discussion

5.1. History of Paleoenvironment Evolution During 6.2–1.3 cal kyr BP in Toushe Basin

The sedimentary, vegetation, and climate characteristics of the Toushe Basin during 6.2–1.3 cal kyr BP were divided into five stages based on the records of lithology, magnetic susceptibility, palynology, and charcoal.

Stage 1 (6.2–5.6 cal kyr BP): The region experienced high water levels and an open water lacustrine environment during 6.2–6.0 cal kyr BP. Fern spores were abundant due to higher surface runoff from offshore wetland vegetation (Zheng & Li, 2000). High arbor pollen counts infer the dominance of evergreen broad-leaved forests under a warm and wet climate. Low charcoal concentrations infer infrequent forest fire events.

Stage 2 (5.6–4.6 cal kyr BP): Dark brown peat with relatively low magnetic susceptibility indicates low water levels and a swamp environment. The peak in arbor pollen indicates a dominance of evergreen broad-leaved forests under a hot and humid climate. Low charcoal concentrations infer infrequent forest fire events.

Stage 3 (4.6–3.0 cal kyr BP): White clay with a high magnetic susceptibility indicates the transition to an open lacustrine environment with high water levels during 4.5–3.0 cal kyr BP. The rapid reduction of arbor pollen is indicative of forest degradation under a cooler and drier climate. The difference in macrocharcoal and microcharcoal concentrations indicates frequent regional fires and infrequent local fires.

Stage 4 (3.0–2.1 cal kyr BP): The sedimentary environment stabilized during this period, and the presence of peat indicates a swamp environment. The dominance of herb pollen during this period suggests a dominance of alpine meadow under cooler and drier climates. High charcoal concentrations indicate a high frequency of forest fires.

Stage 5 (2.1–1.3 cal kyr BP): The dominance of herb pollen during this period indicates swamp meadow vegetation similar to the present day. The presence of pollen taxa such as Poaceae (>37 μm) and Typha (Zhang et al., 2019) reflect the influence of human activity. High forest fire frequency during this period is inferred by high charcoal concentrations.

5.2. Dynamic Change of the EASM During 6.2–1.3 cal kyr BP in Taiwan Island

The change of solar radiation is the main driving force of EASM change as it was continuously decreasing throughout the Holocene (Figure 3a). In mid-Holocene, solar radiation was relatively higher resulting in...
Figure 2. Records of charcoal and pollen in Toushe Basin. (a) Macrocharcoal (arboreal charcoal = AP, herbs charcoal = NAP, and leaves of broadleaved plants = LF.) and microcharcoal concentrations in the Toushe profile; (b) lithology and pollen percent diagram for AP and NAP taxa with biostratigraphic zones determined by constrained cluster analysis (CONISS). (Percentages of all taxa are based on the sum of terrestrial pollen. Evergreen coniferous forest = ECF, evergreen broadleaf Forest = EBF, deciduous broadleaf forest = DBF, shrubs = Shr, and terrestrial herbs = NAP); (c) Lithology, wetland pollen, fern spores percentage, and terrestrial pollen and charcoal concentration diagram.
Figure 3. Comparisons between the pollen and charcoal records in the Toushe Basin with nearby paleoclimate records since 6.2 kyr BP, including (a) left, solar radiation in June at 25°N (Berger & Loutre, 1991), and right, reconstructed EASM index (Zhang et al., 2018); (b) left, integrated stalagmite δ¹⁸O record in South China (Yang et al., 2019), and right, stalagmite δ¹⁸O record in Sanbao Cave (Dong et al., 2010); (c) left, arboreal pollen percentage in Daiyunshan (Zhao et al., 2017), and right, arboreal pollen percentage in Huguanyan maar lake (Wang et al., 2007); (d) left, arboreal pollen percentage in the Toushe Basin (this study), and right, the PCA1 scores of the pollen record in the Toushe Basin (this study); (e) left, precipitation index in southern China (Ran & Feng, 2013), and right, reconstructed temperature anomaly in China (Fang & Hou, 2011); (f) left, ENSO frequency near the equator (Moy et al., 2002), and right, reconstructed ENSO index (Zhang et al., 2018); (g) west to east Pacific sea surface temperature (SST) gradient (Koutavas & Joanides, 2012); (h) left, the concentration of macrocharcoal in the Toushe Basin as a proxy for local fire (this study), and right, microcharcoal/pollen ratio in the Toushe Basin as a proxy for regional fire (this study).
an enhanced EASM and warm-wet climate, while in late Holocene, weak solar radiation led to an impaired EASM and cool-dry climate.

