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中国科学院大学

博士学位论文

基于树轮对喜马拉雅山中部的季风前降水重建

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Ph.D Thesis

Variations of pre-monsoon precipitation derived from tree rings in the central Himalayas

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基于树轮对喜马拉雅山中部的季风前降水重建

摘 要

喜马拉雅山是世界上最长且海拔最高的山脉，沿从南至北的海拔梯度上具有多种气候类型，孕育了从亚热带常绿阔叶林至高寒灌丛等的丰富的森林资源。该地区对气候变化十分敏感，但连续的、长时间尺度的气候变化数据十分匮乏，限制了开展区域气候变化及其对森林生态系统影响等方面的研究。树轮在重建过去气候变化方面发挥着重要作用。然而，喜马拉雅山区尤其是尼泊尔一带的树轮气候研究还相当匮乏。迄今，树轮气候重建仅限于冬或春季温度重建，缺乏对过去降雨变化的重建研究。另外，值得提出的是，喜马拉雅山区的大部分树轮研究仅针对针叶树种，对阔叶树种的研究一直未受到重视。其实，糙皮桦（*Betula utilis* D. Don）在喜马拉雅山区具有十分广泛的分布，且是最常见的高山林线树种。然而，我们仍然不清楚糙皮桦的树轮气候学潜力。

此论文针对喜马拉雅山中部高山林线上的糙皮桦开展树轮研究，旨在揭示林线糙皮桦是否具有建立长树轮年表的潜力？利用林线桦树树轮是否可以重建过去的气候变化历史，尤其是降雨变化历史？喜马拉雅山中部气候变化与大空间尺度上环境事件之间是否存在着显著的联系？由于尼泊尔器测气候资料十分缺乏，而且已有的气象站多位于低海拔区，我们不清楚低海拔处的温度和降水变化是否可以用来指示高海拔处的变化特征。围绕以上问题，此论文主要得到以下结论或认识：

为了揭示海拔梯度上（130 m 至 5050m）温度和降水记录之间的联系，我们比较和分析了 2005 年 1 月至 2008 年 12 月期间的器测温度和降水数据。从平均值的变化幅度和分布来看，不同时间尺度上和不同海拔上的温度和降水记录具有显著的差异。尽管存在这些差异，海拔梯度带上的温度和降水的变化具有很好的一致性，且这种一致性随着时间尺度增长而增强。除平原地区与中部山地和高海拔样点之外，不同海拔之间的温度变化具有显著的相关关系。回归模型的斜率（R^2>0.5）表示了不同海拔处的温度变化的相似性。因此，月平均温度，作为树轮气候学研究中常用校准变量，其低海拔的记录值

能较好地代表高海拔处的变化特征，可以用来进行树轮气候校正。不同海拔处的月降水数据也显示了类似的模式。虽然个别样点之间的月降水量变化的相关性没有温度变化之间的显著，但大多数情况下的相关系数仍达到显著水平。综上所述，我们发现使用喜马拉雅山中段低海拔气候记录来定量估计高海拔区的月平均温度和月降雨量的变化是可行的，这我们进行树轮气候分析奠定了方法基础。然而，值得提出的是，平原低海拔地区的气候变化不能很好地代表中部山地和喜马拉雅高海拔地区的温度和降水的变化。

基于对尼泊尔中部糙皮桦树轮样本的交叉定年，我们建立了一条 458 年的树轮宽度年表，这是目前高亚洲地区最长的糙皮桦树轮年表。年表的统计特征显示，糙皮桦具有树轮气候学研究学研究潜力。尤其是，糙皮桦的生长与当年季风前期（3-5 月份）的降水量之间呈显著的正相关关系（P <0.001），为重建喜马拉雅山中部过去的季风前的降水变化历史提供了可能性。然而，林线糙皮桦的树轮气候学意义还需要多个树轮样点的研究来证明。

通过喜马拉雅山中部由 7 个糙皮桦林线树轮年表构成的树轮网络，此研究进一步证实了林线糙皮桦的生长主要受季风前期降水的限制。这与全球尺度上其他高山和环北极林线上树木的生长对环境响应关系不同。林线糙皮桦树轮所记录的降水信息，与喜马拉雅山南坡降水格局和糙皮桦的树种特性有关。喜马拉雅山中部从南部平原区至海拔 2000-3000 米，降水随海拔的升高而增加，而海拔 2000-3000 米以上的降水会随海拔上升而逐渐减少，甚至林线处（4000 米海拔）的年降雨量仅 650 mm 左右。尤其是，季风前期的降水异常少，经常形成春季干旱。以上降水变化格局导致了高海拔林线上糙皮桦的生长可能受到降水限制。近几十年来，林线糙皮桦在干旱年份（尤其是 3-5 月份的干旱）高频率缺失轮的出现也进一步证实了干旱对糙皮桦生长的影响。另一方面，糙皮桦一般生长于雨影区，更易受到干旱的影响。考虑到糙皮桦在喜马拉雅山脉的广泛分布，该树种可作为调查驱动树线形成机制的一个特例，具有重要的生态学价值。

