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Ages of major Little Ice Age glacier fluctuations on the southeast Tibetan Plateau derived from tree-ring-based moraine dating

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ABSTRACT

Advances and retreats of glaciers on the Tibetan Plateau (TP) are widely regarded as indicators for climate changes sensitive to macroclimatic forcing mechanisms like the Asian summer monsoon. However, it often remains unclear why some glaciers retreat or advance earlier than others, particularly regarding the timing of the so-called 'Little Ice Age (LIA) maximum'. Within this study, we present newly acquired tree-ring data from four glacier forefields in the Nyainqêntanglha Range on the southeastern TP and link them to previous studies. Two of the glaciers formed a double-tongue moraine set during the LIA, with trees providing minimum ages for two different major glacier extents. In combination with evidence from a third glacier, three warm phases within the generally cold LIA can be deduced during the first half of the 16th century, and the mid-17th and 18th centuries. This implies the occurrence of three preceding major cold spells. A minor cool phase between 1790 and 1850 marks the end of the LIA on the southeast TP. Minimum ages for beginning retreat from the last major LIA glacial advance differ by only 40 years for all sampled monsoonal temperate valley glaciers in the Nyainqêntanglha Range. This implies a common forcing, whose impact on glacier dynamics is only slightly altered by topographical factors or local climatic conditions. Regression analysis suggests that the delay of the glacier retreat from the maximum extent is mainly related to glacier size, with minor influence of ablation area aspect. All moraine ages highlight intermediate LIA warm phases on the southeast TP corresponding to warm phases on the northern Hemisphere and thus prove monsoonal temperate glaciers to be highly sensitive archives for northern hemispheric climatic conditions.

1. Introduction

The monsoonal temperate glaciers of Southeast Tibet are very sensitive to climate change, as both yearly accumulation and ablation mainly occur during the summer months (Fujita and Ageta, 2000; Liu et al., 2010). The Asian Summer Monsoon is driving glacial mass balance and glacier response to climate change in southeast Tibet, an area of high importance for the water supply of the densely inhabited surrounding lowlands (Immerzeel et al., 2010). Temperature has a particularly pronounced effect on glacier dynamics, which is supported by the huge landforms shaped by glacial advances associated with cold phases between 1350 A.D. and 1850 A.D., the so-called 'Little Ice Age' (LIA; Bradley and Jones, 1993; Wanner et al., 2008; Mann et al., 2009).

The maximum of the LIA glaciation as well as phases of glacier advances and retreats, are distinctly varying between and within different parts of the Tibetan Plateau (TP; Yi et al., 2008; Xu and Yi, 2014). It has been stated by numerous authors that topographic factors and local climate conditions play an important role for glacier mass balance and equilibrium line altitude (ELA) (Benn and Lehmkuhl, 2000; Owen and Benn, 2005), and also on the succession dynamics of trees in glacier forefields (Sigafoos and Hendricks, 1969; Villalba et al., 1990). Although the eastern Nyainqêntanglha Range is one of the most heavily glaciated areas in high Asia and thus a key region to be affected by a changing climate, a comprehensive analysis of the impact of topographic and climatic factors on moraine ages has not been carried out yet. Further research should therefore focus on retrieving high-quality moraine dating to enable the development of detailed models of regional glacial history. However, better understanding of former glacier movements is essential in order to evaluate today's glacier mass balance changes in a long-term climatic context.

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Several studies have focused on LIA moraine dating in the monsoonal temperate part of the TP since 1980s using ^{14}C ages of buried trees. Li and Zhen (1986) carried out ^{14}C measurements on buried trees and lichen dating in the forefield of Ruoguo glacier. Wang and Fan (1987) used ^{14}C ages of buried trees and tree-rings of living trees on the lateral moraines of Arza glacier to map and to date five moraine stages, the oldest one dating back to ~3000 BP. Zepu glacier was the focus of studies by Li and Zhen (1986), Iwata and Jiao (1993), Jiao and Iwata (1993), and Jiao et al. (2005), the latter three using ^{14}C to date an early advance in the 15th century and one in the late 18th century. Due to the average accuracy of the ^{14}C dating technique of $\pm$40–50 years at best (without wiggle matching, see Geyh, 2005), however, these studies could only give a general view on the most recent period of active glacier fluctuations on centennial resolution.

Dendroglaciology makes use of dead and living trees to date glacial deposits and glacier advance or retreat stages, using methods of dendrochronology (Fritts, 1976). Trees killed or injured by an advancing glacier provide a direct measure when a certain position is reached by the ice. Trees growing on top or on the proximal moraine slope represent a measure of the time of glacier retreat, since it is not possible for a tree to grow on plain ice. Therefore, the germination date of such a tree can be used as a minimum age for a maximum glacier advance or the start of a glacier retreat.

For southeast Tibetan Plateau, only a few dendroglaciological studies were carried out after 1990s. Bräuning and Lehmkuhl (1996) used tree-rings of junipers along with geomorphological mapping to date four moraine stages at Xuequ glacier. Bräuning (2006) used living larch trees to date the minimal age of the maximum advance during the LIA period to 1760 A.D. at Mt. Gyalaperi, and additionally provided ages for glacial advances at Gawalong glacier. Minimum ages of the LIA moraine of the latter glacier were provided by Zhu et al. (2013) using living larch trees. Midui glacier's LIA maximum was dated to 1767 A.D., and three additional retreats from smaller advances date from the 19th and 20th centuries (Xu et al., 2012).