Marine records of pollen, total organic carbon, total nitrogen, and C/N in North Taiwan inferred increasing rainfall during 5.8–3.7 cal kyr BP (Chen et al., 2018), which was supposed to be because of the enhancement of EASM. An alpine lacustrine pollen record from North China suggests a maximum EASM intensity during 7.8–5.3 cal kyr BP (Chen, Xu, et al., 2015). In agreement, pollen records from the Dongyuan Bog (Figure 1a.6, Lee & Liew, 2010; Lee et al., 2010) inferred warmer temperatures during 8.2–4.1 cal kyr BP relative to the present day. Another pollen record from the Daiyun Mountain (Figures 1a.8 and 3c, Zhao et al., 2017) inferred that the EASM was strong and a warm and wet climate existed in southeastern China during 8.0–5.0 cal kyr BP. A warm period from 7.8 to 4.2 cal kyr BP was also deduced from pollen records from the Huguangyan Maar Lake (Figures 1a.2 and 3c, Wang et al., 2007). The intensification of the EASM during 7.0–5.5 cal kyr BP was also determined from a δ18O stalagmite record in the Sanbao Cave (Figures 1a.1 and 3b, Dong et al., 2010) and a stacked synthesized δ18O stalagmite record from China (Figure 3b, Yang et al., 2019). Reconstructed temperature anomalies for China (Figure 3e, Fang & Hou, 2011) also identified a warmer climate during the period 7.0–5.5 cal kyr BP. A period of high precipitation during 7.0–5.5 cal kyr BP was inferred from the application of the precipitation index in Southern China (Figure 3e, Ran & Feng, 2013). In our study, the high percentage of arbor pollen and the PCA1 score (Figure 3d) indicate a stronger EASM and a warmer and wetter climate during 6.2–5.5 cal kyr BP, which is consistent with the above research. In general, in both the south and north of China, EASM was strengthened during 8.0–5.0 cal kyr BP, resulting in a warm and humid climate.

A study from Retreat Lake (Figure 1a.7) suggests a weaker EASM during 4.5–2.1 cal kyr BP (Selvaraj et al., 2011). In agreement, arbor pollen counts from the Huguangyan Maar Lake (Wang et al., 2007) showed a rapid weakening of the EASM during 5.5–4.2 cal kyr BP, which is indicative of drier climates. The δ18O record in the Sanbao Cave (Dong et al., 2010) as well as the stacked synthesized δ18O record from China (Yang et al., 2019) also inferred a weakening of the EASM during 5.5–4.2 cal kyr BP. K/Al ratios in the YJ core (Figure 1a.3, Huang et al., 2018) further confirmed a weaker EASM during this period. In this study, a decline of arbor pollen (Figure 3d) also confirmed a weakening of the EASM in the Toushe Basin during this period. Moreover, an alpine lacustrine pollen record from North China revealed a rapid decline of the EASM since ~3.3 cal kyr BP (Chen, Xu, et al., 2015), and a nearby loess record also inferred a weakening of the EASM since 3.0 cal kyr BP (Lu et al., 2013). Therefore, the weak EASM during this period occurred not only in the Toushe Basin but also in various regions of South China recording regional, rather than local, climate change.

A pollen record in the Chitsai Lake (Figure 1a.4) in central Taiwan indicated dry climatic conditions during 3.7–2.0 cal kyr BP (Liew & Huang, 1994). Mountain loess-like sediments in central Taiwan also inferred a drier climate during 3.8–2.4 cal kyr BP (Wenske et al., 2011). In this study, the low arbor pollen percentages in the Toushe Basin during 3.8–2.0 cal kyr BP indicate drier conditions. In contrast, Selvaraj et al. (2012) observed a temporary strengthening of the EASM during 3.8–2.0 cal kyr BP in northern Taiwan, and pollen sediment records from the Ilan Plain in northeastern Taiwan also inferred wet conditions from 3.2 to 2.2 cal kyr BP (Lin et al., 2007). These observations infer a notable difference in the climatic response between central and northern Taiwan.

