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Advancing Treeline and Retreating Glaciers: Implications for Conservation in Yunnan, P.R. China

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Abstract

Historic climate data and repeat photographs were used to assess and document changes in alpine treeline and glacial recession in northwestern Yunnan, China. Results show that mean annual temperature in the last two decades of the 20th century has been increasing locally at a rate of 0.06 °C yr^{-1} ($p < 0.001$). Furthermore, the annual trend is a result of both summer- and wintertime warming (0.037 °C yr^{-1}, $p < 0.001$; and 0.036 °C yr^{-1}, $p < 0.001$, respectively). Additionally, a local drying trend (−3.80 mm yr^{-1}; $p < 0.001$) was observed during the period 1955–1995. Repeat photos and supplemental measurements show that this warming is causing the retreat of glaciers and contributing to the elevational advance of alpine treeline. Fire, a traditional management tool used to halt the advance of woody species, has been suppressed since 1988. One consequence of these interactions is the encroachment of woody vegetation into alpine meadows, which will have negative impacts on plant species diversity and Tibetan livelihood. Two spatially and temporally distant anthropogenic actions, a rapidly warming climate and local land use policy, appear to be threatening both biodiversity and Tibetan livelihoods. Land managers need to recognize that global warming is occurring and adapt their conservation practices and policies to anticipate and be resilient to threats at all critical scales.

Introduction

The sensitivity of mountain ecosystems to human activities and climate drivers of change has been widely documented. The scales of response to these drivers vary from decades to centuries and are relevant to the understanding of how these ecosystems will respond to various land use and management practices as well as to anthropogenically induced climate change.

One method for increasing our understanding of how land management practices and shifts in climate may affect ecosystems is to look into the past. Repeat landscape photography (the comparison of old photographs with modern retakes) has been widely used to document the effects of land management practices, ecological changes in vegetation, and other changing variables (e.g., glacier mass and extent) in various landscapes around the world (Swetnam et al., 1999; Byers, 2000, 2005; Nüsser, 2000; Gruell, 2001; Turner et al., 2003; Ives, 2004). When combined with climate data and other lines of evidence, the information inferred from photographic pairs can be used as a first approximation of impacts resulting from past environmental and land use changes (Swetnam et al., 1999), thereby providing additional information to help inform and guide land management decision processes.

This paper builds on an assessment of changing landscape trends over a 100-year time scale in the mountainous areas of northwestern Yunnan, China (R. Moseley, unpublished data). Analysis of the 413 photo comparisons revealed that all glacier photographs showed a decrease in extent and volume (five glaciers; $n = 26$ photo pairs). Furthermore, 55% of the alpine pairs showed an increase in the elevational limit of treeline, already among the highest recorded in the world, and canopy coverage (four tree-limit areas; $n = 13$ photo pairs).

We suspected that the changes observed in these photographs were due in part to recent changes in climate. Our assumptions were based on temperature reconstructions from proxy records in China which showed that mean annual temperature has increased rapidly since the end of the Little Ice Age, ca. 1920 in China (Yang et al., 2002). In fact, the warming trend of 0.03 °C yr^{-1} experienced in the last two decades of the 20th century was nearly double the global mean trend of 0.019 °C yr^{-1} (Wang and Gong, 2000).

The objectives of this study were to (1) analyze past changes in two variables that are sensitive to climate change: glacier area/volume and treeline elevation; (2) explore the connection between observed changes in alpine treeline and glacier recession and regional climate change; and (3) link observed climate-change impacts on traditional management practices, biodiversity patterns, and government conservation policy in alpine ecosystems in northwestern Yunnan.

Study Area

The two study sites (Mount Khawa Karpo and Baima Snow Mountain) described in this paper are located in the Hengduan Mountain Range of the eastern Himalayas in the Kham Tibetan region of northwestern Yunnan Province, China (Fig. 1). Biogeographically, the area is in a transitional zone between the southeastern region of the Tibetan Plateau and the northwestern edge of the Yunnan Plateau.

Four of Asia's major rivers, the Jinsha (upper Yangtse), Lancang (upper Mekong), Nu (upper Salween), and Dulong (tributary of the Irrawaddy) converge within a 90 km corridor in this portion of the Hengduan Mountain Range. The resulting deep parallel gorges rise from river valleys (~1500 m) to glaciated peaks

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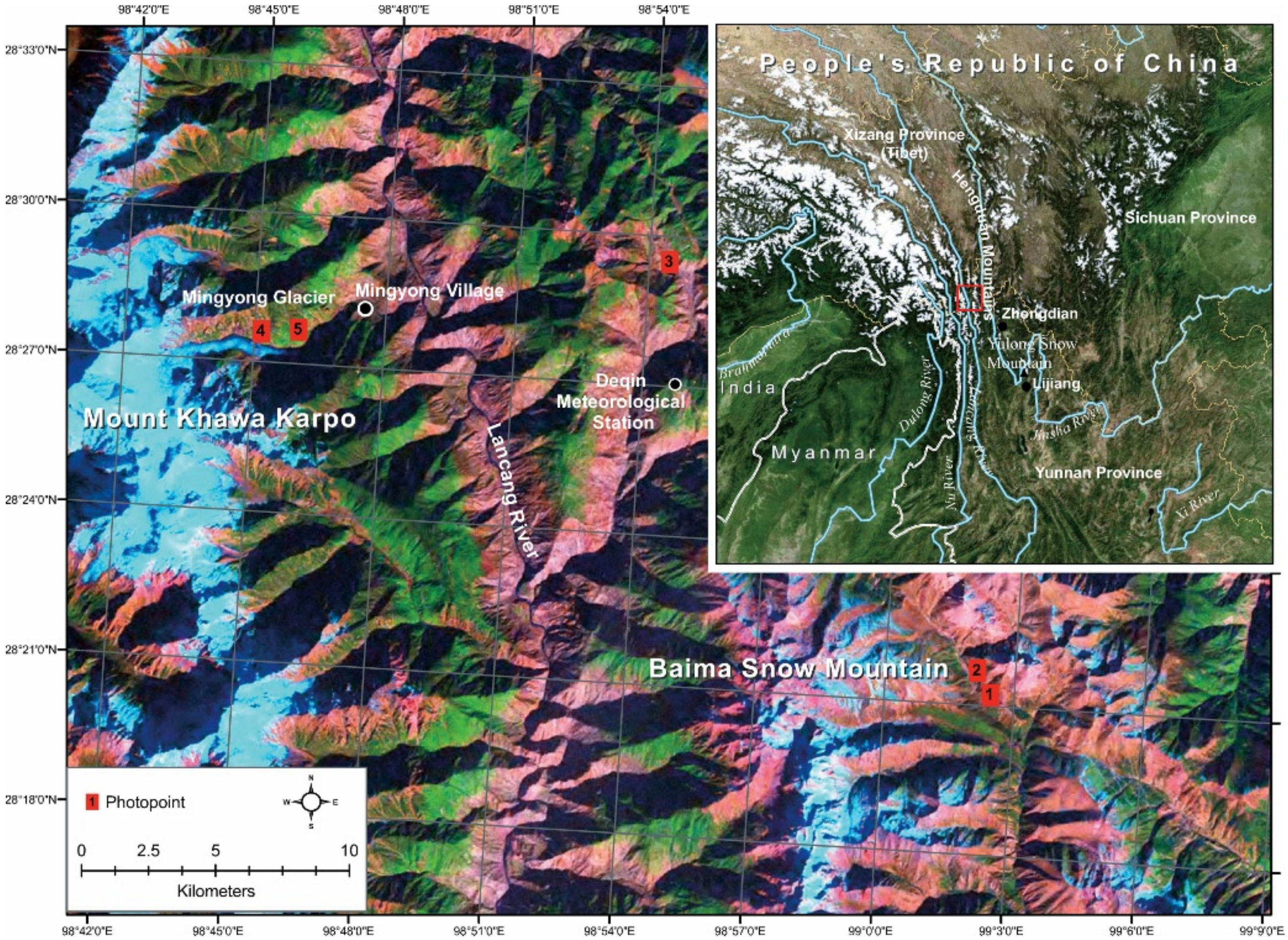


