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Warming-induced unprecedented high-elevation forest growth over the monsoonal Tibetan Plateau

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Abstract

Growth of high-elevation forests is generally temperature-limited and thus sensitive to warming. The Tibetan Plateau has experienced fast warming rates associated with decreased summer monsoon rainfall over the last century. However, whether such warming and monsoon-induced drought could offset a potential warming-driven enhancement of forest growth has not been examined. Here, we have compiled high-elevation forest growth data at 40 sites over the monsoonal Tibetan Plateau (MTP), and combined them in a high-elevation forest growth index (HEFGI) spanning 1567–2010. Tree growth in this region was significantly and positively correlated with July–October minimum temperatures during 1950–2010 ($R^2 = 0.53$ $P < 0.001$), and insignificantly coherent with soil moisture and precipitation. The HEFGI of MTP reaches its highest values from the 2000s onwards. This result suggests that the mean HEFGI of MTP has not been negatively affected by the current drying trend and responded positively to increased temperatures.

1. Introduction:

Annual tree growth at high latitudes and altitudes is generally limited by temperature (Korner 1998, Rossi *et al* 2007). Therefore, warming is expected to increase growth in such forests. However, increased dry condition associated with global warming has been reported in both observations and model simulations (Dai 2013). This 'global-change-type drought' has been profound since the beginning of the 20th century (Marvel *et al* 2019), and has led to a worldwide acceleration of forest mortality and decreases in growth rate (Adams *et al* 2009, Carnicer *et al* 2011, Choat *et al* 2012, Allen *et al* 2015).

Forest growth at high elevations was assumed to benefit from climate warming, as low growing season temperature has been the main limitation (Rossi *et al* 2007). Enhanced high-elevation forest growth was observed (Salzer *et al* 2009, Qi *et al* 2015, Dulamsuren *et al* 2017, Wang *et al* 2017). However, constant, even declined alpine forest growth in association with warming induce moisture limitations was increasingly reported, mainly in the dry areas, such as northwest China, Himalayas and north-eastern

TP (Liang *et al* 2014, 2016, Wu *et al* 2015). The monsoonal Tibetan Plateau (MTP), which received abundant precipitation from South Asian monsoon, is experiencing both fast warming and drying trends (Liu and Chen 2000, Pepin and Lundquist 2008, Wang *et al* 2014). Lots of studies have been conducted for climatic response of alpine forests over the MTP (Borgaonkar *et al* 2011, Liang *et al* 2014, Huang *et al* 2017, Guo *et al* 2019). However, the diverse results based on a few species, or at very local spatial scale are unable to represent the MTP regional mean response pattern.

In order to understand whether the mean growth rate of high-elevation forests over the MTP is stimulated by warming or suppressed by moisture limitation, we developed a tree-ring width (TRW) dataset using 40 forest sites with 6 genera at elevations ⩾3700 m a.s.l. The TRW data were processed following standard dendrochronology methods (Fritts 1976) to compute the local high-elevation forest growth index (HEFGI, see section 2). All local HEFGIs were averaged to estimate the mean HEFGI of the MTP. Local and MTP HEFGIs were calibrated to climate variables to test the climate-growth patterns at local scale and across the MTP.

2. Materials and methods

2.1. Study region and climate data

The Tibetan Plateau, the highest and most extensive plateau in the world, has experienced a much faster warming rate than the global mean and regions at similar latitudes (Liu and Chen 2000). This trend has continued during the warming hiatus period of 1998–2012 (Duan and Xiao 2015) with continued warming at high elevations (Pepin and Lundquist 2008, Wang *et al* 2014). Meanwhile, the South Asian summer monsoon, the main source of summer precipitation to most of the Tibetan Plateau south of 33°N (hereafter monsoonal Tibetan Plateau, MTP, defined as 75–104°E, 27–33°N, figure 1) (Tian *et al* 2001), has weakened over the last century (Yao *et al* 2008, Salzmann and Cherian 2015).

Summer precipitation on the Tibetan Plateau is dominated by the Asian summer monsoon south of ~33°N and by westerlies further north (Tian *et al* 2001, Yao *et al* 2013). Our study domain is bounded by 75–104°E, 27–33°N and is thus under the monsoonal regime. This area is also the most forested region of the Tibetan Plateau. Monthly climate data, including precipitation, self-calibrated Palmer drought severity index (scPDSI), minimum and mean temperature (MinT and MeanT, respectively) covering 1950–2010 were obtained from the Climate Research Unit (CRU) TS4.02 dataset (Harris *et al* 2014), which is a 0.5° by 0.5° gridded interpolation of existing instrumental data from meteorological stations. CRU data before 1950 is interpolated from distant meteorological stations and was not used.