基于以上树轮网络，我们建立了一条 460 年的区域平均树轮年表。该区域树轮年表与季风前期（3-5 月）降水量之间存在显著的相关关系（r=0.61, p<0.001, 1960-2009），基于此年表我们重建了公元 1552 年以来的喜马拉雅山中部春季降水变化历史。这是迄今首次利用糙皮桦树轮来开展气候重建工作，同时也是首次重建了喜马拉雅中部降水变

化历史。重建的降水变化序列显示了年际和年代际的变化特征。其中，1999、1813 和 1954 年的春天是最为干旱的，而 1775、1557 和 1988 年则是春季降雨量最多的年份。重建的序列还显示，公元 1811-1821 以及 1995-2005 是过去 460 年来最干旱的两个十年。降水的减少与 1809 年发生的未知的火山喷发以及 Tambora 火山喷发的影响具有同步性，表明热带和亚热带的火山喷发可能会导致喜马拉雅山中部干旱的发生。另外，所重建的降水序列与加德满都 3-5 月的降水变化以及其他用于指示南亚季风降雨指数之间也存在显著的相关关系。

此研究通过建立喜马拉雅山中部糙皮桦林线树轮网络，揭示了糙皮桦的树轮气候学意义，重建了过去降水变化历史，为喜马拉雅山树轮气候学和高山林线研究填加了新的内容，同时也为深入了解过去的降水变化历史及其驱动机制奠定了数据基础。

关键词：树轮，树轮气候学，糙皮桦，气候变化，前季风期降水重建，干旱，喜马拉雅山中部，尼泊尔

VARIATIONS OF PRE-MONSOON PRECIPITATION DERIVED FROM TREE RINGS IN THE CENTRAL HIMALAYAS

Abstract

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. This region, being highly sensitive to the global climate change, however, is poor in instrumental climatic records in terms of quality and longevity. Tree rings have been playing an important role in reconstructing past climatic change. However, dendroclimatic studies in the Himalayas, in particular in Nepal, were limited. To date, a few tree-ring based climate reconstructions were confined to winter or spring temperature. Little was known about variations in precipitation in a long-term context in the central Himalayas. In addition, most dendrochronologial studies were based on tree-ring samples from coniferous tree species. The dendrochronological potential of broadleaf tree species was less known. In fact, Himalayan birch (*Betula utilis* D. Don) has a wide distribution in the Himalayas. It is also a widespread timberline species. However, we did not know whether this species has dendroclimatic potential.

This study focused on dendrochronology of timberline Himalayan birch in the central Himalayas and tried to answer several questions: Whether is Himalayan birch useful to develop the long tree-ring chronology? Whether are tree rings of Himalayan birch useful for climatic reconstruction, in particular precipitation reconstruction? Whether is there a teleconnection between climate changes in the central Himalayas and other large-scale environmental events or indices? In addition, most meteorological stations are located at low elevations in the central Himalayas. It is not clear whether variations in monthly climate records at low elevations can be used to quantitatively represent those at higher elevations in

the central Himalayas, and hence for dendroclimatic calibration. Focusing on the above questions, this study can be concluded as:

In order to investigate climatic linkages between different elevations, we compared the climatic data representing a wide range of climatic conditions from sub-tropical (130 m a.s.l) to sub-alpine (5050 m a.s.l.) from January 2005 to December 2008. In terms of magnitude of their means and distributions, temperature and precipitation across different altitudes at varying time scales are significantly different to each other. In spite of these differences, the variations of temperature and precipitation are consistent in different altitudes and their agreement increases with lengthening time windows. Strong and significant correlation of temperature was observed between elevations [except between low–elevation (plan area) with the mid hills as well as the high Himalayas]. The slopes of the regression model (R2>0.5) indicated similar changes in temperature between different elevations. As commonly used variable for dendroclimatic calibration, the variations of monthly mean temperature records at lower elevations are better representatives to those at higher elevations. Precipitation data also showed a similar pattern, although the associations between the stations at different elevations were not as stronger as the temperature, however, significant in most of the cases. In summary, we found that it is possible to use lower-elevation monthly climate records to quantitatively assess those at higher elevations in the central Himalayas. However, variations of climatic records in the plane area cannot represent well those in mid hills and the high Himalayas.

Based on Himalayan birch tree-ring samples from the Langtang national park of central Nepal, we developed a 458-year ring-width chronology. The chronology statistics showed a high dendroclimatic potential. The tree-ring growth of Himalayan birch demonstrated positive and significant ($p<0.001$) response to pre-monsoon precipitation. Beyond our expectation, tree rings of timberline Himalayan birch provide a rare opportunity to show variations of past pre-monsoon precipitation in the central Himalayas. However, such a climatic response needed to be tested through a large-scale tree-ring network.