FIGURE 1. Landcover map of the study area in northwestern Yunnan, China, showing the locations of the five photo-points and Deqin meteorological station in relation to Khawa Karpo, the Mingyong Glacier, and Baima Snow Mountain. The landcover map was derived from Landsat Enhanced Thematic Mapper satellite data (GeoCover, 2000). The cyan color represents ice and snow, forests appear as green, and non-forested lands appear as pink. Inset map shows study area (red box) in relation to its geographic position in China and surrounding countries. Country boundaries appear as white with dashed black lines, province boundaries appear as yellow lines, and light blue lines represent rivers. The inset landcover image was derived from MODIS satellite data (Stöckli et al., 2005).

(>6700 m) within a distance of 20 km or less. Compressed within this short distance are subtropical ecosystems in the river valleys, rising through temperate, boreal, and arctic-alpine life zones to permanent snowfields, thus creating one of the most biologically diverse temperate ecosystems on Earth (Mittermeier et al., 1998).

The sites are geographically located at a subtropical latitude (28°15′N, 98°46′E to 28°28′N, 99°13′E); however, the region's climate is temperate and is dominated by the Bay of Bengal and South-Asia monsoons (Xu et al., 2003). Summer rains and winter droughts characterize this monsoonal climate. Annual precipitation ranges from 300 to 950 mm, the snowline occurs approximately 4200–5200 m, and mean annual temperatures vary from −9 °C in the glaciated peaks to 5 °C in the valley bottoms (OSU-SCAS, 2002).

It is estimated that the Hengduan Mountains have approximately 1680 glaciers covering 1619 km^2 (Huang, 1991). Mean annual temperatures at the equilibrium line of these temperate, monsoonal glaciers are relatively high, −6 °C with summer values of 1 to 5 °C (Li and Su, 1996; Shi et al., 1998). Additionally, the glaciers of this region occur at some of the lowest recorded elevations in China. Due to these unique characteristics, these glaciers are extremely sensitive to climatic changes (Su and Shi, 2002).

Methods

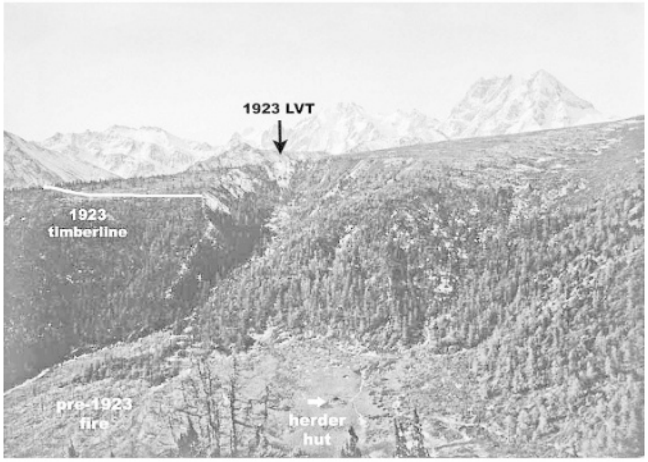
TREELINE TRENDS

Various definitions have been used to describe the upper limits of forests on high mountains. We define ''timberline'' as the upper limit of closed forest (Körner and Paulsen, 2004) and the ''tree-limit ecocline'' as the climatically sensitive zone between the timberline and alpine communities that are characterized by the occurrence of trees >2 m in height, as well as shrub and herbaceous species (Tinner and Theurillat, 2003). We will refer to these two zones collectively as the ''treeline'' for ease of discussion when specific reference to a particular zone is unnecessary.

We selected three photo-pairs taken at three different sites that clearly demonstrated changes in treeline on Baima Snow Mountain. The original photographs were taken by Joseph Rock on 1 December 1923 (Rock, 1926, 1947). The original sites were located and repeat photographs taken (Figs. 2 and 3).

We systematically examined the alpine treeline photo series from the Baima Snow Mountain study site to locate the 1923 and the 2003 timberlines and the last visible tree (LVT1923 and LVT2003) with a height >2 m occurring in the tree-limit ecocline.