2.2. Tree ring width data and HEFGI construction

We collected tree-ring width (TRW) measurements from 159 sites over the MTP (Filled circles in figure 1). Among them, 71 are from our own dataset, and 88 are from the International Tree Ring Data Bank (https://www.ncdc.noaa.gov/data-access/paleoclimatologydata/datasets/tree-ring). Sampling sites with elevations ⩾3700 m a.s.l were defined as high-elevation forests (red circles in figure 1), as 3700 m a.s.l corresponds to the lowest alpine treeline elevation recorded over the MTP (Singh 2018, Shi *et al* 2019). This resulted in 40 out of the 159 sites being selected as high-elevation forests. The trees at high elevations of MTP are almost all conifers, mainly Abies and Juniper (28 out of 40 sites); Picea, Larix, Tsuga and Sabina can also be found (12 out of 40 sites). The TRW data from each site were detrended and standardized into site-chronologies using the signal-free regional curve standardization (sf-RCS) with the CRUST software (Melvin and Briffa 2014a, 2014b). On average 18% and 35% of trees' start year fall in the first 50 and 100 years of each chronology, respectively (Table S1). After selecting the periods with EPS (Expressed Population Signal) values >0.85 (Wigley *et al* 1984), the chronologies of six different genera were *Z*-score normalized (subtracted by the mean value and divided by standard deviation) and averaged into one record representing the high-elevation forest growth index (HEFGI) of the entire MTP. By pooling data from 40 high-elevation forest sites with six genera, we assume that the local non-climatic signals inherent in the TRW records, such as species competitions, growth release and topography changes are largely cancelled out, and thus that the common climate signal is strengthened. Sections of the MTP HEFGI with replications of less than eight sites (equivalent to an EPS value of 0.90) were removed to ensure a well representative of the whole MTP.

2.3. *HEFGI* vs. *climate*

To determine the key climate factors controlling high-elevation forest growth, correlation and response functions between the HEFGI and 1950–2010 monthly CRU climate indices averaged over the MTP were calculated using Dendroclim2002 (Biondi and Waikul 2004). Both HEFGI and climate data were linearly detrended to ensure the reliability of the statistics. In order to test the temporal coherence stability, a 30-year moving correlation analysis was conducted between the 1950–2010 MTP HEFGI and key climate variables high-pass filtered by their 30-year loess smoothing trends. At a local scale, each of the high-elevation TRW chronologies was regressed to