A large-scale of tree-ring network of timberline Himalayan birch (7 forest sites) in the central Himalayas further supported that its growth was primarily controlled by moisture stress rather than by low temperature. In particular, its growth at the timberlines is dominated by moisture availability during the pre-monsoon season, being different with tree growth at other alpine and arctic timberlines. Such a climatic response of timberline tree species is closely

related to the world's largest elevation gradient in association with decreasing precipitation with increasing elevation (above 2000-3000 m a.s.l). On the other hand, it is related to the ecophysiological trait of Himalayan birch preferring to grow in the rain shadow. Given a wide distribution of Himalayan birch forest in the Himalayas, its timberline represents an exceptional case to investigate mechanism driving timberline formation.

Based on the above tree-ring network in the central Himalayas, we developed a 460-year regional mean chronology (RC), which is the longest chronology of this species from the high Asia. Taking into account strong relationship between the RC and pre-monsoon (March-May) precipitation, we reconstructed spring precipitation back to AD 1552. This is, to date, the first climate reconstruction based on this species and the first precipitation reconstruction from the central Himalayas. The reconstructed precipitation series showed annual, multiannual to decadal variations. The years 1999, 1813 and 1954 experienced the driest springs, whereas 1775, 1557 and 1988 the wettest years. It showed the driest decades in 1811-1821 and 1995-2005. The decrease in precipitation was in phase with the unknown volcanic eruption around 1809/10 and the Tambora eruption (1815), suggesting that the subtropical and tropical volcanic eruptions may cause dry conditions in the central Himalayas. The reconstructed precipitation also showed significant correlation with March-May precipitation in Kathmandu and other large-scale regional indices that were used to represent the South Asian monsoon rainfall.

This study represented a new contribution to the dendroclimatology and timberline ecology in the central Himalayas and showed insight into the variability of past precipitation and its driving forcing.

KEYWORDS: Tree ring, dendroclimatology, *Betula utilis*, Climate change, pre-monsoon precipitation reconstruction, drought, Central Himalayas, Nepal

Acronym

AD	of the Christian era (from the Latin *anno domini*)
AMO	Arctic Multiple Oscillation
AWS	Automated weather Station
CE	Coefficient of Error
CRU	Climate Research Unit
DHM	Department of Hydrology and Meteorology
ENSO	Elnino and Southern Oscillation
EPS	Express Population Signal
ERA40	European Center for Medium-Range Weather Forecasts (ECMWF) 40 Year Re-analysis
EV-K2-CNR	Everest K-2 National Research Council
GPCP	Global Precipitation Climatology Project
HKH	Hindu Kush-Himalayan
IITM	Indian Institute of tropical meteorology
IPCC	Intergovernmental panel of Climate Change
NCEP	National Center for Environmental Program
MTM	Multiple trapper method
MS	Mean Sensitivity
NAST	Nepal Academy of Science and technology
NAO	North Atlantic Oscillation
PDO	Pacific Decadal Oscillation
RC	Regional Chronology
RE	Reduction of Error
SPI	Standardized Precipitation Index
SSCH	Southern Slope of central Himalayas
WMO	World Meteorological Organaization

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Chapter One: Introduction

1.1. Basis of thesis topic selection, significance of conducting the research

Climate change is one of the hottest issues of the 21st century. The direct and indirect effects of climate change on the ecosystem have been observed in many parts of the world (IPCC, 2007). Air temperature and precipitation are the most important parameters when evaluating the climatic fluctuations of any regions. The recent scientific assessment of climate change estimated that the globally averaged surface temperature will increase by 1 to 3.5°C by the end of this century, with an associated rise in the sea level of 15 to 95 cm. The warming has affected precipitation patterns over many places including the Asian continent (IPCC, 2007).

The Indian subcontinent is one of the most heavily populated regions in the world and its economy depends largely on the monsoonal rainfall. Therefore, a better understanding on the potential impacts of a regime shift in the monsoon is crucial for social and economical development. Climate proxy records, such as tree-ring chronologies, extended the information of climatic change back to the pre-industrial era, enabling to detect the effects of natural climate variability and anthropogenic impact. The paleoclimatic reconstruction for this region will be useful to develop and validate the climatic models.

