documented as thrust sheets into the Palghat region have the potential to be the heat source and in providing saline brines to aid low aH_2O. We record from PT data that banded charnockites (regional granulite) evolved at deep crustal levels corresponding to a depth of ~ 30 km, which could have been influenced by large-scale CO_2 influx, whereas the arrested charnockites formed at midcrustal levels at a depth of about ~ 20 km. This region can be compared to the zone of K-metasomatism and anatexis in the model proposed by Janardhan *et al.*[20], with the saline brines playing a major role and CO_2 having a subordinate role.

1. Newton, R. C., Smith, J. V. and Windley, B. F., *Nature*, 1980, **288**, 45–50.
2. Touret, J. and Dietvorst, P., *J. Geol. Soc. London*, 1983, **140**, 635–649.
3. Hansen, E. C., Newton, R. C., Janardhan, A. S. and Lindenberg, S., *J. Geol.*, 1995, **103**, 629–651.
4. Harlov, D. E., Hansen, E. C. and Bigler, C., *Chem. Geol.*, 1998, **151**, 373–386.
5. Newton, R. C., Aranovich, L. Y., Hansen, E. C. and Vandenheuvel, B. A., *Precambr. Res.*, 1998, **91**, 41–63.
6. Aranovich, L. Y. and Newton, R. C., *Contrib. Mineral. Petrol.*, 1996, **125**, 200–212.
7. Aranovich, L. Y. and Newton, R. C., *Contrib. Mineral. Petrol.*, 1997, **127**, 261–271.
8. Perchuk, L. L. and Gerya, T. V., *Chem. Geol.*, 1993, **108**, 175–186.
9. Watson, E. D. and Brenan, J. M., *Earth Planet. Sci. Lett.*, 1987, **85**, 497–515.
10. Ramakrishnan, M., *Mem. Geol. Soc. India*, 1993, **25**, 45–62.
11. Ravindra Kumar, G. R. and Raghavan, V., *J. Geol. Soc. India*, 1992, **39**, 293–302.
12. Ravindra Kumar, G. R. and Srikantappa, C., *J. Geol. Soc. India*, 1995, **45**, 145–162.
13. Soman, K., Thara, K. G., Arakelyants, M. M. and Golubyev, V. N., *J. Geol. Soc. India*, 1990, **35**, 82–86.
14. Safanov, D. G., Perchuk, L. L. and Gerya, T. V., International Symposium on Charnockite and Granulite Facies Rocks, Geologist's Association of Tamil Nadu, 2000, pp. 239 251.
15. Weinberg, R. F., *Lithos*, 1999, **46**, 393–410.
16. Weinberg, R. F. and Searle, M. P., *J. Geol.*, 1999, **107**, 27–48.
17. Hansen, E. C., Janardhan, A. S., Newton R. C., Pram, W. K. B. N. and Ravindra Kumar, G. R., *Contrib. Mineral. Petrol.*, 1987, **97**, 225–244.
18. Stähle, H. J., Raith, M., Hoernes, S. and Delfs, A., *J. Petrol.*, 1987, **28**, 803–834.
19. Ferry, J. M. and Gerdes, M. L., *Annu. Rev. Earth Planet. Sci*, 1998, **26**, 255–287.
20. Janardhan, A. S., Newton, R. C. and Hansen E. C., *Contrib. Mineral. Petrol.*, 1982, **79**, 130–149.

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Tree-ring indications of recent glacier fluctuations in Gangotri, western Himalaya, India

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A 410-year-old (AD 1590–1999) ring-width chronology of Himalayan pine (*Pinus wallichiana*) based on large replication of samples derived from a pure, mixed age stand growing on thick soil with almost even topography near Chirbasa, Gangotri has been developed. This makes the longest chronology of this species developed so far from the Indian region. The chronology shows abrupt surge in tree growth during the late 20th century, with the highest growth indices recorded in the 1990s. Strong correlation noted between tree growth and winter temperature shows that the winter warmth is one of the main factors responsible for the twentieth century growth surge. This growth surge is closely associated with the area vacated by the Gangotri glacier. Low growth prior to the 1950s reflecting cooler conditions indicates that the glacier should have been stationary for a long time with some episodic advances.