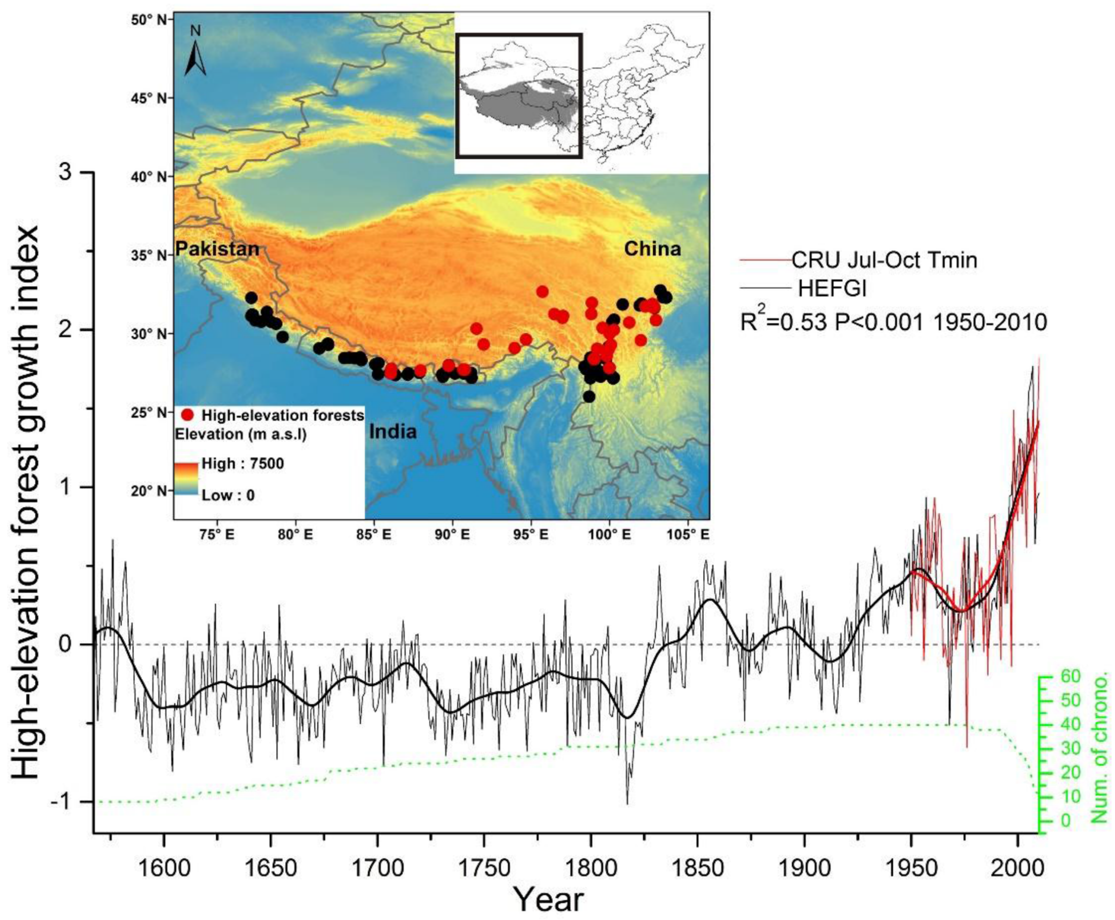

Figure 1. Inset map. Filled circles are locations of all tree-ring width records available over the MTP; red filled circles are the 40 high-elevation forests (growing at ⩾3700 m a.s.l). The grey shading in the inset box highlights the region of Tibetan Plateau (elevation > 3000 m a.s.l). The thin black and red lines show high-elevation forest growth index (HEFGI) and July–October averaged minimum temperature (MinT) of the MTP, respectively. Thick lines represent their 30-year loess smoothing. The dashed green line corresponds to the number of TRW chronologies combined for HEFGI of the MTP.

the key climate variables of the corresponding CRU grid point over 1950–2010.

3. Results

3.1. High-elevation forest growth index (HEFGI) of the monsoonal Tibetan Plateau (MTP)

The mean correlation coefficient among HEFGIs is 0.46, suggesting a large common variability embedded in these records. The mean HEFGI in figure 1 depicts an above-average growth rate since the 1820s with an unprecedented growth enhancement since the 1980s, with highest values from 2000s onwards. The lowest growth rate was found in 1817–1819, two years after the 1815 Tambora volcanic eruption (Stothers 1984). HEFGIs composited by genera showed Abies, Juniper and Larix have experienced an above-average growth rate and an unprecedented fast growth since the 1820s and the 1980s as well (supplementary figure 1 (stacks.iop.org/ERL/15/054011/mmedia)).

3.2. *Tree growth* vs. *climate indices*

Significant positive correlation was found between the HEFGI and July–October minimum temperature (MinT) from instrumental records (figure 2(a), 1950–2010) suggesting that the HEFGI was mainly dominated by thermal variability in the warm season. No significant correlation or response was found between HEFGI and moisture variability (here the self-calibrated Palmer drought severity index scPDSI and precipitation) (figures 2(a) and (b)). A total of 53% of the HEFGI variability on the MTP between 1950 and 2010 can be explained by the July–October averaged MinT (figure 1). Moreover, the 30-year moving correlation coefficients between the high-pass filtered HEFGI and MinT are significant above 95% level over 1950–2010 in spite of a general decreasing trend (figure 2(c)). Thesame analysis for HEFGI and scPDSI shows the significance level is below 95% within the entire instrumental period (figure 2(c)).

The Pearson correlation coefficients of individual site-level HEFGI time series with July–October MinT, precipitation, and scPDSI derived from the