Nepal is a mountainous country, where mountains and hills occupy more than 68% of its total area. Due to large variations in altitude from Terai (lowest elevation: 60 m a.s.l) to the Himalayas (highest elevation: 8,848 m a.s.l Mt. Everest), air temperature and precipitation show a great variability along with changing altitudes. Based on instrumental climatic records from 49 meteorological stations in Nepal, Shrestha et al. (1999) found that the warming was consistent and continuous after the mid-1970s. The average warming in the annual maximum temperature between 1977 and 1994 was 0.06^{o}C/year. Such a warming trend is more pronounced at higher elevations such as the middle Mountains and high Himalayas, while it is less significant in the Terai and Siwalik regions. The recent studies also indicated that progressively increasing warming in high-elevation regions is a general phenomenon in Nepal (Practical Action Nepal, 2009) as well as the whole Hindu Kush–Himalayan (HKH) regions (Shrestha, 2009).

The distribution of precipitation patterns in the Nepal Himalayas is strongly controlled by topography, spatial arrangement of topographic gradients, steep altitudinal contrast (Barros et al. 2004, Shrestha, 2000, Anders et al. 2006) and varies from place to place at both local as well as macro scales. Hence there is spatial and inter annual variability in precipitation in Nepal (Shrestha et al. 2000).

In Nepal, in situ measurement history for the meteorological record is very short. Longer perspectives on climatic variability can be obtained by the study of natural climatic proxies. Therefore, for the study of past climate and climate change, we have to depend on the proxy sources such as tree rings, ice cores and lake sediments. Due to the annual resolution, continuous records (up to several thousand years), high sensitivity and fidelity to climate and high coverage, tree ring is one of the best climatic proxies in the Himalayas.

The climate in Nepal is dominated by two types of monsoon systems: southeasterly and westerly flows. According to Shrestha et al. (2000), the seasons in Nepal were classified into four categories: winter season (Dec-Feb), pre monsoon (March- May), monsoon season (June-September) and post monsoon (October-November). Around 80-85% of the total annual precipitation occurs during the monsoon season. The agriculture and economy of the country is directly or indirectly dependent on the viabilities of the monsoon, but the instrumental records of the monsoon are not long enough to make reliable models for climatic predictions. In this context, tree-ring based climate reconstructions can have a pivotal role in providing high-resolution records that cover the last several centuries given the availability of tree-ring samples from the older trees in the Himalayas.

1.2. Concept of dendrochronology

Dendrochronology is a science based on the examination of tree rings and other aspects of dateable wood structures in predominantly long-lived trees. The centre of the tree is known as pith and outside is marked by bark. Just inside the bark, there is a vascular cambium, where cells that form rings are produced (Fritts 1976; Schweingruber 1996). In each year, the cambium layer produces xylem and phloem cells. Xylem cells are formed in the cambium layer and their function is to transport water from the roots up through the trunk of the tree. Phloem cells, formed outside of the cambium layer, were used to transport sugar and other photosynthetic products throughout the tree (Frits 1976). The cells of the phloem layers are compressed over the time and become part of the bark. The xylem cells remain rigid wood, as shown by tree rings. During years with favorable growing conditions, wide growth rings will be formed. Conversely, during years when the trees suffered the stress, narrow growth rings will be formed (Fritts 1976). These variations in ring width allow dendrochronologist to date environment and disturbance events, and determine the severity of the events.

The common practice in dendrochronology is to synchronize the variance among the samples from one tree, among decadal trees of a stand, or among regional dataset. Systematic use of this synchronization, called as tree-ring cross dating, is most appropriately characterizing the discipline of dendrochronology (Stock, 1968; Fritts 1976; Fritts and Swetnam 1989). In cross dating the exact year during which each ring was formed can be determined in relation to all other cross-dated samples. Tree-ring width is often used in the dendrochronological studies. In addition to the total ring width variations in the width of earlywood or latewood, wood density or isotopic compositions of tree rings can be measured and cross-dated (Schweingruber 1996; Hughes et al. 2012).

1.3. Subfields of Dendrochronology

Natural or disturbance stresses can be recorded by variations in tree-ring width or structures. Dendrochronology may be divided into several subfields, focusing its application to solve the environmental problems. The prefix *dendro* is used in conjunction with name of the particular scientific discipline. Dendroclimatology, dendroecology, dendrogeomorphology, dendroarcheology, dendrochemistry, dendrohydrology and dendroglaciology are some of the applications of dendrochronology to the study of past climate, ecology, geologic phenomenon (landslides, mudflows, and seismic activity), archeological issue, chemical changes in the environment, history of stream flow or runoff and glacial movement, respectively (Fritts 1976; Schweingruber 1996).

1.4. Dendroclimatology and extraction of climate signal from tree rings

Dendroclimatology mainly focuses on tree-ring based climate reconstructions. However, climate is not the only factor bearing impact on the tree-ring growth, in many cases it is not even the most significant factor, but its signal can be strengthened in the processes of tree-ring data analysis. Variations in tree–ring width depend on various factors such as tree age, climate, and pulses of local indigenous and stand-wide exogenous growth disturbances (Fritts 1976).