Increasing tree pollen concentrations in the Toushe Basin signify a warming climate during 2.1–1.3 cal kyr BP, and higher percentages of fern spores and wetland taxa are indicative of wet conditions. Some cash crops such as Poaceae (>37 μm) and Typha occurred in low percentages, which indicates a gradual influence of human activity near the research site, but in low level. Our findings are in agreement with Liew et al. (2014) who identified a warming period during 1.9–1.6 cal kyr BP, and lacustrine geochemical indicators in northeastern Taiwan also inferred wet conditions since 2 cal kyr BP (Selvaraj et al., 2012).

In brief, during 6.3–5.0 cal kyr BP, a higher solar radiation resulted in an enhanced EASM and warm-wet climate in both southern and northern China, while during 5.0–2.0 cal kyr BP, a weaker solar radiation caused to an impaired EASM and cool-dry climate in both southern and northern China. After 2.1 cal kyr BP, the climate in Toushe Basin became wet, and human activity began to take place.
5.3. Links Between Fires and ENSO During 6.2–1.3 cal kyr BP in Toushe Basin

El Niño is defined as the irregular development of an anomalously warm pool of surface water in the eastern tropical Pacific lasting 12–18 months (Glantz, 2001). ENSO plays an important role in the regulation of precipitation in the western tropical Pacific (Kim & Ha, 2015; Yim et al., 2016). The occurrence of wildfires requires sufficient fuel, oxygen, and temperature to reach the ignition point. We assume temperature to be the dominant control on wildfire occurrence in the Toushe Basin, as fuel and oxygen were in sufficient supply at our study site. Precipitation is also a dominant control on wildfire occurrence, as high fuel humidity reduces the ignition point. We observed a strong correlation between charcoal concentration (Figure 3h) and ENSO frequency (Figure 3f) in the Toushe Basin. High ENSO frequency during 5.3–4.8 and 2.8–1.3 cal kyr BP correlated with peaks in charcoal concentration, indicating frequent wildfire occurrence during these periods. The west to east sea surface temperature anomalies in the tropical Pacific (Figure 3g, Koutavas & Joanides, 2012) are commonly used to determine the ENSO state, where negative/positive values indicate the dominance of El Niño/La Niña events, respectively. According to Figures 3g and 3h, charcoal peaks typically coincide with El Niño years. El Niño years typically have lower precipitation according to winter and spring observational precipitation data in South China from 1953–1994 (Chen et al., 2014).

Therefore, we confirm that the climate was relatively dry with frequent wildfires during El Niño years in the study region. Similar results were also inferred in northeast China. For example, analysis of fire-scarred trees in northeast China from 1774–2010 inferred a dominance of regional wildfires during drought conditions of El Niño years, which also coincided with positive phases of the Pacific decadal oscillation and negative phases of the North Atlantic oscillation (Yao et al., 2017). Moreover, satellite data of pantropical forests during 1997–2016 inferred peak fire activity in equatorial Asia during the early part of the ENSO cycle when El Niño was strengthening (August–October) (Chen et al., 2018). In agreement, massive wildfires in lowland Borneo over the past two decades were found to occur during years of hydrological drought, coinciding with strong El Niño events (Taufik et al., 2017).

We conclude that El Niño years were characterized by relatively dry climatic conditions, which triggered the occurrence of wildfires in the Toushe Basin and the wider East Asia region.