(a)



(b)

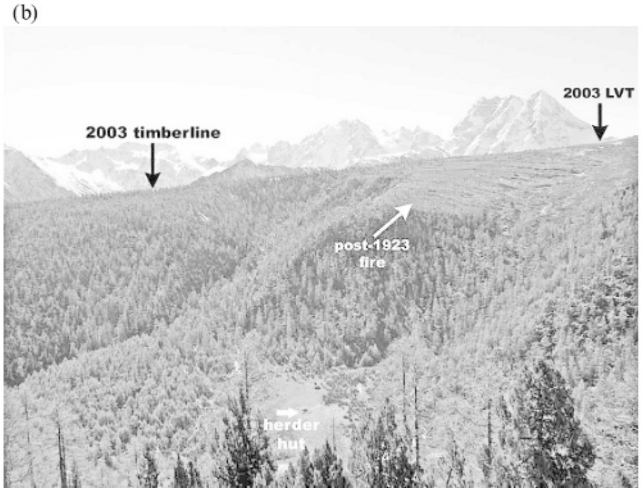


FIGURE 2. Repeat photo-pair of Baima Snow Mountain illustrating human disturbance patterns and the elevational increase of alpine timberline and the last visible tree (LVT). The photographs look to the southwest. Original photo (a) taken on 1 December 1923 by Joseph Rock/National Geographic Image Collection. Modern photo (b) taken on 1 December 2003 by Robert Moseley/The Nature Conservancy. Photo-point elevation is 4130 m (point 2 in Fig. 1).

Locations were marked on the photographs and verified in the field in late October 2004.

Once in the field, we located the photo-point where both the original and repeat photographs were taken. An observer was stationed at the original photo-point. Using landforms clearly visible in both the original and current photographs, the observer was able to direct a second person to both the timberline and last visible tree in Rock's 1923 photographs. The slope, aspect, elevation and geographic coordinates were recorded for both the current and 1923 timberline and the last tree >2 m occurring in the upper limits of the tree-limit ecocline.

Establishing a dendrochronology for the site was beyond the scope of this study; however, we wanted to establish that the ages of the last tree, >2 m in height, visible in both the 1923 and 2003 photographs. In order to establish a preliminary ring age, an increment core was taken at breast height (1.37 m) on the upslope sides of both trees. In addition to removing cores, we recorded the geographic locations, elevations, slopes, aspects, heights, and diameters at breast height (DBH) of the trees. In the laboratory, we fixed the cores to a rigid surface and sanded until optimal surface resolution allowed annual rings to be counted.

GLACIER TRENDS

Because glaciers are sensitive to temperature and precipitation, their behavior provides a good indication of climatic changes (Thompson, 2000). We therefore selected two photo-pairs and one photo-triplet taken at three different sites that clearly demonstrated changes in the mass and extent of the Mingyong Glacier on Mount Khawa Karpo. The original photographs of the glacier were taken in June 1913 by Frank Kingdon Ward (Ward, 1916, 1923, 1924) and on 29 November 1923 by Joseph Rock (Rock, 1926). The original sites were located and repeat photographs taken in 2002, 2003, and 2004 (Figs. 4 and 5).

We located and recorded the geographic coordinates and elevation of the terminal moraine of the Mingyong Glacier at its maximum extent as well as its current position. The geographic location of the terminus in 1998 (Z.-D. Fang, personal communication) and in May 2002 (B. Baker, unpublished data) was also obtained in order to document more recent changes.

CLIMATIC TRENDS

Complete historical climate records covering the 90-year period are difficult to obtain. Therefore, we analyzed two different data sets in order to identify past changes in temperature and precipitation. We obtained observed historical monthly climate data (maximum temperature, minimum temperature, and precipitation) for the period 1955–2003 from the Deqin County Meteorological Station (28°27′N, 98°55′E, 3319 m a.s.l.). In order to evaluate climatic pattern from the beginning of the photographic record, we used the Global Historic Climate Network Version 2 (GHCN V2) data set (GHCN, 2007). This data set is composed of observed annual gridded temperature data, expressed as an anomaly relative to the 30-year period 1961–1990, at a spatial resolution of 5.0° latitude × longitude covering the entire 90-year period. The anomalies are calculated for each station and averaged within each 5° × 5° grid box (Peterson and Vose, 1997). For this study we selected data from the grid cell 27.5°N, 97.5°E, which is bounded by the area 25°N, 95°E to 30°N, 100°E and completely contains the study area.

We conducted annual and seasonal (winter [October, November, December, January, February, and March] and summer [April, May, June, July, August, and September]) time series analysis on the observed historical temperature and precipitation data. We used the non-parametric Mann-Kendall (M-K) test (Sneyers, 1990) to detect significant trends in the data. For the M-K test, a two-tailed p-value of 0.05 was used to determine significance. If the M-K test indicated a statistical significance, we then used the Theil-Sen's slope algorithm (Theil, 1950; Sen, 1968) to estimate the magnitude of the trend. Lastly, we applied a locally weighted regression (Lowess) smoothing algorithm (Cleveland, 1979) to the data for visualizing trends.

Results

TREELINE TRENDS

Photographs at the Baima Snow Mountain site were taken looking generally west (225–315°) at the northeast slope (aspect 32–35°) of a southeast-trending ridge. The dominant tree and shrub species seen in the photographs include *Larix potaninii* Batal. var. *macrocarpa* Cheng et Y. W. Law, small patches *Abies georgei* Orr var. *smithii* (Viguie et Gaussen) Cheng et L. K. Fu, *Rhododendron phaeochrysum* Balf. et W. W. Smith, and a dwarf shrub complex consisting of *Rhododendron rupicolum* W. W. Smith