If variations in tree-ring width due to other factors than climate can be removed, the remaining variances will be composed of climate signals. Such a method is the procedure of tree-ring standardization (Fritts 1976; Cook 1985; Cook and Kairiukstis 1990). Dendroclimatological examination is therefore an empirical test for detecting the climate variables bearing significant impact on tree-ring variability. The strength and the sign of the variables can be ideally determined. If a strong co-variation between climate and tree rings is evident and relatively unchangeable as a function of time, the statistical equation for the relationship can be successfully established and verified. If the length of tree-ring record is beyond that of the meteorological record, it may be possible to estimate the variations of the past climate using tree-ring time series.

1.5. Applications of palaeoclimatology

Instrumental records span only a tiny fraction ($<10^{-7}$) of the Earth's climatic history (Bradely 1999) and may be not adequately represent the range of natural climatic states that have existed in the geologically recent past and that could record fairly soon.

Instrumental weather observations are the most accurate measures of climatic fluctuations, but their length is usually no more than or slightly over one hundred years in a global context and slightly over forty years in Nepal with uneven spatial distribution. Instrumental observations are therefore commonly inadequate to resolve the full spectrum of the climate variability and in particular to assess the amplitude of the recent warming in a long-term time scale. A longer perspective on climatic variability can be obtained by the study of natural phenomena which are climate dependent, and which incorporate into their structure (a measure of the dependency). These records bear indications of past climate in different seasons at the resolution depending on the proxy and methodologies. Therefore, it is necessary to rely on the proxy records such as tree rings, ice cores, lake sediments etc to understanding variability in climate.

1.6. Dendroclimatology in the field of palaeoclimatology

Tree ring offers absolute time resolution on an annual or seasonal timescale and is applicable over a large part of the globe (Fritts, 1976; Cook and Kairiukstis 1990), i.e. in climate regions where woody plants experience a distinct period of dormancy due to a cold or dry season. Thus, tree–ring time series represent an exceptionally valuable source of paleoclimatic information (Fritts, 1976). The attributes are the facts that:

- Tree-ring width is easily measured for the continuous sequence of year up to several thousand years.
- Tree ring can be dated to specific years in which they were formed. Therefore, the climatic information is precisely placed in time.
- The advantage of tree ring as palaeoclimate information in relation to many other proxies is that tree rings can be statistically calibrated against the instrumental weather records and further transferred into the estimates of the climatic variables.

1.7. The objectives of this study

The major objective of this study is to study the variations in pre-monsoon precipitation derived from Himalayan birch tree rings in the central Himalayas, Nepal.

The specific objectives include:

- To study the climatic linkages between the stations at different elevations and to test their applications in paleoclimatic calibration.
- To investigate the dendroclimotological potential of Himalayan birch from the high hills of the Nepal Himalayas.
- To develop a tree-ring network of Himalayan birch from the central Himalayas, Nepal.
- To compare tree growth-climate relationships of timberline Himalayan birch with other global timberline trees.
- To reconstruct pre-monsoon precipitation for the central Himalayas.
- To investigate past precipitation dynamics and its possible driving force.

1.8. Scientific questions

- Whether climate records from lower elevations can be use to represent those at higher elevations?
- Is Himalayan birch (*betula utilis*) from the central Himalayas a potential species for the dendroclimatic study?
- Whether are tree growth and climate relationships of timberline Himalayan birch similar as other worldwide timberline species?

1.9. Synopsis of the thesis

This thesis includes seven chapters. Chapter one introduced the importance of dendroclimatology in the context of paleoclimatology. Chapter two provided a review of dendrochronological research from the Himalayan regions. Chapter three investigated the climatic linkages between the stations along an altitudinal gradient ranging from 130-5050 m a.s.l. It detected the possibility to use in-situ meteorological data from lower elevations to represent those at higher elevations. Chapter four examined the dendroclimatic potential of the Himalayan birch from the central Himalayas and its growth responses to climate. Chapter five developed a tree-ring network of Himalayan birch from the central Himalayas and compared tree growth and climatic relationships of timberline Himalayan birch with other alpine and arctic timberline species. Chapter six presented a 460-year pre-monsoon precipitation reconstruction (AD1552-2011) and determined its linkages with other regional and global climatic events. In addition, it emphasized the possible impact of major volcanic eruptions in Southeast Asia on the pre-monsoon precipitation of the central Himalayas. Finally, chapter seven summarized this thesis with major findings and proposed the future research plan. Chapters from three to six are based on the published paper and the manuscripts prepared for the submission.

Chapter Two: Literature review

2.1. Brief historical review

The discovery that tree rings could be used as records of past climatic conditions is a quite recent notion that took form in the work of astronomer Andrew Ellicott Douglass (Douglass 1920). Previous studies in ancient Greece to medieval Leonardo da Vinci etc. noted a connection between trees annual growth rings and climate. However, A. E. Douglass initiated the systematic methods for dendrochronological study and he was considered as the father of dendrochronology (Fritts 1976).

