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Impacts of recent climate extremes on spring phenology in arid-mountain ecosystems in China

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ABSTRACT

Phenological responses of terrestrial ecosystems to climate extremes are of growing concern due to the increasing frequency and intensity of extreme climatic events associated with climate change which will in turn affect vegetation seasonality more than gradual changes. However, studies are rare in arid mountain regions where plant development is commonly regulated by both temperature and precipitation. To better understand how arid mountain (AM) ecosystems may respond to climate anomalies, we identified recent extreme climatic events (including intense warming, severe drought, and excessive wetness), and analyzed spring onset of vegetation growth in the Qilian Mountains of northwestern China. Phenological sensitivity was assessed from satellite-based data as departures from maps displaying mean onsets of growth for years 1983–2013. Our results revealed remarkable shifts in the start date of the growing season (SOS) under climate extremes, with different responses depending on ecosystem and altitude. Recent warming induced a general advancement of SOS. Higher spring temperatures enhanced the accumulation of heat needed for budburst and leaf expansion; elevated winter temperatures reduced the chilling days before bud dormancy release, significantly decreasing the risk of freezing injury in AM plants. Changes in SOS observed in this study suggested that AM plants may have relatively low chilling requirement for dormancy release. Contrary to warming, a drought resulted in a widespread delay in spring phenology, with sensitivity peaking over a shrubland ecosystem at medium elevations. This result demonstrated that subalpine shrubs were most susceptible of the studied ecosystems to hydroclimatic extremes, highlighting the great importance in this biome of concerns. Moreover, during the year when multiple extreme events (e.g. intense warming and heavy rainfall) coincided, their combined influence appeared to arise from synergistic mechanisms that are in urgent need of further research.

1. Introduction

Climate change places the structural and functional stability of terrestrial ecosystems at risk, with possible effects on the patterns of biogeographical distribution, interactions with the physical environment, and on species diversity and persistence (Walther et al., 2002; Parmesan and Yohe, 2003; Heyder et al., 2011). Several studies documented a close coupling of the dynamics of plant growth and animal migration over the past decades with patterns of climate change (Nemani et al., 2003; Thuiller et al., 2005; Richardson et al., 2013). Recent research indicates that extreme climate events increased dramatically in the frequency, intensity, duration, and spatial extent during the course of climate change over the past half century (e.g. Menzel et al., 2011; Butt et al., 2015; Ma et al., 2015). These extreme changes impose a substantial challenge on natural ecosystems because extreme climate may exceed the ability of species to adapt to new conditions through phenotypic plasticity or adaptive evolution, and may result in a decrease in fitness and a potential increase in the risk of local extinctions (Ghalambor et al., 2007; Siegmund et al., 2016).

Vegetation phenology—the timing of annually-recurring growth events—represents a key attribute of ecosystem functioning, and plays an important role in regulating terrestrial biochemical cycles, such as energy exchange, water balance, and carbon sequestration (Badeck et al., 2004; Peñuelas and Filella, 2009; Richardson et al., 2013). Changes in phenology are among the first signals of adjustments in species responses to climate anomalies (Walther et al., 2002), and they have been unequivocally attributed to temperature variation (Menzel et al., 2011; Richardson et al., 2013). Though the evidence for

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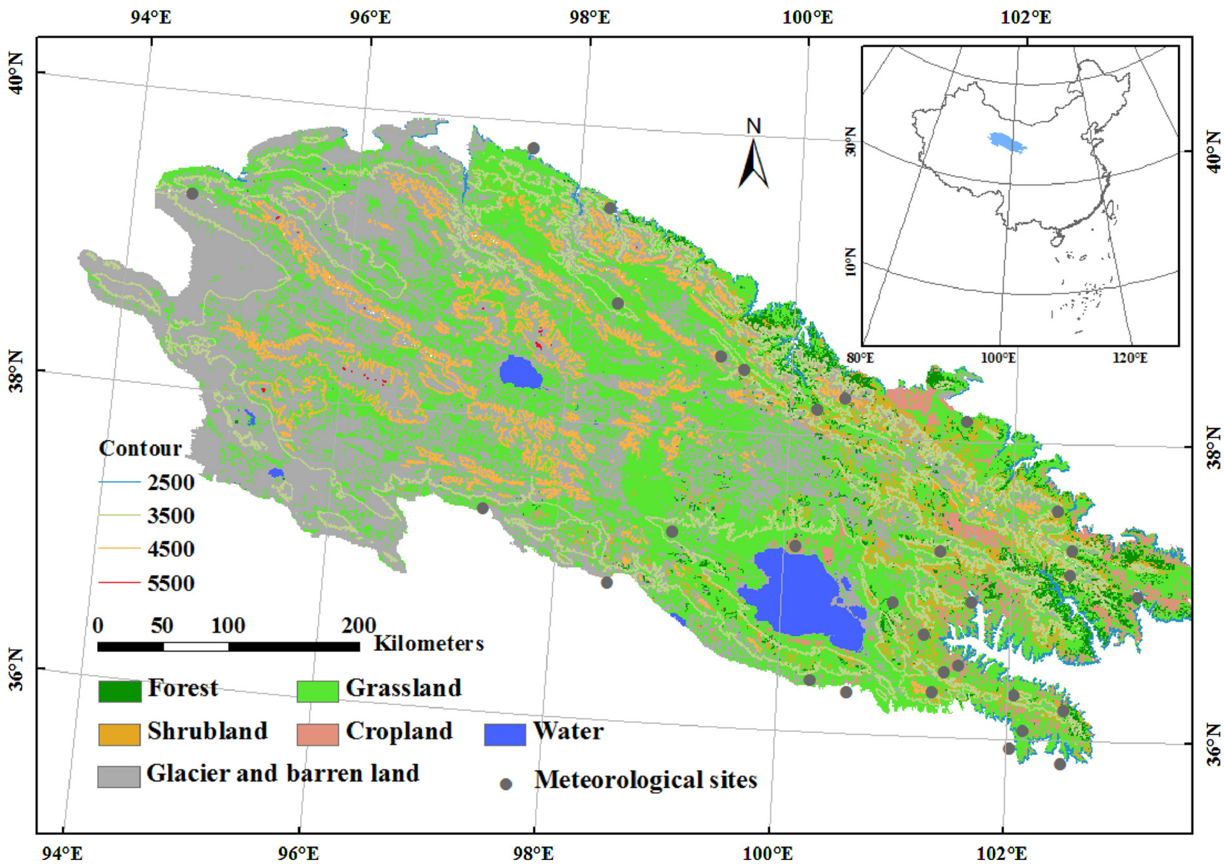