GANGOTRI glacier, around 30 km in length covering an area of 143 km^2, flowing north-west, is one of the largest valley-type glaciers in the western Himalaya. It originates from Chaukhamba group of peaks at an altitude of 7100 m asl. Observational records show that during 1935–1996, the Gangotri glacier has retreated around 1147 m (ref. 1). Such a fast retreat of the glacier, a major freshwater resource for the people of the peninsular region in India, is of great concern to the human society. As the climate change directly influences the size, flow rate and even the existence of glaciers, there is now a growing belief that the anthropogenically-induced warming is one of the major contributing factors to the accelerated pace of glacier recession. To develop a better understanding of the linkage between glacier and climate dynamics, high-resolution, long-term data are needed. The glacier fluctuations measured with geological, geomorphological and other proxy methods could be calibrated with long-term climate records. Tree-rings provide valuable proxy of various environmental parameters with the resolution of calendar years. Such long-term proxy records developed from tree-rings covering the 'Medieval Warm' and 'Little Ice Age', recognized major climatic events of the pre-industrial period, would provide valuable database to estimate the magnitude of anthropogenically-induced warming on glacier dynamics.

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The tree-rings, with precise dating control, have been found to be valuable proxy of glacier fluctuation[2–5]. In India such studies, though of immense potential in the Himalayan region, excepting a very elementary study based on few Himalayan pine samples from Kinnaur, Himachal Pradesh[6], have not yet been explored. Tree-ring studies so far carried out in the Himalayan region indicate strong potential of developing millennium-long chronologies for various conifer species[7,8]. Some of the chronologies developed from the Himalayan region have been found to be suitable for long-term climate reconstruction[8–13]. Long-term climate responsive chronologies developed from tree-line zones could be sensitive indicators of glacier fluctuation. Here we report the ring width chronology of Himalayan pine (*Pinus wallichiana*) prepared from the tree-line zone and its relationship with the Gangotri glacier behaviour.

Himalayan pine (*P. wallichiana*) is a large evergreen tree with its natural distribution from Afghanistan to all along the Himalaya from Pakistan to Arunachal Pradesh in India, through Nepal and Bhutan at altitudes ranging from 1800 to 3900 m (ref. 14). It usually prefers to grow on deep moist soils, pure or mixed with Himalayan cedar (*Cedrus deodara*), Himalayan fir (*Abies pindrow*), Himalayan spruce (*Picea smithiana*) and oak (*Quercus semecarpifolia*). At higher elevations it is usually associated with birch (*Betula utilis*) and juniper (*Juniperus macropoda*).

The environmental signals in tree-ring chronologies largely depend on the nature of site from which constituent samples are derived. We emphasized to collect tree-ring samples from sites where temperature signals in tree-rings could be maximized. For this a pure, mixed age stand of Himalayan pine growing in a mesic tree-line site with even terrain, occasionally with gentle slope near Chirbasa, Gangotri (3400 m asl) was selected for sampling (Figure 1). The sampling of old trees was preferred to get long tree-ring records. However, in many cases the lengths were abbreviated by heart rot and do not represent the full length of the sampled trees. A total of 96 tree core samples from 47 healthy, disjunctly growing trees not showing any visible mark of injury or any other human disturbance were collected. Usually two cores from each tree from opposite directions were collected. The tree-core samples were processed following standard dendrochronological procedures[15–17]. Ring widths of precisely-dated samples were measured to the nearest 0.01 mm using linear encoder interfaced with a personal computer. The ring-width measurements were used to check the quality of cross-dating by using the computer program COFECHA[18]. This program helps in the identification of segments of a core or group of cores where dating problems might be present. The segments of samples where dating problems were indicated by this program were rechecked under the stereozoom binocular microscope to correct errors if any. Few samples where dating errors could not be corrected were excluded from further analyses. Finally we selected 85 radii of 43 trees for chronology preparation. A good quality cross-dating with high mean inter-series correlation (0.61) was noted among the selected samples. The high mean inter-series correlation noted among the samples also reflects the presence of strong climatic signal in samples. After verification of the cross-dating, ring-width measurement series of individual samples was standardized following standard techniques[16,17,19], so as to remove the age-and-size-related biological growth trend and maximize the common signal among the samples, which is mostly due to climate. The individual tree-sample chronologies were then averaged using biweight robust procedure[19] to develop the mean chronology (AD 1590–1999), which is so far the longest for this species from the Indian region. The mean acceptable chronology confidence level (0.85) gauged using the sub-sample signal strength (SSS – a combination of mean inter-series correlation and the number of tree-core samples represented in the chronology[20]) is achieved with a minimum replication of 10 tree samples, i.e. AD 1754 onwards. The chronology confidence level gradually decreases backward with the decrease in sample replication to 0.70 at AD 1650, with the sample depth to 4 tree samples. We truncated the chronology at AD 1650 (Figure 2). The chronology features (Table 1) such as common variance (per cent Y) among the samples (37) and high signal/noise ratio (20.12) indicate the potentiality of the chronology in climate studies. High auto-correlation (Lag-1) noted in the chronology (0.67) indicates low frequency variations.

