



Pre-monsoon precipitation signal in tree rings of timberline *Betula utilis* in the central Himalayas

Binod Dawadi^{a,c,1}, Eryuan Liang^{a,*}, Lide Tian^a, Lochan Prasad Devkota^b, Tandong Yao^a

^a Key Laboratory of Tibetan Environment Changes and Land Surface Processes, Institute of Tibetan Plateau Research, Chinese Academy of Sciences, PO Box 2871, 4A Datun Road, Chaoyang District, Beijing 100101, China

^b Central Department of Hydrology and Meteorology, Tribhuvan University, Kathmandu, Nepal

^c Graduate University of Chinese Academy of Sciences, Beijing 100049, China

ARTICLE INFO

Article history:

Available online 1 June 2012

ABSTRACT

Himalayan birch (*Betula utilis* D. Don) is a long-lived, broadleaf tree species native to the Himalayas. However, it has received limited attention for dendroclimatological studies. Based on 49 tree-ring cores from 41 Himalayan birch trees at two sites in the Langtang National Park, central Nepal, a 458-year chronology (back to AD 1552) was developed. To date, this is the longest for this species in the Himalayas despite a low sample depth before AD 1785. The chronology statistics show the potential of Himalayan birch for dendroclimatology, as indicated by a positive correlation with precipitation in May and March–May ($p < 0.001$) and an inverse relationship with temperature in May and precipitation in August ($p < 0.05$). The Himalayan birch ring-width chronology is thus an indicator for pre-monsoon precipitation variations in the central Himalayas. The wide distribution of Himalayan birch in High Asia presents an outstanding opportunity for developing a large-scale, single-species tree-ring network.

© 2012 Elsevier Ltd and INQUA. All rights reserved.

1. Introduction

The Himalayas are the longest and highest mountain system of the world with a variety of climates and abundant forest resources from tropical to alpine growth conditions. Dendrochronological studies in the Himalayas began during the late 1970s, after which several studies have been conducted to explore the potential of species and sites in the eastern and western Himalayas (see a review by Bhattacharyya and Shah, 2009). However, dendrochronological exploration is still fragmentary in the central (Nepal) Himalayas (Bhattacharyya et al., 1992; Cook et al., 2003; Bräuning, 2004; Sano et al., 2005; Bhuju et al., 2010; Chhetri and Thapa, 2010), where instrumental climatic records are very short and climatic proxies, such as tree rings, are essential in understanding past climate changes. In comparison with a variety of coniferous tree species being used for dendrochronological studies in the central Himalayas (Bhattacharyya et al., 1992; Cook et al., 2003; Bhuju et al., 2010; Chhetri and Thapa, 2010) and surrounding regions (Borgaonkar et al., 1996, 2011; Esper et al., 2002; Bräuning and Mantwill, 2004; Yadav et al., 2004; Bhattacharyya and Shah,

2009; Liang et al., 2009, 2011b; Cook et al., 2010; Lv and Zhang, in press; Yadav, 2011; Zhu et al., 2011b), the application of broad-leaf tree species is rather limited. However, broadleaf tree species, such as birch, show a great potential to further extend the present tree-ring network (Eckstein et al., 1991; Bräuning, 2004; Takahashi et al., 2005; Yu et al., 2005; Bhattacharyya et al., 2006; Levanič and Eggertsson, 2008).

The Himalayan region has large areas of natural Himalayan birch (*Betula utilis* D. Don) forests. It is long-lived (more than 400 years old) (Bhattacharyya et al., 2006) with the promise for developing long tree-ring chronologies. Unfortunately, to date, little is known about its dendrochronological potential (Bräuning, 2004; Bhattacharyya et al., 2006). As reported, Himalayan birch growth responds positively to the mean temperature of July and September in the previous year in west Nepal (Bräuning, 2004) and March, April and June precipitation in the western Himalayas (India) (Bhattacharyya et al., 2006). Taking its wide distribution in High Asia into account, further efforts are needed to investigate its potential to develop a long, high-elevation tree-ring chronology, in particular in the central Himalayas.

The objectives of this study, therefore, are to develop a high-elevation, long tree-ring chronology of Himalayan birch and to investigate its dendroclimatological potential in central Nepal. It was hypothesized that the radial growth of Himalayan birch at timberline may show a positive response to summer temperature,

* Corresponding author.

E-mail address: liangey@itpcas.ac.cn (E. Liang).