Though there are various techniques applicable to study glacial history in general, only some are suited to cover the last few centuries with sufficient precision for reconstructing gradual changes over a wider region. This is crucial, since the magnitude of the influence of the human-induced climate change occurring since ca. 1870 A.D. is still not fully understood and quantified. A thorough understanding of the geomorphological settings is also explicitly important. This reduces the number of comparable studies significantly, although the number of palaeoclimatic studies has been increasing in the last decade (Hren et al., 2009; Liang et al., 2009; Grießinger et al., 2011; Gou et al., 2013; He et al., 2013a; Yang et al., 2014). Comparisons between different palaeoclimate proxies are also difficult because of different temporal and/or spatial resolution and representativity (Yang et al., 2009). The variability that inherits each subregion of the TP though requires a number of case studies, otherwise general conclusions inferred from single case studies of specific locations may be skewed. It is therefore crucial to improve the quantitative basis of regional palaeoenvironmental data, especially on the topographically very complex southeastern TP, where mountain ranges are dissected by deeply incised river gorges.

In this study, we first analyze maximum ages of trees growing on glacier deposits to gain minimum ages for LIA maxima of the respective glaciers. The achieved dates are then compared with all late-Holocene moraines from the region that have been dated by previous studies. The resulting ages of LIA maxima are correlated against a set of geomorphological parameters for each glacier which are likely to have significant influence on glacier mass balance. The results allow for a simple linear model, explaining a high degree of variance between the minimum ages between individual glaciers. To test whether the retreat of the monsoonal temperature glaciers during the last 250 years is related to a) a rise in temperature (and thus increased ablation and less solid precipitation) or b) a decrease in precipitation and thus less accumulation and albedo, tree-ring derived moraine ages are compared to local, regional and north-hemispheric reconstructions of spring and summer temperatures and precipitation anomalies.

2. Material and methods

2.1. Study area and climate

The study area is located in southeastern Tibet, Xizang autonomous region, China (Fig. 1). The region of the Yarlung Tsangpo great bend is dominated by the massifs of Namche Barwa and Gyalaperi (7782 m and 7294 m a.s.l.), forming the eastern edge of the Himalayas. Though still being strongly glaciated, the ice masses of the region declined rapidly during the last decades (Ding et al., 2006; Yang et al., 2008b; Bolch et al., 2012; Yao et al., 2012). The glacial retreat since the 19th century leaves prominent moraines and large forefields located at elevations below 4000 m a.s.l. This is far below the upper forest limit located at around 4500 m a.s.l. (Bräuning, 2006), leading to a quick primary vegetation succession on freshly formed land surfaces (Suppl. 1).

The regional climate is strongly influenced by the Indian Summer Monsoon (ISM) system during the vegetation period (May–September). Valley bottoms receive 700–900 mm precipitation/year, while mountains, glaciers and their adjacent valleys are expected to receive a multiple of that (e.g. Su and Shi, 2002; Böhner, 2006; Suppl. 2). Therefore, high-elevation tree stands are not expected to be stressed by water deficiency/drought, but more likely by temperature. All glaciers included in this study belong to the monsoonal temperate valley glacier type, with an equilibrium line mean annual temperature above −6 °C and mean annual precipitation of at least 1000 mm (guidelines after He et al., 2003). This definition excludes parts of the northern Nyainqêntanglha Range as well as the eastern Kangri Garpo Mountains. Calculations of the climatic borders of the monsoonal temperate region (Fig. 7) were based on High Asia Reanalysis (HAR) data (Maussion et al., 2014).

2.2. Site characteristics and determination of minimum ages

Sikkim Larch (*Larix griffithii* J. Hooker) is a shade intolerant deciduous conifer tree species. Larch forests in southeastern Tibet usually occur at morphologically active and well drained slopes at 3000–4100 m a.s.l. (Wu and Raven, 1999). *L. griffithii* is a pioneer species covering LIA moraines in the tributary valleys of the Yigong- and Parlung Tsangpo valleys (Fig. 1; Mill, 1999). *Picea balfouriana* (syn. *P. likiangensis var. rubescens*) is the dominant species of late-successional forest stands in undisturbed sites. Thus, it is of similar or lower age than larch at sites that underwent a vegetation succession within the past centuries. *Hippophae* is a pioneer shrub genus on open grounds, and various *Rhododendron* species are dominant in the understory of conifer forests. No evidence of fire and insects disturbances was found at the respective sites.

Xinpu glacier descends from the northern slope of Mount Pulongu (6310 m a.s.l.) towards Yigong Tsangpo valley. According to local inhabitants of Yigong valley, the glacier has not been visited by humans since more than 50 years. Therefore, no sign of human influence was detected near to the recent glacier or the LIA moraines. Tree-ring samples were collected at five locations: on both lateral moraines (*P. balfouriana*), on the frontal moraine (*P. balfouriana* & *L. griffithii*), and below the frontal moraine (*P. balfouriana*). Larch trees were sampled to determine if spruce was the primary successor on the respective glacial sediments, and trees growing below the frontal moraine were sampled as control to detect possible missing rings at the ice-proximal sites.

Gongpu glacier descends from Pulongu summit towards the south. All trees on the lateral moraines were rotten from the core, indicating humid climate favouring fungal attack (Li, 1993). Gongpu glacier has only one lobe and the frontal moraine is composed of large unconstrained boulders forming a steep slope. Tree succession on the lateral moraines is driven by forests occurring further upslope, resulting in an