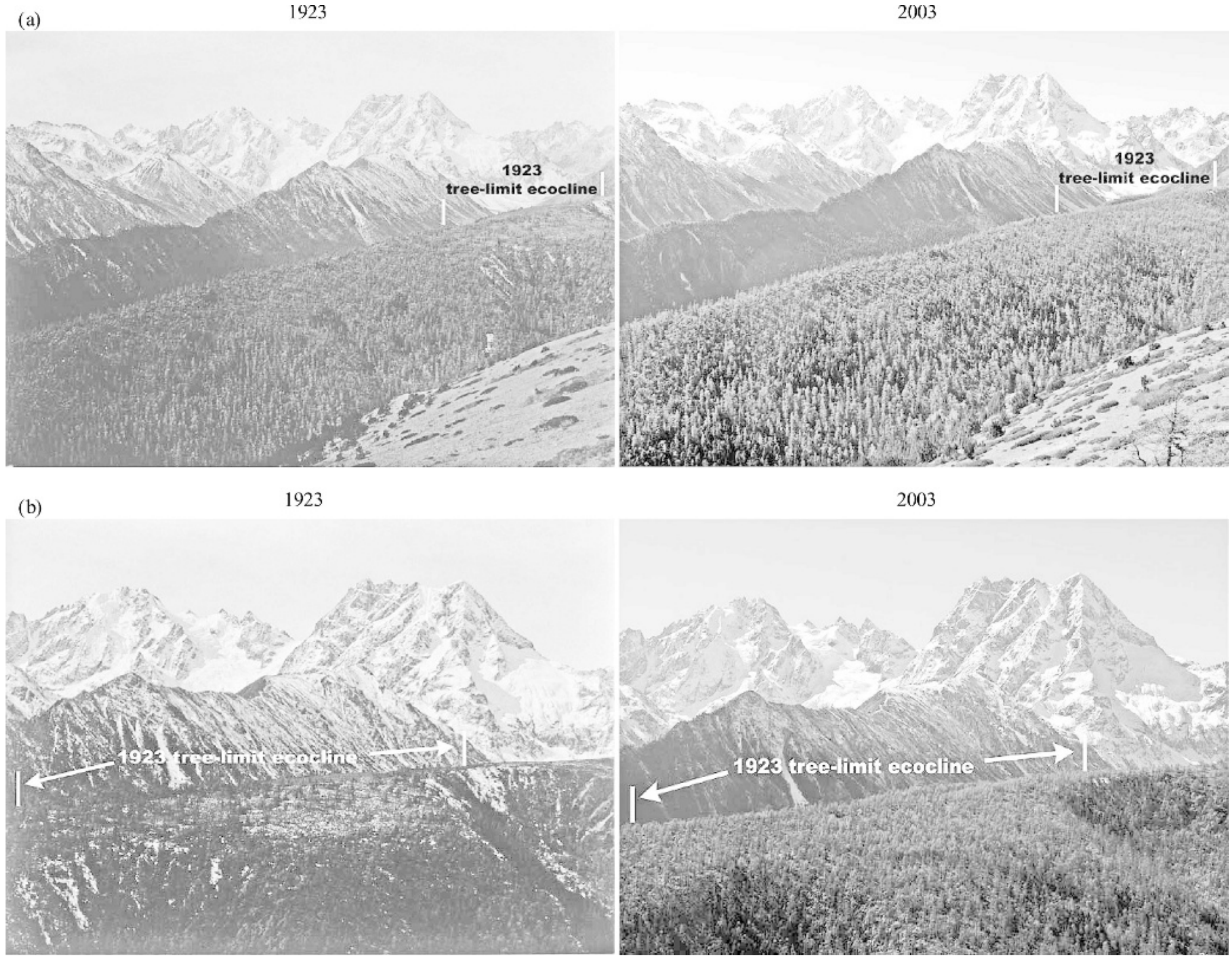


FIGURE 3. Two sets of repeat photo-pairs of Baima Snow Mountain illustrating infilling by *Larix potaninii* of the same 1923 tree-limit ecocline from two perspectives. The photographs were taken on the same dates and by the same photographers as in Figure 2 and look generally to the southwest and west. The photo-point for (a) is further south than (b). Elevation of photo-point (a) is 4295 m and (b) is 4280 m. Both photo-points are near each other and indicated as point 1 in Figure 1.

var. *chryseum* (Balf. et Ward) Philipson et Philipson, *R. nivale* Hook. var. *boreale* Philipson et Philipson, *R. tapetiforme* Balf. et Ward, and *R. yungningense* Balf.

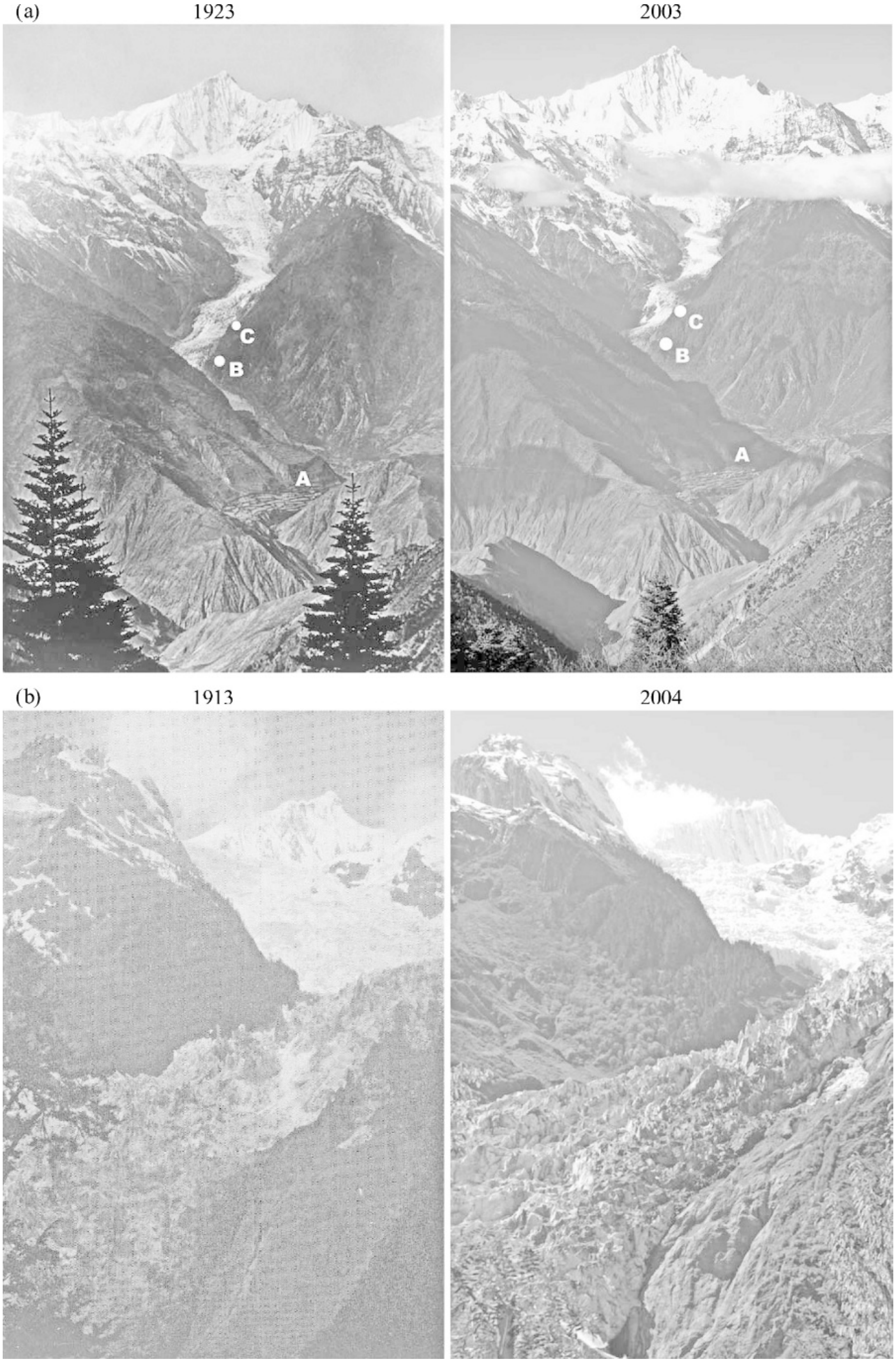
Evidence of past disturbances as well as changes in forest cover and treeline have been captured in the photographs. The presence of the herder's hut at the bottom of the ridge in both the 1923 and 2003 photos provides indirect evidence that the area has been used for grazing during the last 80 years (Fig. 2). The photographs also show that at least two fires have occurred in the past. The 1923 photograph shows standing dead trees as a result of a fire down-valley (left) from the hut, while the 2003 photograph shows *Larix* regeneration in the same area. The photo-pair also shows that another fire on the slope above the hut occurred sometime between 1923 and 2003.