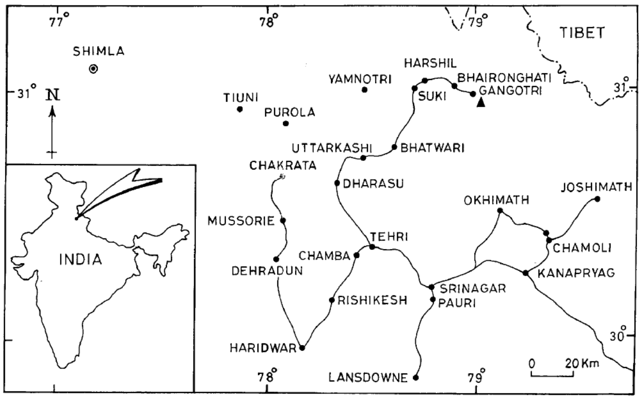

Figure 1. Map showing the tree-ring sampling site and the meteorological station, Shimla.

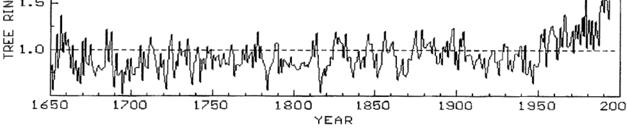

Figure 2. Ring-width chronology of *Pinus wallichiana* (AD 1650–1999) developed from Gangotri.

To understand the relationship between climate and tree-ring chronology, climate data from stations close to the sampling site are required. However, in the Himalayan region this is the major limitation as the meteorological stations for which considerably good data length are available are situated far from the high-altitude potential tree-ring sites. We used the climate data of Shimla with long continuous record for detailed tree growth and climate relationship using response function analysis[16]. For this a set of 26 predictor variables (mean monthly temperature and total monthly precipitation) from September of previous growth year to the September of the current year, for the period 1876–1989, were used as predictors in step-wise multiple regression analysis with current year ring-width index as predictand. No significant relationship was noted with the precipitation of any month of the dendrochronological year taken, which could be expected in the mesic sites like ours. This could also be due to the non-representativeness of the precipitation of Shimla for the study area. This is a common feature in the Himalayan region, as the precipitation varies in short distances with topography and aspect. The response function of the mean monthly temperature is shown in Figure 3. The total variance accounted for in tree-rings by temperature alone is found to be 20%. The mean winter (December–February) temperature shows direct relationship with tree growth. This direct relationship between tree growth and winter temperature indicates that the Himalayan pine trees carry on significant amount of photosynthesis during warm winters, the reserves of which are used in the ensuing growing season. Similar observations have been earlier noted with the Himalayan pine trees growing even at lower altitudes[21]. Other empirical studies from elsewhere have also indicated that several species of pine carry out photosynthesis at significant rates during the dormant winter season[22,23].

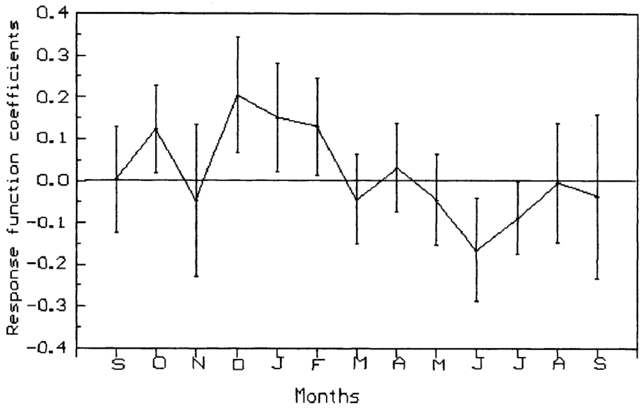

Figure 3. Response function of the residual chronology with mean monthly temperature from September of the prior growth year to the September of the current growth year. Vertical bars show 95% confidence limits.