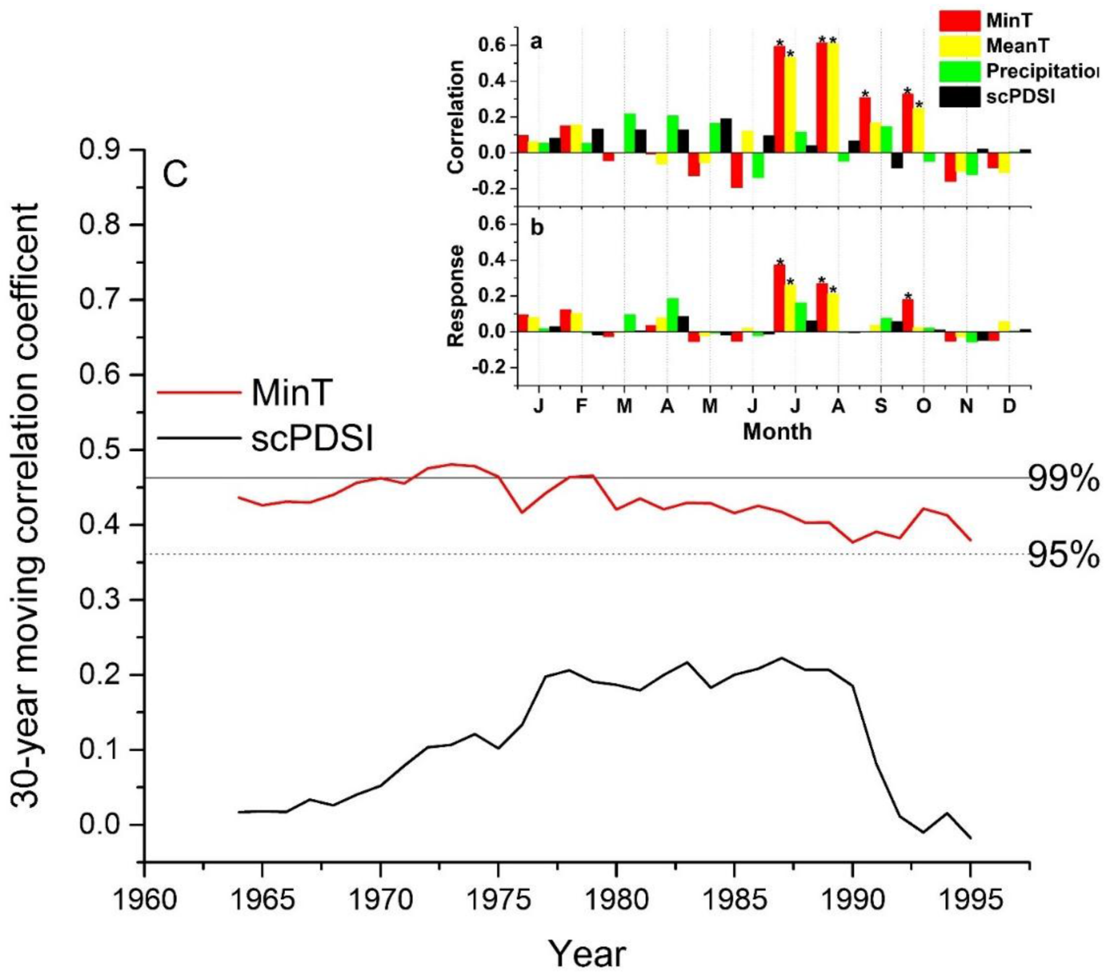

Figure 2. Top right insert: monthly correlation (a) and response (b) coefficients of high-elevation forest growth index (HEFGI) and 1950–2010 regional averaged CRU climate indices of the monsoonal Tibetan Plateau (MTP) (75–104°E, 27–33°N), including minimum temperature (MinT), mean temperature (MeanT), precipitation and scPDSI. All data used for this analysis were linearly detrended. *: Statistically significant above 95% level. Main figure: 30-year moving correlation coefficients of the HEFGI with july–october MinT and scPDSI over the MTP (c), all data used here were high-pass filtered by their 30-year loess smoothing trends.

corresponding Climate Research Unit (CRU) grid points are shown in figures 3(a)–(c), respectively. Thirty-three out of the 40 chronologies were positively correlated with MinT (18 of which at 95% significance level). Whereas 26 and 25 chronologies exhibited positive correlations with precipitation and the scPDSI, respectively; only 2 and 8 being significant at the 95% level.

4. Discussion and conclusion

A weakening of the South Asian summer monsoon intensity over the last century has been recorded in instrumental observations (Roxy *et al* 2015), glacier accumulation and tree-ring stable isotopes across the MTP (Davis *et al* 2005, Sano *et al* 2012, Wernicke *et al* 2015) (supplementary figure 2). This July–October rainfall was decreasing over 1950–2010, compounded by rapid warming and generally large evaporation rates (supplementary figure 3), has increased hydrological stress on the MTP vegetation growth (Liang *et al* 2014, 2016). However, site-specific results analyses over a large elevation belt show a dominant and constant relation between forest growth and July–October MinT, and a much smaller effect of water availability variables on tree growth. The low correlations observed with moisture availability could also due to the inaccuracy of gridded datasets to represent the high spatial variability in moisture availability. Furthermore, the mean HEFGI is closely related to the MTP averaged MinT at interannual and decadal time scales, despite the increasing temperature, decreasing precipitation, and accelerating drought stress shown by the instrumental records in recent decades (supplementary figure 3). We thus conclude that the drying and warming trends over the MTP have not reached the level beyond which overall high-elevation tree growth show signs of hydrological stress, although warming-induced drought stress and associated growth declines were reported at some alpine treeline forests in the Himalayan region (Liang *et al* 2014).