The most striking changes in the Baima repeat photo-pairs are the amount of infilling by *Larix* of the 1923 tree-limit ecocline on the northeast slope and ridgeline, as well as the two cirques, and a shift in both the timberline and the tree-limit ecocline (Figs. 3a and 3b). The location of the last visible tree in the 1923 photograph is now the upper limit of the timberline (Fig. 3b), whereas the LVT2003 is upslope well beyond the 1923 position.

Our measurements indicate that the current timberline has moved 67 m in elevation and a distance of 270 m upslope from its1923 location. Likewise, the position of the last visible tree, as seen in the 1923 photograph and observed in the field, has moved 45 m in elevation and a distance of 675 m upslope from the 1923 location.

We were able to identify the largest tree in the stand of what was the 1923 upper limit of the tree-limit ecocline. Unfortunately, the tree was dead and the center had decomposed, thus preventing the collection of an increment core. However, we were able to locate the largest living tree and designated it as LVT1923. Analysis of tree rings from the increment core taken at DBH revealed the tree to be 82 years old at breast height. A second increment core was taken from the uppermost tree ($>$2 m in height) of the current tree-limit ecocline. This tree was found to be 39 years of age at DBH and designated as LVT2003. Clearly, these ages are approximate and valid for the age of both trees at 1.5 m in height. Additional information regarding elevation, slope, aspect, height, and DBH are presented in Table 1.

As might be expected, *Larix* saplings are establishing themselves in the shelter of dwarf shrubs in altitudinal zones higher than LVT2003. Our measurements indicate that the sapling furthest from LVT2003 was found 114 m above and ~600 m distant from LVT2003. The elevation, slope, aspect, and height were recorded for the sapling and are presented in Table 1. The diameter of the sapling was too small to allow us to remove a core


(a)
1923
2003
C
B
A
C
B
A
(b)
1913
2004

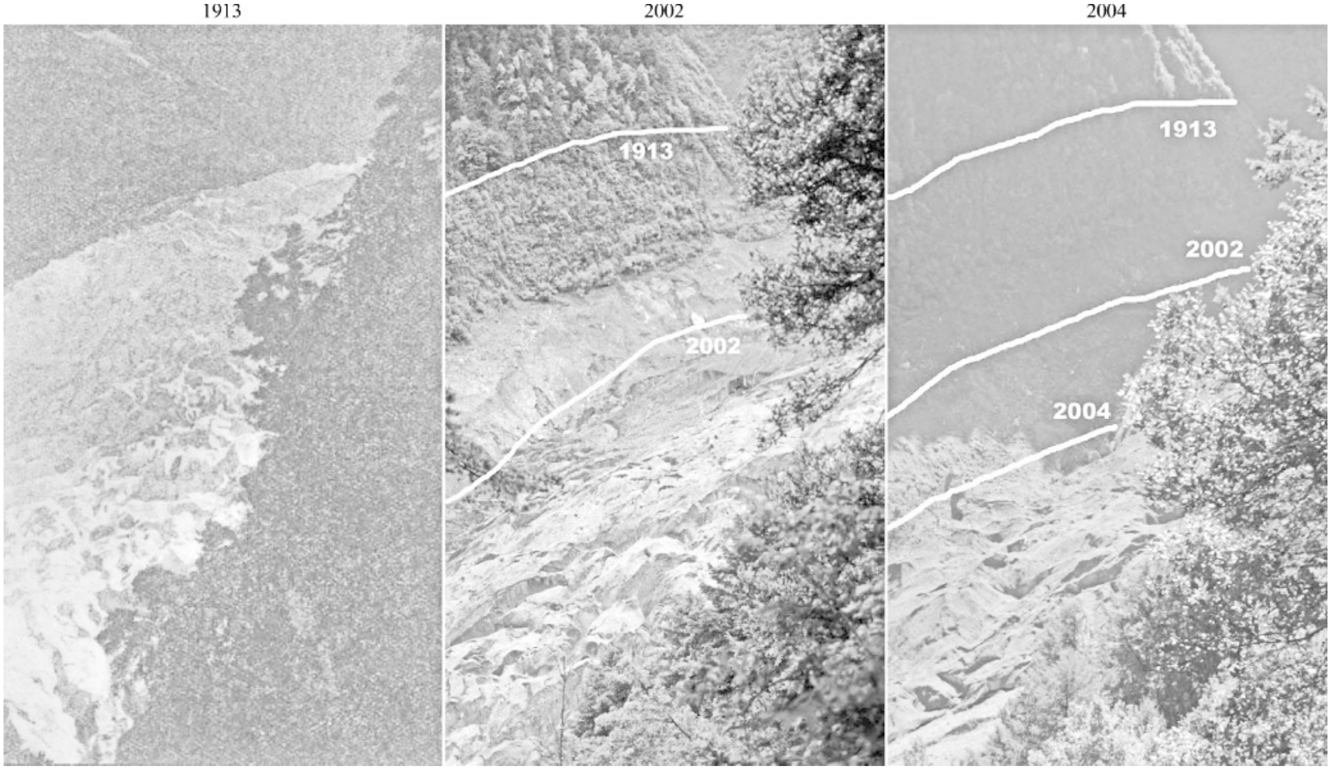


FIGURE 5. Repeat photo-triplet of the tongue of Mingyong Glacier on Mount Khawa Karpo. The original photo was taken by Frank Kingdon Ward in June 1913, with the two modern images from 20 May 2002 and 19 October 2004, both by Robert Moseley/The Nature Conservancy. Photo-point elevation is 2905 m and indicated as point 5 in Figure 1. The solid white lines represent the trimline (1913) and ice margins from the preceding and current photographs.