2.2. Dendrochronological research in the Himalayan region

G. B Pant initiated the simple correlation between tree-ring width and climatic data in the Himalayan region in 1979. However, systematic tree-ring research based on accurate dating of long sequences of growth rings started in the end of the 1980s (as described by Bhattachryya and Shah, 2009). Since then, extensive work has been carried out to understand the potential species and sites for the dendrochronological/ dendroclimatological studies in the Himalayas. In the recent decades, considerable researches are going on for tree-ring based climate reconstructions. Here, we briefly summarized the progresses in dendrochronological studies in the Himalayan regions.

2.2.1. Dendrochronological research from the western Himalayas

2.2.1.1. Investigating the potential sites and species

The preliminary attempts on dendrochronological analysis for the Himalayan region were made by Pant (1979, 1983). He noted that the trees from the Himalayan region are appropriate for dendroclimatic research with well-defined growth rings, which generally display a very prominent response to temperature. From the Karakoram Mountains in the western Himalayas, Bilham et al. (1983) developed a millennium long tree-ring chronology from *Juniperous macropoda* and detected that this species was potential for the dendrochronological studies. Ramesh et al. (1985) analyzed the samples of *Abies Pindrow* from Kashmir and concluded that the stable isotope ratios of hydrogen, carbon and oxygen in tree cellulose can be used for the dendroclimatic studies. Isotopic analysis of *Abies pindrow* growing in Gulmarg, Kashmir, revealed that δD was more sensitive to precipitation and the mean maximum temperature, whereas $\delta^{13}C$ was sensitive to temperature, and $\delta^{18}O$ to the amount of clouds and humidity (Ramesh et al. 1985). Bhattacharaya et al. (1988) analyzed six coniferous species collected around the Jammu and Kashmir and concluded that coniferous species are suitable for dendrochronological study. Yadav and Singh (2002a) developed a 345-year chronology of *Taxaus baccata* from the western Himalayas. This species showed a high potential in the dendrochronological studies by indicating a significant correlation with pre-monsoon (March-June) temperature. In another study, Singh et al (2004) developed an 1198-year tree-ring chronology of Himalayan cedar from Uttaranchal Pradesh and pointed out the possibilities for millennial long temperature reconstruction. Yadav et al. (2006) developed a millennia long tree-ring chronology (AD420–2003) of Himalayan pencil cedar. Based on tree-ring width and density, Borganokar et al. (2007) concluded that Himalayan coniferous species from the western Himalayas are potential for the pre-monsoon precipitation and temperature reconstruction. Singh and Yadav (2007) developed a 1087-year chronology (AD 919-2005) of *Pinus gerardiana*. Yadav (2007) studied the tree-ring width of Himalayan cedar from the different basins of the western Himalayas and noticed an extremely low growth during the 1816s in all basins may be due to the impact of the Tambora volcanic eruption.

Tree-ring chronologies pointed out the possibilities using tree-ring width, density as well as isotopic for dendrochronological/dendroclimatological studies in the western Himalayas and showed some prominent species for the studies. Most of the conifers showed the potentiality for the climate reconstruction for pre-monsoon temperature or precipitation.

2.2.1.2. Tree ring and glacier movement

Vast areas of glaciers cover over the mountainous region in the third pole, providing valuable information for understanding past climatic fluctuations (Thompson et al. 2000: Yao et al. 2012). Glacier movements (advancement, stationary and retreating phases), chemical and physical properties of ice cores are useful parameters to investigate spatial variability of climate in this region. The Himalayas are one of the richest regions with the glaciers, giving the birth of many perennial rivers in the Indian subcontinent. Many glaciers and their moraines are abundant in the Himalayan region that could provide excellent opportunity for the study of dendroglaciology, however, this is not developed so far. *Pinus wallichiana* growing in the sub-alpine region of the Kinnaur (Bhattacharyya and Yadav 1996) and *Abies pindrow* from the snout of the Dokriani Bamak Glacier (Bhattacharyya et al. 2001) showed the potential for dendroglaciology by exhibiting low growth rates during years with a positive glacial mass balance and glacial advances during the recent decades in the Himalayan and Trans-Himalayan regions.

Based on tree-ring width chronology of *Pinus wallichiana* from the Gangotri region of the western Himalayas, Singh and Yadav (2000) showed significant correlation between tree growth and winter temperature and concluded that warmer winter is one of the main factors responsible for the increase in tree growth. In addition, tree-ring based winter temperature reconstruction would provide valuable insights on the long-term glacier dynamics. Bhattacharyya et al. (2006) analyzed tree rings of Himalayan birch (*Betula utilis*) and reported that increased tree growth in recent years coincided with the rapid retreat of the glaciers. Furthermore, they hypothesized that faster retreat of the glacier might be a cumulative effect of several climatic parameters that enhanced tree growth by increased precipitation in March, April and June and enhanced winter temperature. Borgaonkar et al. (2009) developed a 458-year chronology of *Cedrus deodara* and found that the years with wider tree rings in the recent decade coincided with the periods with rapid glacier retreat.