¹ Present address: Central Department of Hydrology and Meteorology, Tribhuvan University, Kathmandu, Nepal.

as reported from timberline conifer trees and an alpine rhododendron shrub on the southeastern Tibetan Plateau (Bräuning and Mantwill, 2004; Liang and Eckstein, 2009; Liang et al., 2009; Lv and Zhang, 2012; Zhu et al., 2011b; Wang et al., 2012).

2. Site description

The study areas, Kyanjing Gumpa and Langtang villages, are part of the Langtang National Park. They are located on a west-facing slope of the Langtang Valley (Fig. 1), approximately 55 km north of Kathmandu and about 15 km south of the Tibetan border, China.

The local meteorological station at Kyanjing is ~2.5 km from the sampling sites. The average annual precipitation (1989–2008) is 604 mm, of which 75.5% occurs in the monsoon season, June–September (JJAS). Precipitation in the form of snow is common except for the monsoon season. Precipitation during the pre-monsoon season, March–May (MAM), post-monsoon season, October–November (ON), and winter season, December–February (DJF) contributes to 15.6, 4.0 and 4.9% of annual precipitation, respectively. The monsoon season has an average temperature of 8.5 °C, followed by the post-monsoon (3.3 °C), pre-monsoon (3.1 °C) and winter season (−1.6 °C) (Fig. 2).

3. Material and methods

3.1. Himalayan birch and tree-ring sampling

Himalayan birch is a moderate-sized tree growing up to 20 m tall at elevations up to 4500 m on a variety of substrates from sandy to heavy clay soils. It is widely distributed in Afghanistan, Bhutan, India, Nepal, Pakistan and northern and western China. As a pioneer tree species, Himalayan birch in the central Himalayas occupies the timberlines. It grows closer to glaciers than do other tree species.

Tree-ring cores of Himalayan birch were collected in May 2010 from the timberlines at Kyanjing (28.20°N, 85.56°E, 3950 m asl) and Langtang villages (28.21°N, 85.49°E, 3780 m asl) in the Langtang National Park, central Nepal (Fig. 1). The two sampling sites are characterized by a thin layer of rocky soil. They are located in a natural forest with some human disturbances mainly from deforestation for timber and firewood. Dominant trees without obvious signs of crown or root damage were selected for sampling. One or two increment cores per tree at breast height were taken. In

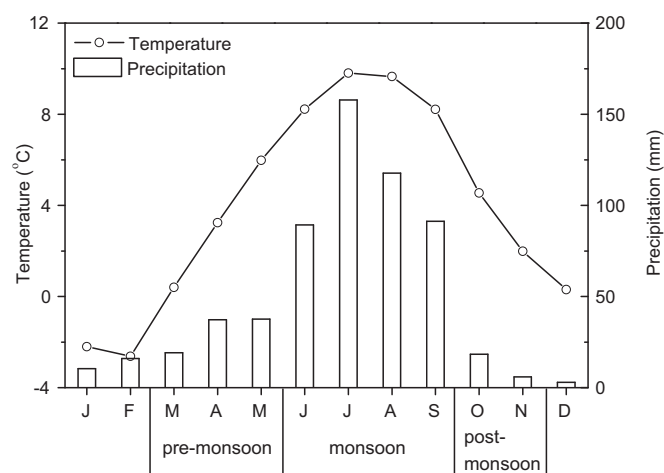


Fig. 2. Variations of monthly mean temperature and sum of precipitation at the Kyanjing station (3920 m a.s.l.) based on the average from 1989 to 2008. Annual mean temperature is 4.0 °C and average annual precipitation is 604 mm.

total, 49 cores from 41 trees growing on moderate to steep slopes were collected.

3.2. Sample preparation and dating

Tree-ring samples were processed in the laboratory following standard dendrochronological procedures (Cook and Kairiukstis, 1990). Cores were air dried and fixed to slotted wooden bars, then sanded with progressively finer sandpaper and polishing paper to make the tree-ring borders clearly visible. Each ring in all cores was dated to the calendar year of its formation using the crossdating technique (Stokes and Smiley, 1968). The ring widths were measured to an accuracy of 0.01 mm using the LINTAB measuring system (Rinntech, Heidelberg, Germany). The tree-ring borders in birch are faint, delineated by a light line of terminal parenchyma. Thus, careful examination is required for successful crossdating and accurate measurement of ring widths. The quality of crossdating and measurement was checked using the COFECHA program (Holmes, 1983). Out of 11,014 rings counted and measured, 138 (1.25%) were missing.