TABLE 1

Measurements taken on the oldest live tree and the last adult tree seen in the 1923 Rock and 2003 Moseley photographs, and highest (elevational) *Larix* sapling at the Baima Snow Mountain site. DBH = diameter at breast height.

Sample	Elevation (m)	Slope (°)	Aspect (°)	Height* (m)	DBH (cm)	Ring age*,** (yr)
LVT1923	4331	3	138	6.99	21.6	82
LVT2003	4376	11	74	3.18	13.7	37
Larix sapling	4490	15	87	0.20	—	—

* Ring age in 2004.
** Taken at DBH.

and not inflict damage, therefore a ring age was not determined. We also found the tall, broadleaf-evergreen form of rhododendron, *R. phaerochrysum*, normally found in the forest understory, growing within upper elevational stands of the dwarf shrub complex as well.

GLACIER TRENDS

Figures 4 and 5 clearly demonstrate that significant changes in the mass, margins, and extent of the Mingyong Glacier have occurred in the past 90 years. The accumulation zone is not visible in the photographs; however, changes in the margins of the icefall region are quite apparent when compared to the 1923 Rock (Fig. 4a) and the 1913 Ward (Fig. 4b) photographs.

The most dramatic changes are evident in the extent and volume of the glacier tongue (Figs. 4a and 5). The 1923 photograph (Fig. 4a) of the glacier shows the tongue terminating close to Mingyong Village. By 2003 the tongue had retreated well up the valley (Fig. 4a). Changes in the margins of the upper portions of the tongue are also apparent (Fig 4b).

The photo-triplet in Figure 5 clearly demonstrates changes in the margins and surface albedo of the glacier since 1913. The

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FIGURE 4. Two sets of repeat photo-pairs illustrating the loss in volume and length of lower Mingyong Glacier. Photo set (a) is an overview showing the location of Mingyong village (A), photo-point for Figure 5 (B), and photo-point for Figure 4b (C). The original was taken on 29 November 1923 by Joseph Rock/National Geographic Image Collection and looks west at Mount Khawa Karpo. The modern photo was taken on 2 December 2003 by Robert Moseley/The Nature Conservancy. Photo-point elevation is 4005 m. Photo set (b) is a close-up of Mingyong Glacier. The original was taken by Frank Kingdon Ward looking west up the glacier in June 1913, with the modern taken on 19 October 2004 by Robert Moseley/The Nature Conservancy. Photo-point elevation is 3210 m. The photo-points for (a) and (b) are indicated as points 3 and 4 in Figure 1, respectively.

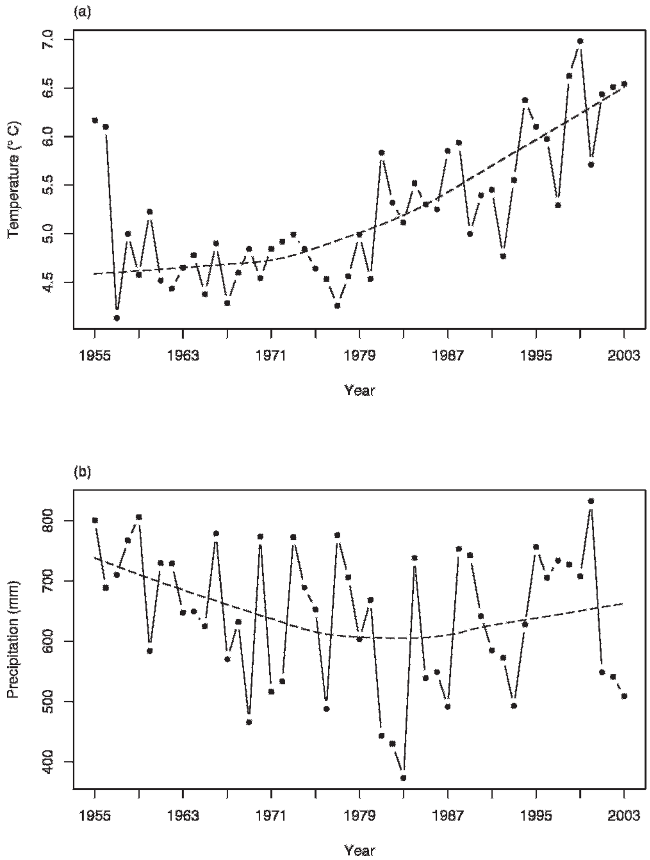

FIGURE 6. Time series of (a) mean annual temperature and (b) total annual precipitation for the period 1955–2003 from observed climate data at the meteorological station in Deqin, Yunnan, China. The dashed lines (- - -) represent the Lowess smoothing of the annual values.

Ward photograph taken in 1913 (Fig. 5a) shows that the ice margins of the glacier tongue extended to the trimline, and the surface of the glacier is relatively white in appearance. However, by 2002 (Fig. 5b) the surface of the tongue was several meters below the trimline and the surface was generally darker. Further changes were captured by the 2004 photograph (Fig. 5c).

The only terminal moraine of Mingyong Glacier is located at 28°28′59.7″N, 98°47′25.62″E (outside the village of Mingyong) at an elevation of 2324 m, which is nearly 2.3 km distant and 343 m below the current position (2667 m) of the terminus. Anecdotally, records indicate that Joseph Rock was told by villagers of Mingyong that the glacier ended outside the village approximately 50 years prior to his visit in 1913. This information would indicate the glacier has been receding from the terminal moraine since ca. 1870, which corresponds to the end of the Little Ice Age, ca. 1850 (Overpeck et al., 1997).