5.4. Possible Forcing Mechanisms of EASM and ENSO in Taiwan Island

In previous studies, numerous evidences have shown that the intensity of EASM is controlled by changes in boreal summer solar insolation (Cheng et al., 2016; Wang et al., 2001). Recently, there are increasing researches suggesting that the change in boreal summer solar insolation is not the direct factor in EASM change (Chiang et al., 2020; Xu et al., 2020). As one of the main processes that regulates the interannual variability of the atmospheric circulation at intercontinental and global scales, ENSO has been widely studied (Chen, Lian, et al., 2015; Chen et al., 2020; McPhaden et al., 2006). Western Pacific subtropical high (WPSH) is a high-pressure system in the western subtropical North Pacific which plays an important role in summer precipitation in East Asia (Rong Hua et al., 2006; Wu & Zhou, 2008; Yu et al., 2019). Modern observation records show that colder SSTs in the tropical western Pacific will lead to a weaker convective activity in the Philippines, causing this instance the WPSH will turn to southwestward shift; eventually, it will lead to wet conditions in south China and dry conditions in north China (Huang & Sun, 1992). A study based on speleothem oxygen isotope records (from 1979 to 2017) suggests that changes to the seasonal migration of westerlies across the Tibetan Plateau are the dominant cause of East Asian paleomonsoon changes (Chiang et al., 2020). In our study, at mid-Holocene, the SSTs in the tropical western Pacific were relatively lower; therefore, the convective activity in the Philippines weakened, and a southwestward shift of WPSH occurred leading to a humid condition. In this warm and wet condition, trees and shrubs flourished and forests thrived. While from middle to late Holocene, SSTs in the tropical western Pacific gradually increased; then, the convective activity in the Philippines enhanced and an northeastward shift of WPSH occurred causing a dry condition. With a relatively dry climate, coupled with the impact of early human activities, trees and shrubs decreased and forests gradually degraded, and finally, it became a modern Alpine swamp grassland.

As an important source of Earth’s interannual climate variability, ENSO’s response to global warming remains uncertain (Collins et al., 2010). Through a simulation study, Liu, Wen, et al. (2014) found that the intensity of ENSO during the Holocene was caused by increasing positive ocean-atmosphere feedbacks. Reconstructed ENSO index (Zhang et al., 2018; Figure 3f) by simulation suggested that the intensity of ENSO
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Data Availability Statement
The raw data and details used in this paper can be obtained online (https://issues.pangaea.de/browse/ PDI-22568)

6. Conclusions
We present a high-resolution middle to late Holocene (6.2–1.3 cal kyr BP) paleoclimate record of vegetation, fire, and climate based on pollen and charcoal proxies in the Toushe Basin. Based on the pollen, charcoal analysis, magnetic susceptibility, and lithological data, we reached the following conclusions:

1. Changes in climate during 6.2–1.3 cal kyr BP were closely linked to the intensity of the EASM, in which a stronger EASM resulted in warmer and more humid climate. Similar results were observed in a number of records from southern China. The period 6.2–4.6 cal kyr BP was characterized by a warm and wet climate dominated by subtropical evergreen broad-leaved forest. The climate cooled and dried and forested regions declined during the period 4.6–3.0 cal kyr BP. The EASM continued to weaken, leading to a cooler and drier climate as well as the development of alpine meadows during 3.0–2.1 cal kyr BP. A warmer and wetter climate developed during 2.1–1.3 cal kyr BP, with increased forest development and the appearance of low levels of human activity.

2. The frequency of fire events increased under drier climates. A weakening EASM during 4.6–2.1 cal kyr BP resulted in a drier climate and increased frequency in the occurrence of forest fires. Charcoal concentrations reached a maximum at the beginning (4.5–4.1 cal kyr BP) and end (2.4–2.2 cal kyr BP) of this period. Charcoal concentrations correlated with ENSO frequency during 2.1–1.3 cal kyr BP, suggesting the dominant influence of ENSO on fire activity in the study area. The climate in the study area and in the wider East Asia region during El Niño years was relatively dry, which likely facilitated the occurrence of frequent wildfires.

was correlated with the record of ENSO frequency near the equator (Moy et al., 2002; Figure 3f). Meanwhile, the intensity of ENSO has a strong correlation with our records of pollen and charcoal (Figures 3d and 3h). The change in pollen can indicate different moisture and heat conditions. The peak intensity of charcoal revealed frequent wildfires, which were mainly controlled by dry conditions. During El Niño years, the Toushe Basin was relatively dry, and hence, forest loss and wildfires became frequent.
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