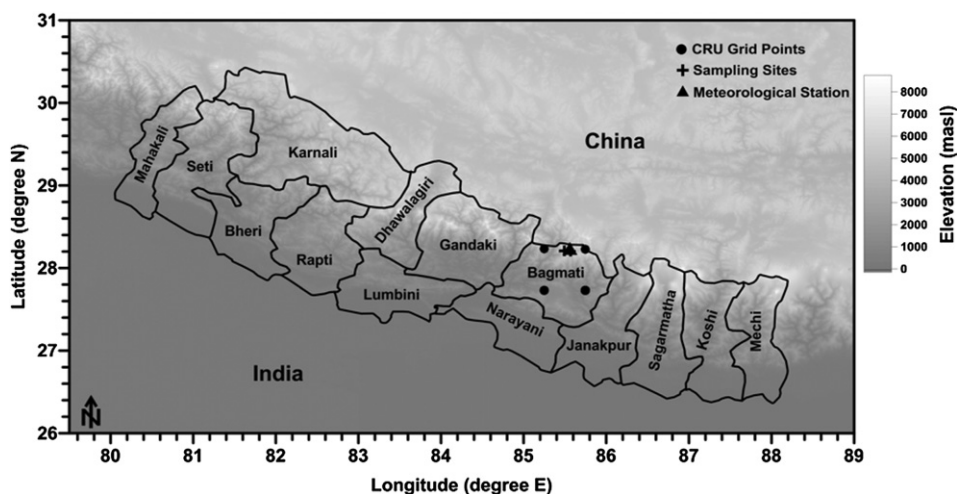


Fig. 1. Map of Nepal showing the study area in the Bagmati zone with the tree-ring sampling sites, a local meteorological station at Kyanjing and four CRU grid points.

3.3. Standardization and chronology construction

Tree-ring width data were standardized using the program ARSTAN (Cook, 1985) to remove growth trends related to age and stand dynamics while retaining the maximum common signal to form tree-ring indices. A smoothing spline of 67% of the series length was applied for the detrending. The standardized tree-ring series of the individual samples were then averaged into a standard chronology. To evaluate the chronology signal, a common interval from 1900 to 2000 was determined. The running average correlation between all possible series in a 50-year window with a 25-year overlap (RBAR) and the expressed population signal (EPS) (Wigley et al., 1984) were calculated to estimate the signal strength over time.

3.4. Climate data

The paucity of climatic records from meteorological stations close to the sampling sites for the calibration of tree-ring data is one of the major difficulties for dendroclimatological studies in Nepal (Bhattacharyya et al., 1992; Cook et al., 2003; Bräuning, 2004; Sano et al., 2005) and the surrounding Himalayan regions (Borgaonkar et al., 2011; Yadav, 2011; Liang et al., 2011a). The remote sampling sites likewise did not have respective nearby long-term meteorological records. The local meteorological station at Kyanjing has temperature/precipitation data available from 1989/1988 to 2008 with some gaps, too short for dendroclimatological calibration. Therefore, high-resolution gridded monthly temperature and precipitation data for the period of 1950–2009 from CRU TS 3 at 0.5° spatial resolution (Mitchell and Jones, 2005) were used. Large differences in climatic conditions can occur over short north-south distances in the Himalayan region, since grid points can shift from vegetated surfaces to glacier regions and vice versa. Therefore, the monthly mean temperature and precipitation datasets from the four nearest grid points (85.25°E, 27.75°N; 85.75°E, 27.75°N; 85.25°E, 28.25°N; 85.75°E, 28.25°N) were merged by simple arithmetic averaging. The merged monthly mean temperature and

precipitation data are highly correlated with the locally observed data at Kyanjing (for temperature: $r = 0.90$, $n = 240$ months, $p < 0.001$ and for precipitation: $r = 0.56$, $n = 240$ months, $p < 0.001$) than between the respective data at the individual grid points. Thus, the variations of the merged gridded monthly temperature and precipitation datasets appear to represent well those in the tree-ring sampling areas and hence are deemed suitable for analyzing the climate–growth relationships of Himalayan birch.

3.5. Analysis of climate-growth response

Pearson correlation coefficients were determined to describe the climate–growth relationships. A 95% confidence level was used to determine the statistical significance of the correlations. The monthly mean temperature and sum of precipitation from July of the previous year to September of the current year were correlated with the standard tree-ring chronologies. In addition, the pre-monsoon, post-monsoon and winter season mean temperature and sum of precipitation were used to test their relationships with tree growth.