Table 1. Statistics *of Pinus wallichiana* chronology from Chirbasa, Gangotri

Chronology type	Standard
Period (years)	1590 to 1999 (410)
Trees (radii)	43 (85)
Mean sensitivity	0.16
Standard deviation	0.27
Lag-1 autocorrelation	0.67
Variance analysis	
Period (years)	1856 to 1999 (144)
Trees (radii)	35 (60)
Mean correlations:	
Among all radii	0.37
Between trees (*Y* variance)	0.37
Within trees	0.61
Signal-to-noise ratio	20.12
Agreement with population chronolgy	0.95

The analysis of tree-ring chronology (AD 1650–1999) shows abrupt surge in growth since the 1950s. The 1990s recorded the maximum growth in trees, with the highest in 1998. The northern hemisphere proxy climate records show that the 1990s were the warmest in the last millennium, with 1998 being the warmest[24]. The increasing growth trend observed in recent decades closely matches with the retreat of Gangotri glacier (annual ice cave retreat) measured periodically since 1935 (ref. 25) and mean winter (December–February) temperature of Shimla meteorological station (Table 2). The correlation between tree-ring chronology and mean winter (December–February) temperature has been found to be 0.41 ($P < 0.05$). The December–February temperature data of Shimla (1876–1989) show warming of 0.22°C/100 years[11]. It could be possible that the winter warmth is one of the important factors for the 20th century growth surge in Himalayan pine. The ring-width series plotted along with the mean winter temperature is shown in Figure 4. Except in the early part of the meteorological records, mean winter temperature shows general correspondence with the growth trend. It is possible that the multiple set of such chronologies prepared from similar sites should provide valuable proxy of winter temperature and also glacier fluctuations. According to Puri and Shukla[25], the accelerated pace of glacier retreat could be attributed to global warming. However, multi-century tree-ring data network covering the 'Medieval Warm' and 'Little Ice Age' periods are needed to get better insight into the

Table 2. Relationship between the ring-width indices, mean winter (December–February) temperature and the annual ice cave retreat of the Gangotri glacier (after Puri and Shukla[25])

Year	Mean ring-width index	Mean winter (December–February) temperature (°C)	Annual ice cave retreat (m/year)
1935–1956	0.9122	5.2	10.16
1956–1971	1.1307	5.5	27.33
1971–1977	1.1868	5.6	30.84
1977–1990	1.2742	5.8*	28.08

*Mean is for the period 1977–1989.

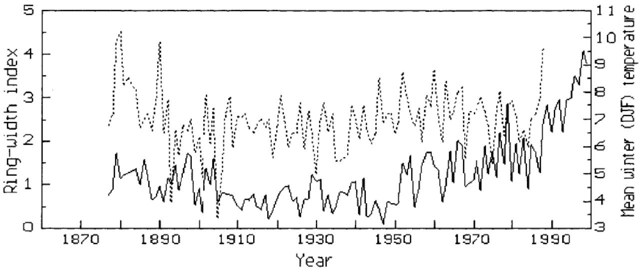

Figure 4. Mean winter temperature (°C) (broken line) and ring-width chronology (solid line) showing general correspondence plotted together (AD 1877–1989).

intricacies of climate *vis-à-vis* glacier dynamics. The chronology does not show any other such episode of high growth in the pre-1950s. The tree growth had been rather more frequently low, usually below the long-term mean. The correlation study between ring-width chronology and temperature indicates that the winters must have been cooler prior to the 1950s, reflecting advanced glacier state compared to its present position. The geomorphological studies[26] also support the fact that during the last 200–300 years, the Gangotri glacier maintained an advanced state. The longest period of low tree-growth as indicated in our data was in the first half of the 20th century. The other prominent low growth periods recorded in our data were around 1780–1810, 1740–1760 and 1690–1710. The low growth indices possibly reflect the episodic advance of the glacier.