Measurements taken in October 2004 indicate that the terminus of the glacier has retreated ~190 m since our first recorded position in 1998. In addition, the rate of retreat appears to be increasing. The terminus retreated ~80 m between 1998 and 2002, but our recent measurement indicates that in the last two years (2002–2004) the terminus has retreated nearly 110 m. These results are consistent with the observations of other glaciers in northwestern Yunnan. Reports indicate that the Baishui Glacier Number 1 on Yulong Snow Mountain near Lijiang retreated 150 m from 1982 to 1997 and ~100 m from 1998 to 2002 (He et al., 2003, 2004).

CLIMATE TREND

Results of the trend analyses for the observed mean annual temperature and total annual precipitation are presented in Figure 6. The M-K analysis for mean annual temperature revealed a significant warming trend of 0.04°C yr^{-1} ($p < 0.001$) with a noticeable rate change occurring in the early 1980s (Fig. 6a). Further analysis revealed that mean temperature between the periods of 1980–2003 increased at a rate of 0.06 °C yr^{-1} ($p < 0.001$). The downward trend observed in total annual precipitation was not significant. However, a significant downward trend (−3.11 mm yr^{-1}, $p = 0.001$) was detected from the beginning of the record till 1995 (Fig. 6b). These data are consistent in direction with the 20th century dry-warming trend revealed in analyses of tree rings in China (Wu and Zhan, 1991).

Seasonal trends for temperature and precipitation are shown in Figure 7. Both winter and summer average temperature showed significant positive trends of 0.037 °C yr^{-1} ($p < 0.001$) and 0.036 °C yr^{-1} ($p < 0.001$), respectively (Figs. 7a and 7b). A slight periodicity exists in the winter precipitation, although the trends were not significant (Fig. 7c). The M-K test showed a significant downward trend (−3.80 mm yr^{-1}, $p < 0.001$) for summer precipitation for the period 1955–1995 (Fig. 7d). The slight increasing trend from 1995 to 2003 was not significant.

Examination of the GHCN data set revealed the 20th century warming trend ($p < 0.029$) for the region was not monotonic (Fig. 8). Mean annual temperature, relative to the 1961–1990 30-year average, generally increased from the early part of the century till the mid 1950s. The regional pattern of warming of 0.04 °C yr^{-1} ($p = 0.0016$) after 1980 was somewhat lower than what was observed in the Deqin record.

Discussion

While the mechanism is unclear, this region of Yunnan appears to be highly sensitive to larger-scale climate forcings. The rate of the observed warming since the 1980s (0.06 °C yr^{-1}) in the study was double the national average (0.03 °C yr^{-1}) reported by Wang and Gong (2000). Further evidence of this regional trend has been documented by He et al., (2004). They reported that mean annual temperature has increased ~0.04 °C yr^{-1} and ~0.01 °C yr^{-1} for Zhongdian and Lijiang, respectively, two cities south of Baima Snow Mountain, over the same time period.

Although temperature has been reported as the primary factor controlling the distribution of trees in the alpine (Körner and Paulsen, 2004), precipitation has been shown to influence species composition in the treeline. In particular, *Larix* tend to respond more favorably to warmer, drier conditions than *Abies* or *Picea*, the other two treeline species (Liu et al., 2002; Song et al., 2004). This may partially explain the relatively unchanged stands of *Abies* seen in the repeat photo-pairs (Fig. 3a).

Our measurements and repeat photographs of the Mingyong Glacier terminus support the conclusion that the rate of recession appears to be accelerating with the warming and drying trend observed in the region. However, local topography may have profound effects on the ice front and recession of the terminus (Cook et al., 2003). Therefore, changes in the terminus alone may not be an accurate indicator of shrinkage or lowering of the ice level in the upper reaches of the glacier. Repeat photo-pairs of the icefall region and higher on the mountain indicate changes in the