4. Results and discussion

4.1. Chronology statistics

A 458-year tree-ring standard chronology from AD 1552–2009 was developed (Fig. 3). Individual tree ages ranged from 71 to 458 years, and the average age of the trees included in the final chronology was 225 years. The years 1999, 1608 and 1787 are characterized by the lowest growth, whereas the years 1634, 1735 and 1620 have the widest rings.

The chronology statistics indicate a high dendrochronological potential. Mean sensitivity (MS) is 0.19 and the correlation among all radii (RBAR) is 0.26 (Table 1), being comparable to alpine rhododendron with a medium signal strength (Liang and Eckstein, 2009). The chronology statistics are lower than those of Himalayan birch in the western Himalayas (Bhattacharyya et al., 2006) and *Betula ermanii* in the Changbai Mountains, northeast China (Yu

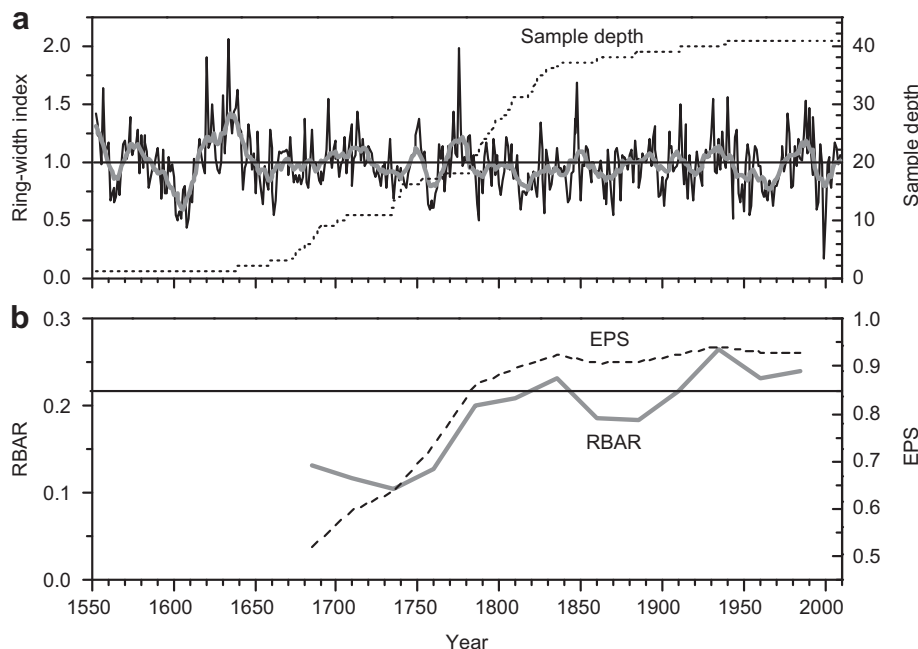


Fig. 3. (a) Tree-ring width chronology with a 10-year moving average curve superimposed (thick solid line) and sample depth (number of trees) (dashed line); (b) Variation of RBAR and EPS over time; the horizontal line marks EPS = 0.85.

Table 1
Selected statistics of the standard tree-ring chronology.

Parameters	Duration/value
Chronology time span (year)	1552–2009 (458)
Mean series length (year)	225
Number of trees (radii)	41 (49)
Mean sensitivity	0.19
Standard deviation	0.23
First-order autocorrelation	0.45
Expressed population signal ^a	0.93
Signal-to-noise ratio ^a	12.87
Variance in first eigenvector ^a	30%
Correlation among all radii ^a	0.26

^a For the common interval from 1900 to 2000.

et al., 2005). Generally, as compared with arid sites, trees in subalpine-temperate regions have lower MS and RBAR (Gou et al., 2005; Liang et al., 2009; Liu et al., 2009; Shao et al., 2010; Lv and Zhang, 2012). As reported, trees growing in the western (Borgaonkar et al., 1996), central (Bhattacharyya et al., 1992; Sano et al., 2005) and eastern Himalayas (Chaudhary and Bhattacharyya, 2000) also show lower MS and RBAR.

Though the ring-width chronology (Fig. 3) extends back to AD 1552, the EPS threshold value of 0.85 (Wigley et al., 1984) is reached only after AD 1785 with 25 samples. The error limits of the running RBAR statistics are also larger in the chronology prior to AD 1785 due to lower sample replication.