2.2.1.3. Climatic reconstruction for the western Himalayas

Dendroclimatic reconstructions from the western Himalayas began around a decade after the identification of potential species and sites. Hughes and Davies (1987) collected *Abies pindrow* and *Picea smithiana* from the 14 subalpine forests. By using ring width and densitometry, they reconstructed variations in spring and summer temperature and precipitation for the western Himalayas. Probably, this is the first climate reconstruction of the Himalayan region. Later on, Hughes (1992) used *Abies pindrow* for the reconstruction of April-May, Aug-Sept temperature and April-Sept precipitation for the period of AD 1620-1982. This reconstruction did not show any evidence of long-term trend. Afterward, Bhattacharyya and Yadav (1989) used *Cedrus deodara* reconstructed summer and winter temperature and precipitation reconstructions in Kashmir. The dendroclimatic researches from the western Himalayas were summarized in the Table 2.1

These studies revealed that tree-ring data of conifers in the western Himalayan region are suitable climatic proxies to reconstruct past pre-monsoon temperature and precipitation for the past several centuries to millennia. Either temperature or precipitation series do not show any long-term trend. Most dendroclimatic studies from the western Himalayas focused on March-May temperature/precipitation reconstructions in which *C deodara* is widely used species. Some precipitation reconstructions showed severe drought during the fifteenth and sixteenth centuries and an unprecedented wet period during the late twentieth century (Singh et al. 2006). The wet conditions during the 20th century are consistent with other long-term precipitation reconstructions from high Asia (Treydte et al. 2006; Anderson et al. 2002; Thompson 1995), an indication of large-scale intensification of the hydrological cycle.

Table2. 1 Table showing major dendroclimatological investigations from the Western Himalaya

References	Species	Time span	Climate signals	Major findings
Borgaonkar et al. (1996)	*C. deodara*	1775-1988	March-May temperature	Cooling/warming condition during AD1780-1840 and AD1841-1890 not showing any significant trend
Yadav et al. (1997)	*C. deodara, P. smithiana, P. wallichiana*	1698-1988	Apr-May temperature	Exceptionally cold periods during 1810s and 1830s
Pant et al. (1998)	*P. smithiana*	1673-1990	Mar-May temperature/ precipitation	Neither precipitation nor temperature show any long-term trends
Yadav et al. (1999)	*C. deodara*	1390-1987	Mar-May temperature	Warm spring conditions in the seventeenth century
Yadav and Park (2000)	*C. deodara*	1988-1171	Oct-May Precipitation	Wettest and the driest conditions during the 14th and13th centuries
Yadav and Singh (2002)	*C. deodara*	1600–1987	Mar-May temperature	Long-term cooling trend since the late 17th century until the early 20th century
Yadav et al. (2004)	*C. deodara*	1226–2000	Mar-May temperature	Rapid decrease of minimum temperatures
Singh and Yadav (2005)	*C. deodara*	1731-1987	Mar-May precipitation	The twentieth century was the driest and wettest period
Singh et al. (2006)	*C. deodara*	1560-1997	spring precipitation	Unprecedented precipitation increase during the late twentieth century
Singh et al. (2009)	*C. deodara / P. gerardiana*	1310-2005	Mar-July precipitation	Driest period occurred in the eighteenth and the wettest in the twentieth century
Yadav (2011a)	*C. deodara*	1330–2008	Aug-July precipitation	Multi-decadal droughts during the 14th and 15th centuries. The 20th century was the wettest period
Yadav (2011b)	*C. deodara*	1410 - 2005	March-June precipitation	Severe drought during 15th and 16th centuries。The decreasing trend in reconstructed precipitation in the last decade of the twentieth century
Yadav et al (2011)	*J. polycarpos*	940-2008	May-Aug temperature	Warming form 11-15 centuries and the 15th century, the 18th and 19th centuries were the coldest period

2.2.2. Dendrochronological research from the Eastern Himalayas

The dendrochronological research in the eastern Himalayas is in the preliminary stage in comparison with the western Himalayas. Chaudhary and Bhattacharyya (2000) found that *Larix griffithiana* from Arunachal Pradesh of the eastern Himalayas is a potential species for dendroclimatic studies. In another study, Chaudhary and Bhattacharyya (2002) collected tree-ring samples of *Pinus kesiya* from five sites of northeastern India and found that *Pinus kesiya* at different sites did not show similar responses to climate. Based on a tree-ring width chronology of *Abis densa*, Bhattacharyya and Chaudhary (2003) reconstructed a 237-year July-September temperature which showed warmer temperature during 1801-1810, whereas cold temperature during the period of 1978-1987.