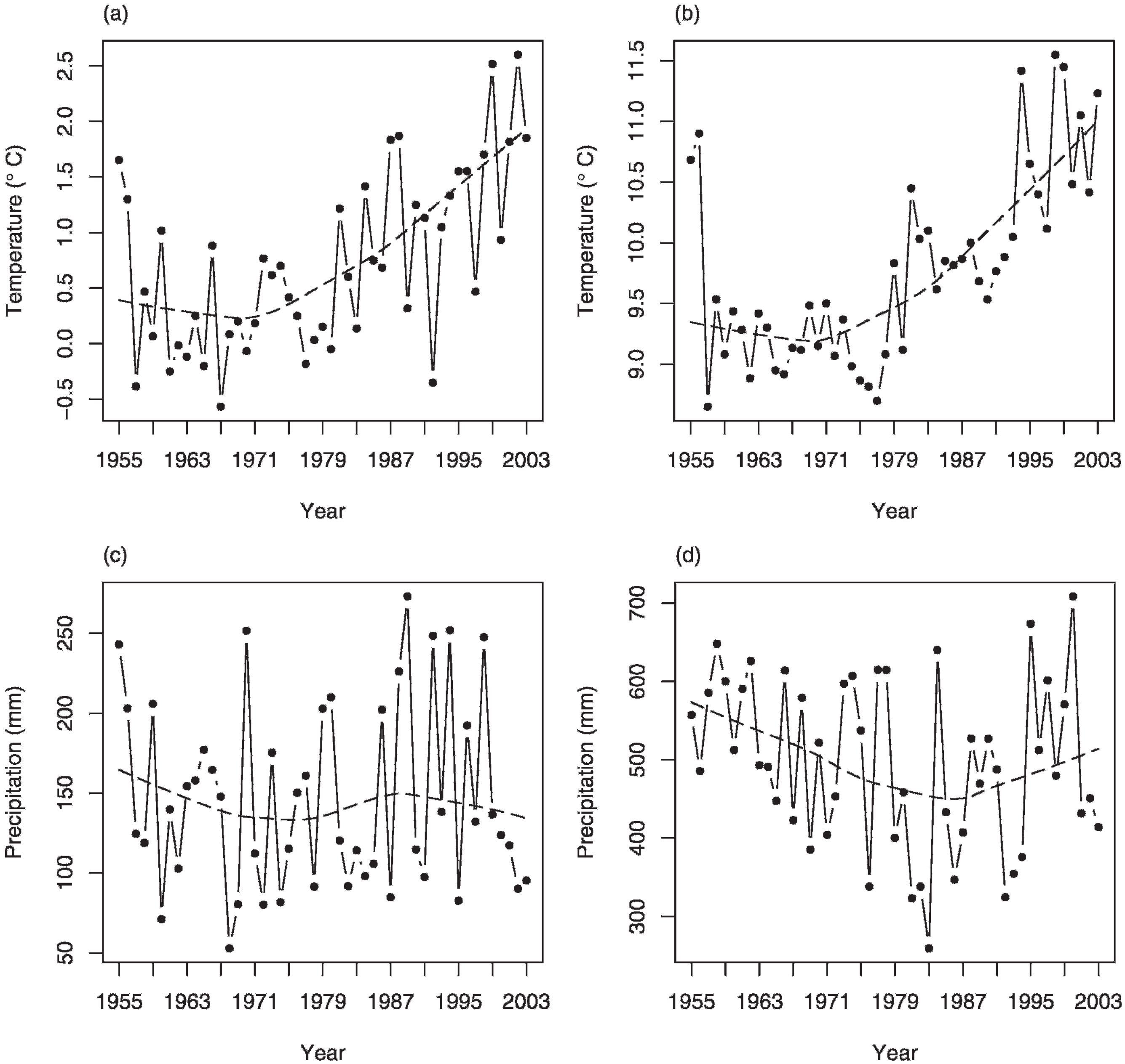

FIGURE 7. Forty-nine year (1955–2003) times series of seasonal mean temperature and precipitation: (a) winter (Oct, Nov, Dec, Jan, Feb, Mar) temperature, (b) summer (Apr, May, Jun, Jul, Aug, Sep) temperature, (c) winter (Oct, Nov, Dec, Jan, Feb, Mar) precipitation, and (d) summer (Apr, May, Jun, Jul, Aug, Sep) precipitation. The dashed lines (- - -) represent the Lowess smoothing of the seasonal values. The data were obtained from the meteorological station in Deqin, Yunnan, China.

mass balance of the glacier may be occurring (Fig. 4b). Clearly, more detailed studies and instrumentation of the glacier are needed to establish these relationships.

Repeat photo-pairs taken at Baima Snow Mountain conclusively demonstrate that stands of *Larix* and other woody-shrub species in our study area are advancing higher into the alpine tundra. While climate is an important driver of ecological change, other disturbances such as grazing and fire influence the altitudinal limits and distribution of vegetation (Carcaillet and Brun, 2000; Körner, 2000; Butler and DeChano, 2001; Motta and Nola, 2001). Historic records indicate that human activities have been shaping the alpine landscape of Yunnan since the first Tibetan herders entered the region more than 2000 years ago (Duan, 1997; Ma, 2002). Our repeat photo-pairs show that both grazing and fire have been part of the disturbance regime in the study area for the last century, and that they are now interacting with a rapidly warming climate to make conservation management of these systems increasingly difficult.

Salick et al., (2004) have shown that alpine meadows are the most diverse in the Mount Khawa Karpo area, in terms of both plant species richness and in the number of plants collected by local people for medicine or cash income. Additionally, Tibetan yak herders rely on alpine meadows for butter production and have traditionally used fire to control shrub and tree invasions into this habitat (Luo et al., 2001). A burning ban was instituted in Yunnan in 1988, primarily for the protection of forest stands at lower elevation. The ban was universally applied across ecosystems, however, and has halted traditional alpine pasture management practices. We suspect that this change in fire regime, along with a warming climate, may be an important component of the

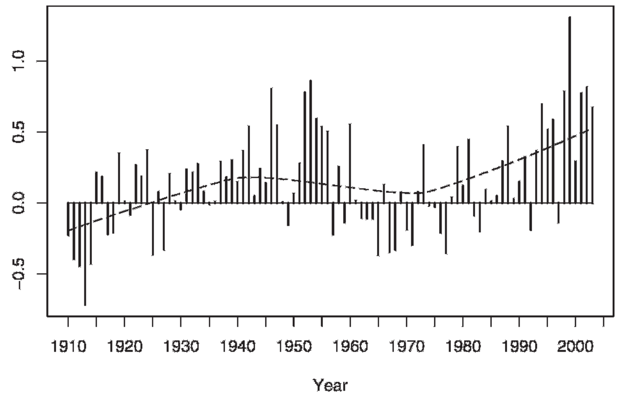

FIGURE 8. Mean annual temperature anomaly (relative to the 1961–1990 average) for the period of the photographic record, 1910–2003. The data are from the Global Historic Climate Network (Peterson and Vose, 1997) for the grid cell 27.5° North latitude × 97.5° East longitude which is bounded by the area 25°N, 95°E and 30°N, 100°E. The dashed lines (- - -) represent the Lowess smoothing of the annual values.

advancing treeline and the establishment of *Larix* seedlings and tall *Rhododendron* above the current elevational limit of adult trees that we are currently witnessing. Although data from Yunnan are lacking, several studies have referred to changes in species composition and increased shrub density in alpine meadows following the 1988 ban (Bao et al., 2001; Luo et al., 2001; Chan, 2003; Xu and Wilkes, 2004). Dendroclimatological studies are needed to help untangle the effects of climate and management on the movement of treeline and vegetation community shifts in this region.

In terms of atmospheric warming as a driver of change, studies from both arctic and other alpine regions have documented this trend of advancing woody species into previously unoccupied areas (Sturm et al., 2001; Anthelme et al., 2003). Positive feedbacks that promote further invasion of woody species are likely to occur as increasing shrub density alters microclimate (Sturm et al., 2005).

Conclusion

Two extremes of anthropogenic disturbance, a rapidly warming climate and changes in land use practice and policy, appear to be responsible for affecting alpine and upper treeline vegetation dynamics, thus threatening both biodiversity and Tibetan livelihoods. While conservation managers are competent at addressing the proximate causes of disturbance or threats to biodiversity, such as fires ignited by humans, they tend to ignore the distal drivers of change, such as shifts in global climate. However, the loss of alpine meadows to encroachment of woody vegetation that we documented here, and the documented acceleration of this trend, points to the need for strategies addressing all critical scales. For instance, in northwestern Yunnan, this might entail developing fire policies that account for variation in ecosystem patterns and processes instead of a universal ban to protect forests. While local land managers in northwestern Yunnan may not be able to directly affect national or global policy debate on greenhouse gas emissions, they can recognize that warming is occurring and adapt their conservation practices and policies to anticipate and be resilient to this global change.

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