4.2. Climate-tree growth relationship

The standard tree-ring width chronology shows statistically significant ($p < 0.001$) positive correlations with precipitation in May and the pre-monsoon season (MAM) and inverse relationships ($p < 0.05$) with May temperature and precipitation in August of the current year (Fig. 4). Thus, cool/wet conditions during the pre-monsoon season favor the growth of Himalayan birch in central Nepal, contrary to the hypothesis that growth would positively respond to higher temperature.

Moisture availability in the pre-monsoon season appears to be a primary growth-limiting factor for timberline Himalayan birch growth despite an elevation of nearly 4000 m. Precipitation during the pre-monsoon season is around 94 mm in the study area, being a limit for Himalayan birch growth on steep slopes. Under very strong solar radiation at high elevation, temperature could increase drought stress by enhancing evapo-transpiration, resulting in a negative correlation between tree growth and the mean March–May temperature, as reported by Liang et al. (2012).

Such climatic responses are consistent with those of the same species (Bhattacharyya et al., 2006) in the western Himalayas, *B. ermanii* on the Changbai Mountains, northeast China (Yu et al., 2005), Mount Norikura, central Japan (Takahashi et al., 2005) and the Kamchatka Mountains, Russia (Pugacheva et al., 2008). The growth of most conifers negatively responds to pre-monsoon temperature (Borgaonkar et al., 1996; Yadav et al., 2004) and positively responds to pre-monsoon precipitation (Sano et al., 2005; Singh et al., 2009; Borgaonkar et al., 2011; Yadav, 2011) in the Himalayan region. Alpine juniper trees and shrubs on the south-eastern Tibetan Plateau exhibit similar climate vs. growth relationships as does Himalayan birch (Zhu et al., 2011a; Liang et al., 2012).

The significant and negative correlation between Himalayan birch and August precipitation is similar with *B. ermanii* in central Japan (Takahashi et al., 2005). The predominant period of high cloud cover in the Himalayas is in the second half of the monsoon season (August–September) with more than 20 days (Barros et al., 2004). The precipitation associated with cloud cover in August may decrease solar radiation and air temperature, which in turn reduces photosynthesis of plants and hence tree growth decline (Takahashi et al., 2005).

4.3. Pre-monsoon drought events derived from tree rings

The tree-ring width chronology of Himalayan birch could be taken as a proxy record of variations in pre-monsoon precipitation in central Nepal. However, instrumental records from most meteorological

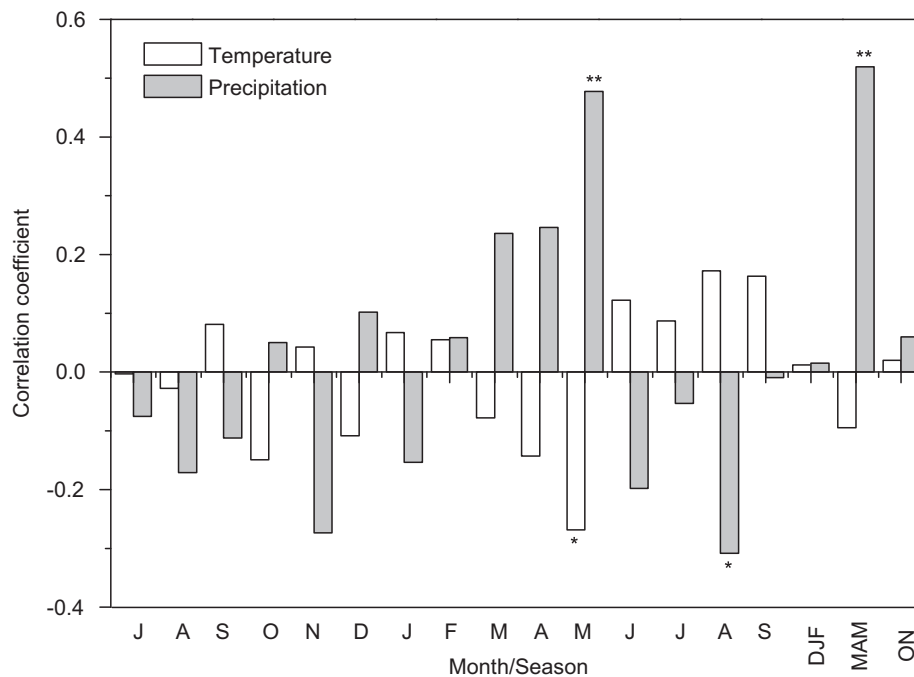


Fig. 4. Correlations between the standard ring-width chronology and the merged gridded CRU temperature and precipitation data from July of the previous year to September of the current year. DJF, MAM and ON represent winter, pre-monsoon and post-monsoon seasons, respectively. Statistically significant relationships are indicated by * $p < 0.05$ and ** $p < 0.001$.