Fig. 1. Location of the Qilian Mountains and spatial distribution of meteorological stations.

phenology-climate relationships is increasing, the magnitude and direction of phenological responses to extreme climate events such as drought and heat spells remain largely uncertain. It is very likely that the seasonal trajectory of vegetation activities is more sensitive to the extremes than to the gradual changes in climate (Butt et al., 2015; Crabbe et al., 2016; Siegmund et al., 2016). During droughts, for example, severely-delayed or even undetectable phenological cycles were noted in dryland ecosystems in Australia (Ma et al., 2015). Indeed, phenological responses to climate extremes can be diverse and highly complex, and vary with the type of event, across regions, and among biomes. In a recent study of four shrub species in Germany, authors found a generally strong negative effect of temperature on flowering, but hardly any systematic influence of increased spring rainfall (Siegmund et al., 2016). In a mixed woody-herbaceous ecosystem, Rich et al. (2008) observed that herbaceous plants responded to a drought event faster, and tracked optimal growing conditions more closely than did woody plants. Across different climatic zones from northeastern to southeastern China, Zhang and Tao (2013) simulated changes in rice phenology, and reported that the rice growing season under extreme temperatures would decrease by up to 6 days at the national scale, but varied regionally, and in fact exhibited an opposite trend in the northeast. These findings highlight the imperative need to develop a greater knowledge of climatic controls on vegetation phenology, especially of the effects of extreme events on species in regions that are infinitely sensitive to climate change.

Arid mountains (AMs) constitute a special geomorphic unit that develops in arid/semi-arid climate zones at high altitudes. The environmental components are affected by the climate type of baseband, and exhibit characteristics of vertical zonality. AMs normally act as islands of biodiversity in relatively barren areas, and are rich in rivers that nourish piedmont oases and natural plants (Diaz et al., 2003). Because of high heterogeneity in landscape types, AMs have long been regarded among the most fragile environments in the world (Nogués-Bravo et al., 2007). Biomes in the AMs are undergoing profound changes due to recent climate anomalies (Beniston, 2003; Crimmins et al., 2010; He et al., 2015). In particular, alterations in the temporal niche of vegetation phenophases caused a significant concern among ecologists (Lesica and Kittelson, 2010; Du et al., 2014; Prevéy and Seastedt, 2014; Zhou et al., 2016). Additionally, the magnitude of climate change in the northern-latitude mountains including AMs is often greater than that in other natural systems (Nogués-Bravo et al., 2007). In China, northwest inland AMs experienced a rapid temperature rise of 0.26 °C per decade during the past 50 years, higher than the national rate of 0.14 °C/decade (Du et al., 2014). More importantly, ongoing occurrences of many types of climatic extremes, such as heavy rains and high nighttime temperatures, have become extraordinarily frequent (Lin et al., 2017). Extreme winter warming has also been observed recently, conditions that were rare or unprecedented in early climatological records (Lin et al., 2017). With abrupt warming, the timing of leaf-unfolding in subalpine shrubs in the AMs exhibited a significant trend toward earlier dates, at about 3.7–4.9 days per decade (He et al., 2015). Changes in ecological functioning of AMs are thought to be closely associated with extreme climate events, indicating great uncertainty in the role of arid mountain ecosystems in regional carbon cycling.

Two of the most critical climate variables regulating phenological dynamics of AM plants involve temperature and precipitation; vegetation activity at high altitudes is often affected by temperature variability, while plant growth in lowlands tends to be limited by water stress (Crimmins et al., 2010). The interaction between temperature and precipitation compounds the difficulty with understanding the mechanism of phenological responses (Lesica and Kittelson, 2010). In addition, snowmelt in some high-altitude ecoregions such as the Tibetan Plateau, where snow accounts for most of the precipitation (Wang et al., 2013), often provides an important supplemental water source,