The 1815 Tambora Eruption led to the coldest period over the last millennium (Ahmed *et al* 2013,

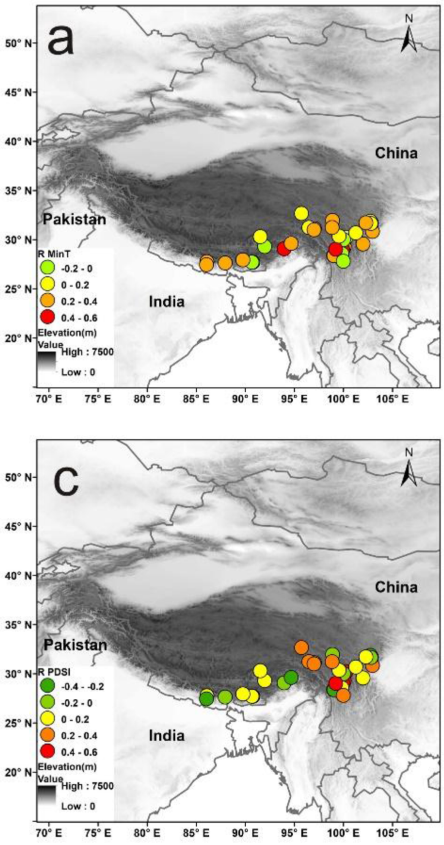

Figure 3. Correlation coefficients between high-elevation tree-ring width chronology and CRU mean July–October minimum temperature (a), total precipitation (b) and mean scPDSI (c) of nearest grid point with the 1950–2010 climate data.

Stoffel *et al* 2015), which coincided with the lowest HEFGI. Paleoclimate studies have shown that the Tibetan Plateau and much of the Asian continent have experienced an unprecedented warm period in recent decades relative to the last millennium (Ahmed *et al* 2013, Wilson *et al* 2016). The HEFGI of the MTP paralleled the fast warming trend from the 1970s and reached a growth rate in the 2000s that was unprecedented over the past 444 years (figure 1), even when the instrumental climate conditions were prone to the moisture limitation condition (supplementary figure 3). The abrupt growth enhancement is not due to decreased tree replications because there are 28 trees on average at the end year of chronologies (supplementary table 1).

Although increasing CO_2 has been projected to increase plant water-use efficiency and could stimulate forest growth (Keenan *et al* 2013), the HEFGI of the MTP is unlikely to be enhanced by increasing CO_2 concentrations since high-elevation forest growth is largely thought to be limited by low thermal availability in the growing season (Korner 1998, 2003, Hoch *et al* 2002, Korner and Paulsen 2004) rather than by scarcity of photosynthetic products, as higher concentrations of photosynthetic products (non-structural carbohydrates) are observed for trees growing at higher elevations on the TP (Shi *et al* 2006). Moreover, decreasing HEFGI values from the 1950s to the 1970s closely followed the cooling trend detected in the instrumental record (figure 1), while the air CO_2 concentration continued to increase, although such finding does not preclude per se the possibility of CO_2 concentrations affecting tree growth in future, non-analogous conditions.

The warming-enhanced forest growth is not limited to the alpine treeline ecotone, as observed in western north America (Salzer *et al* 2009), but was found over a wide elevation range in the sub-alpine forests of the MTP in this study and alpine treeline forests on the south-eastern TP (Shi *et al* 2019). Synchronous growth enhancement of treeline and sub-alpine forests was also reported in the European Alps (Paulsen *et al* 2000). However, with a lasting warming and drying trend, there are still large uncertainties for future hydrological conditions and high-elevation forest growth trends.

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Data availability statement

The climate data used are available at http://www.cru.uea.ac.uk/data. Part of tree-ring width data are available at the International Tree-Ring Data Bank (ITRDB, https://www.ncdc.noaa.gov/data-access/paleoclimatology-data/datasets/tree-ring). The rest tree-ring width data that support the findings of this study are available from the corresponding author upon reasonable request.

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