stations are available only after the 1960s, and no other long-term precipitation proxies in central Nepal could be used to validate drought events derived from tree rings (Fig. 3). As observed with instrumental records, large-scale droughts after 1960 occurred in 1965, 1967–1973 and 1999–2001 in Nepal (Sigdel and Ikeda, 2010). In these years, Himalayan birch showed extreme narrow tree rings, confirming that its growth is a reliable indicator of drought. In particular, extreme droughts in March–April in 1999 and March–May in 2000 corresponded to a high frequency of missing rings of both years (65% and 35%, respectively) at the site close to Langtang village. The drought events around the 1810s and 1950s were observed in other tree-ring based precipitation reconstructions in the western Himalayas (Singh et al., 2009; Yadav, 2011) and the snow accumulation record from the Dasuopu ice core (Yao et al., 2000; Duan et al., 2004). The well-documented historical megadroughts, such as the Strange Parallels drought (1756–1768), the East India drought (1790–1796) and the late Victorian-era Great Drought (1876–1878) (Cook et al., 2010), appear to be embedded in much longer drought periods in this series. In this context, the persistent pre-monsoon droughts in the central Himalayas seem to be harbingers of the megadroughts induced by the South Asian monsoon failure.

5. Conclusions

Based on Himalayan birch tree-ring samples from central Nepal, a 458-year chronology was developed, currently the longest of this species in High Asia. The chronology statistics indicate a high dendroclimatological potential. It is significantly and positively related to precipitation and inversely related to temperature in the pre-monsoon season. This Himalayan birch chronology provides a unique opportunity to show variations of past pre-monsoon precipitation in the Nepal Himalayas. Most drought events derived from tree rings could be confirmed by the instrumental records after 1960 and historical documents. However, pre-monsoon droughts derived from only one tree-ring width chronology of Himalayan birch in central Nepal should not be over-interpreted. A forthcoming study will extend the chronology further back, increase sample depth for the early period and explore other mountainous areas for Himalayan birch sampling, enabling reconstruction of past pre-monsoon precipitation over a large area of the central Himalayas.

Acknowledgements

This work was supported by the “Strategic Priority Research Program – Climate Change: Carbon Budget and Relevant Issues” of the Chinese Academy of Sciences (XDA05090311), the Special Scientific Research Project for Public Interest (GYHY201106013-2-2), and the National Natural Science Foundation of China (40890051, 40871097). The fieldwork is partly supported by the TPE (Third Pole Environment) program. We thank Prof. Dr. Dieter Eckstein, Prof. Dr. Achim Bräuning and Dr. Haifeng Zhu for helpful discussions, the co-guest editor (Prof. Dr. Steven Leavitt) and two anonymous reviewers for their constructive comments.