The present study reflects the utility of the Himalayan pine chronologies, developed from high-altitude tree-line sites, in the study of glacier dynamics. The 20% variance in tree-rings explained by temperature alone shows that multi-site chronologies will help in developing robust climatic reconstructions. Such long-term climate records reconstructed from tree-rings would provide valuable insight into the understanding of the long-term glacier dynamics and estimate the impact and magnitude of anthropogenic warming on glacier fluctuation.

1. Ravi Shanker and Srivastava, D., Symp. on Snow Ice Glacier: A Himalayan Perspective, 9–11 March 1999, pp. 1–7.
2. Luckman, B. H., *Quat. Sci. Rev.*, 1993, **12**, 441–450.
3. Luckman, B. H., *Holocene*, 1995, **5**, 149–159.
4. Kaiser, K. F., *Dendrochronologia*, 1994, **11**, 101–122.
5. Wiles, G. C., Post, A., Muller, E. H. and Molnia, B. F., *Quat. Res.*, 1999, **52**, 185–195.
6. Bhattacharyya, A. and Yadav, R. R., *Curr. Sci.*, 1996, **70**, 739–744.
7. Yadav, R. R., *Palaeobotanist*, 1992, **40**, 394–398.
8. Yadav, R. R., Park, W-K. and Bhattacharyya, A., *Holocene*, 1999, **9**, 85–90.
9. Hughes, M. K., in *Climate Since AD 1500* (eds Bradley, R. S. and Jones, P. D.), Routledge, London, 1992, pp. 415–431.
10. Borgaonkar, H. P., Pant, G. B. and Rupa Kumar, K., *Holocene*, 1994, **4**, 299–306.
11. Borgaonkar, H. P., Pant, G. B. and Rupa Kumar, K., *Int. J. Climatol.*, 1996, **16**, 1409–1422.
12. Yadav, R. R., in Proceedings of International Conference on Dendrochronology and Environmental Trends (eds Stravinskiene, V. and Juknys, R.), Vytautas Magnus University, Kaunas, Lithuania, 1998, pp. 288–291.
13. Yadav, R. R., Park, W.-K. and Bhattacharyya, A., *Quat. Res.*, 1997, **48**, 187–191.
14. Sahni, K. C., *Gymnosperms of India and Adjacent Countries*, Bishen Singh and Mahendra Pal Singh Pub., Dehradun, 1990, p. 169.
15. Stokes, M. A. and Smiley, T. L., *An Introduction to Tree-Ring Dating*, Chicago, University of Chicago Press, Chicago, 1968, p. 73.
16. Fritts, H. C., *Tree Rings and Climate*, Academic Press, New York, 1976, p. 567.
17. Cook, E. R. and Kairiukstis, L. A. (eds), *Methods of Dendrochronology*, Kluwer Academic Press, Dordrecht, 1990, p. 394.
18. Holmes, R. L., *Tree-Ring Bull.*, 1983, **44**, 69–75.
19. Cook, E. R., Ph D dissertation, The University of Arizona, Tucson, University Microfilms International, Ann Arbor, 1985.
20. Wigley, T. M. L., Briffa, K. R. and Jones, P. D., *J. Clim. Appl. Meteorol.*, 1984, **23**, 201–213.
21. Yadav, R. R., Bhattacharyya, A. and Park, W.-K., *Kor. J. Ecol.*, 1997, **20**, 95–102.
22. Hepting, G. R., *Phytopathology*, 1945, **35**, 106–119.
23. Kramer, P. J., in *The Physiology of Forest Trees* (ed. Thinmann, K. V.), The Ronald Press Co, New York, 1958, pp. 156–186.
24. Hughes, M. K., Mann, M. E. and Bradley, R. S., *Pages Workshop on South Asian Palaeoenvironments*, Pune, India, 4–5 February 2000, pp. 11–15.
25. Puri, V. M. K. and Shukla, S. P., *Geol. Surv. India Spl. Publ.*, 1996, **21**, 89–291.
26. Sharma, M. and Owen, L. A., *Quat. Sci. Rev.*, 1996, **15**, 335–365.

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