References

- Barros, A.P., Kim, G., Williams, E., Nesbitt, S.W., 2004. Probing orographic controls in the Himalayas during the monsoon using satellite imagery. *Natural Hazards and Earth System Science* 4, 29–51.
- Bhattacharyya, A., Shah, S.K., 2009. Tree-ring studies in India, past appraisal, present status and future prospects. *IAWA Journal* 30, 361–370.
- Bhattacharyya, A., LaMarche Jr., V.C., Hughes, M.K., 1992. Tree-ring chronologies from Nepal. *Tree-Ring Bulletin* 52, 59–66.
- Bhattacharyya, A., Shah, S.K., Chaudhary, V., 2006. Would tree ring data of *Betula utilis* be potential for the analysis of Himalayan glacial fluctuations? *Current Science* 9, 754–761.
- Bhujia, D.R., Carrer, M., Gaire, N.P., Soraruf, L., Riondato, R., Salerno, F., Maharjan, S.R., 2010. Dendroecological study of high altitude forest at Sagar-matha National Park, Nepal. In: Jha, P.H., Khanal, I.P. (Eds.), *Contemporary Research in Sagarmatha (Mt. Everest) Region, Nepal*. Nepal Academy of Science and Technology, Kathmandu, Nepal, pp. 119–130.
- Borgaonkar, H.P., Pant, G.B., Rupa Kumar, K., 1996. Ring width variations in *Cedrus deodara* and its climatic response over the Western Himalaya. *International Journal of Climatology* 16, 1409–1422.
- Borgaonkar, H.P., Sikder, A.B., Ram, S., 2011. High altitude forest sensitivity to the recent warming: a tree-ring analysis of conifers from Western Himalaya, India. *Quaternary International* 236, 158–166.
- Bräuning, A., Mantwill, B., 2004. Summer temperature and summer monsoon history on the Tibetan Plateau during the last 400 years recorded by tree rings. *Geophysical Research Letters* 31, L24205. doi:10.1029/2004GL020793.
- Bräuning, A., 2004. Tree-ring studies in the Dolpo-Himalaya (western Nepal). *TRACE – Tree Rings in Archaeology, Climatology and Ecology* 2, 8–12.
- Chaudhary, V., Bhattacharyya, A., 2000. Tree ring analysis of *Larix griffithiana* from the Eastern Himalayas in the reconstruction of past temperature. *Current Science* 79, 1712–1716.
- Chhetri, P.K., Thapa, S., 2010. Tree ring and climate change in Langtang National Park, central Nepal. *Our Nature* 8, 139–143.
- Cook, E.R., Kairiukstis, L.A. (Eds.), 1990. *Methods of Dendrochronology: Applications in the Environmental Sciences*. Kluwer Academic Publishers, Dordrecht, The Netherlands, p. 394.
- Cook, E.R., Krusic, P.J., Jones, P.D., 2003. Dendroclimatic signals in long tree-ring chronologies from the Himalayas of Nepal. *International Journal of Climatology* 23, 707–732.
- Cook, E.R., Anchukaitis, J.K., Buckley, B.M., D'Arrigo, R.D., Jacoby, G.C., Wright, W.E., 2010. Asian monsoon failure and megadrought during the last millennium. *Science* 328, 486–489.
- Cook, E.R., 1985. A Time Series Approach to Tree-Ring Standardization. Unpublished Ph.D. dissertation, University of Arizona, Tucson.
- Duan, K., Yao, T., Thompson, L.G., 2004. Low-frequency of southern Asian monsoon variability using a 295-year record from the Dasuopu ice core in the central Himalayas. *Geophysical Research Letters* 31, L16209. doi:10.1029/2004GL020015.
- Eckstein, D., Hoogesteger, J., Holmes, R.L., 1991. Insect-related differences in growth of birch and pine at northern tree-line in Swedish Lapland. *Holarctic Ecology* 14, 18–23.
- Esper, J., Cook, E.R., Schweingruber, F.H., 2002. Low-frequency signals in long tree-ring chronologies and the reconstruction of past temperature variability. *Science* 295, 2250–2253.
- Gou, X., Chen, F., Yang, M., Li, J., Peng, J., Jin, L., 2005. Climatic response of thick leaf spruce (*Picea crassifolia*) tree-ring width at different elevations over Qilian Mountains, northwestern China. *Journal of Arid Environment* 61, 513–524.
- Holmes, R.L., 1983. A computer-assisted quality control program. *Tree-Ring Bulletin* 43, 69–78.
- Levanič, T., Eggertsson, O., 2008. Climatic effects on birch (*Betula pubescens* Ehrh.) growth in Fnjoskadalur valley, northern Iceland. *Dendrochronologia* 25, 135–143.
- Liang, E.Y., Eckstein, D., 2009. Dendrochronological potential of the alpine shrub *Rhododendron nivale* on the south-eastern Tibetan Plateau. *Annals of Botany* 104, 665–670.
- Liang, E.Y., Shao, X.M., Xu, Y., 2009. Tree-ring evidence of recent abnormal warming on the southeast Tibetan Plateau. *Theoretical and Applied Climatology* 98, 9–18.
- Liang, E.Y., Liu, B., Zhu, L.P., Yin, Z.-Y., 2011a. A short note on linkage of climatic records between a river valley and the upper timberline in the Sygera Mountains, southeastern Tibetan Plateau. *Global and Planetary Change* 77, 97–102.
- Liang, E.Y., Wang, Y.F., Eckstein, D., Luo, T.X., 2011b. Little change in the fir tree-line position on the southeastern Tibetan Plateau after 200 years of warming. *New Phytologist* 190, 760–769.
- Liang, E.Y., Lu, X.M., Ren, P., Li, X.X., Zhu, L.P., Eckstein, D., 2012. Annual increments of juniper dwarf shrubs above the tree line on the central Tibetan Plateau: a useful climatic proxy. *Annals of Botany* 109, 721–728.
- Liu, Y., Linderholm, H.W., Song, H.M., Cai, Q.F., Tian, Q.H., Sun, J.Y., Chen, D.L., Simelton, E., Seftigen, K., Tian, H., Wang, R.Y., Bao, G., An, Z.S., 2009. Temperature variations recorded in *Pinus tabulaeformis* tree rings from the southern and northern slopes of the central Qinling Mountains, central China. *Boreas* 38, 285–291.
- Lv, L.X., Zhang, Q.B., 2012. Asynchronous recruitment history of *Abies spectabilis* along an altitudinal gradient in the Mt. Everest region. *Journal of Plant Ecology* 5, 147–156.
- Mitchell, T.D., Jones, P.D., 2005. An improved method of constructing a database of monthly climate observations and associated high-resolution grids. *International Journal of Climatology* 25, 693–712.
- Pugacheva, E., Solomina, O., Mikhalev, V., 2008. The first attempt of spring precipitation reconstruction in South Kamchatka, using ring width of stone birch (*Betula ermanii* Cham.). *Geophysical Research Abstracts* 10, EGU2008-A-00412.
- Sano, M., Furuta, F., Kobayashi, O., Sweda, T., 2005. Temperature variations since the mid-18th century for western Nepal, as reconstructed from tree-ring width and density of *Abies spectabilis*. *Dendrochronologia* 23, 83–92.
- Shao, X., Xu, Y., Yin, Z.-Y., Liang, E., Zhu, H., Wang, S., 2010. Climatic implications of a 3585-year tree-ring width chronology from the northeastern Qinghai-Tibetan Plateau. *Quaternary Science Reviews* 29, 2111–2122.

- Sigdel, M., Ikeda, M., 2010. Spatial and temporal analysis of drought in Nepal using standardized precipitation index and its relationship with climate indices. *Journal of Hydrology and Meteorology* 7, 59–74.
- Singh, J., Yadav, R.R., Wilmking, M., 2009. A 694-year tree-ring based rainfall reconstruction from Himachal Pradesh, India. *Climate Dynamics* 33, 1149–1158.
- Stokes, M.A., Smiley, T.L., 1968. *An Introduction to Tree-Ring Dating*. The University of Chicago Press, Chicago. 63 p.
- Takahashi, K., Tokumitsu, Y., Yasue, K., 2005. Climatic factors affecting the tree-ring width of *Betula ermanii* at the timberline on Mount Norikura, central Japan. *Ecological Research* 20, 445–451.
- Wang, Y., Cufar, K., Eckstein, D., Liang, E., 2012. Variation of maximum tree height and annual shoot growth of Smith fir at various elevations in the Sygera Mountains, southeastern Tibetan Plateau. *PLoS One* 7 (3), e31725. doi:10.1371/journal.pone.0031725.
- Wigley, T.M.L., Briffa, K.R., Jones, P.D., 1984. On the average value of correlated time series, with applications in dendroclimatology and hydrometeorology. *Journal of Climatology and Applied Meteorology* 23, 201–213.
- Yadav, R.R., Park, W.K., Singh, J., Dubey, B., 2004. Do the western Himalayas defy global warming? *Geophysical Research Letter* 31, L17201. doi:10.1029/2004GL020201.
- Yadav, R.R., 2011. Long-term hydroclimatic variability in monsoon shadow zone of western Himalaya, India. *Climate Dynamics* 36, 1453–1462.
- Yao, T., Duan, K., Tian, L., Sun, W., 2000. Dasuopu ice core accumulation record and Indian summer monsoonal precipitation change in the past 400a. *Science in China Series D: Earth Science* 30, 619–627.
- Yu, D.P., Gu, H.Y., Wang, Q.L., 2005. Relationships of climate change and tree ring of *Betula ermanii* tree line forest in Changbai Mountain. *Journal of Forestry Research* 16, 187–192.
- Zhu, H.F., Shao, X.M., Yin, Z.Y., Huang, L., 2011a. Early summer temperature reconstruction in the eastern Tibetan Plateau since AD 1440 using tree-ring width of *Sabina tibetica*. *Theoretical and Applied Climatology* 106, 45–53.
- Zhu, H.F., Shao, X.M., Yin, Z.-Y., Xu, P., Xu, Y., Tian, H., 2011b. August temperature variability in the southeastern Tibetan Plateau since AD 1385 inferred from tree rings. *Palaeogeography, Palaeoclimatology, Palaeoecology* 305, 84–92.