2.2.3. Dendrochronological research from the central (Nepal) Himalayas

High–elevation forests are potential for dendroclimatological studies, both for climate reconstruction and for the assessment of the impact of climate change on ecosystems (Tessier et al. 1997). In spite of a wide distribution of subalpine forests in the central Himalayas (Nepal), dendrochronological studies there were rather limited.

Dendrochronological studies in Nepal started in the later 1970s after the collection of tree-ring samples from different habitats by Rudolf Zuber (1979-1980) (Bhattachryya et al. 1992). Since then, several work on tree ring analyses have been made for both the high altitudes as well as the mid hills of Nepal, including the work by Suzuki (1990), Bhattachryya et al. (1992), Cook et al. (2003), Bräuning (2004), Sano et al. (2005, 2009, 2011). Herein we provided an overview of published papers and unpublished academic thesis/reports related to dendrochronological studies from Nepal.

The first published paper from the tree ring studies of Nepal was made by Suzuki (1990), who reported that annual rings from *Abies spectablis, Pieca smithiana* trees in western Nepal were suitable for the dendrochronological study and concluded that the growth of *Abies spectablis* was primarily limited by precipitation during the growing season (May-Aug). Bhattachryya et al. (1992) analyzed tree-ring samples from *Abies spectabilis, Cedrus deodara, Tsuga dumosa, Pinus roxburghii* and *Pinus wallichiana* across a wide range of ecological zones from temperate or sub-alpine forest (2500-3700 m a.s.l) and sub tropical zone (1320-2080 m a.s.l), showing the perspective for dendroclimatic studies in Nepal. However, they did not analyze tree growth and climate relationships due to the lack of meteorological data. Furthermore, Regmi (1998) reported that *P roxburgii* did not show clear rings. *P. wallichiana* showed clear annual ring boundary, but can not be cross-dated well because of severe human disturbances in the mid hills of central Nepal. Douglas (2000) reconstructed variations in temperature of Kalinchok, central Nepal based on tree-ring chronology (1729-1978) of *Abies Spectabilis*. However, He did not describe clearly why the climate reconstruction only up to AD 1979.

A tree-ring network, composed of 32 tree-ring width chronologies, was developed by Cook et al. (2003). Most of them covered the past 300-500 years. This tree-ring network also included samples collected by Zuber in 1979-1980 and contribution from Dr Burghardt Schmidt for pine ring-width data sets collected from living trees and archeological wood (Schmidt, 1993) in the dry inner valley of north central Nepal. The different species covered a wide range of ecological zones ranging from 1830-3630 m a.s.l. The species included *Abies spectabilus*, *Picea smithiana*, *Tsuga dumosa*, *Juniperus. recurva*, *Pinus wallichiana*, *Ulmus wallichiana*. Furthermore, they reconstructed February-June and February-October temperature based on the above tree-ring network, extending back to 1546 AD and 1605 AD, respectively. They were also the first temperature reconstructions in Nepal. Both reconstructions indicated the occurrence of unusually cold temperature in 1815-1822, coinciding with the effects of the Tambora eruption in Indonesia. The October–February temperature reconstruct showed no evidence for late 20th century warming, whereas the February–June temperature reconstruction showed actually cooling period since 1960. Although this tree-ring network covered the large area with 32 forest sites, none of them were from treeline/timberlines. Meanwhile, they did not describe the growth responses of individual species to climate.

Zech et al. (2003) developed 50-211 year chronology from *Abies spectabilis* from the Machha Khola valley, Gorkha Himal, central Nepal and pointed out the two phases of reduced growth between 1815 and 1825 and between 1900 and 1910. These growth depressions, lasting for about 10 years, are most strongly expressed in the years

1821/1822 and 1906/1907, respectively. Bräuning (2004) analyzed tree-ring samples from *Abies spectabilis, Betula utilis* and *Pinus wallichiana* in western Nepal and developed 334, 344 and 324-year chronologies, respectively. However, these tree-ring series did not enable to have climate reconstructions. In western Nepal, Sano et al. (2005) reconstructed a 249-year pre-monsoon (March-May) temperature based on the ring width and wood density of *Abies spectabilis*, showing notable cold conditions in the recent decades. Sano et al. (2009) pointed out that $\delta^{18}O$ of *A. spectabilis* in the western Nepal is useful to reconstruct rainfall variability. Furthermore, they reconstructed the monsoon season drought as showed by Palmer Drought Severity Index (PDSI) based on the $\delta^{18}O$ tree-ring chronology of *Abies spectabilis* in western Nepal (Sano et al. 2011). This reconstruct showed a drying trend over the past two centuries. Chhetri and Shrestha (2010) developed a 231-year (AD1776-2006) tree-ring chronology of *Abies spectabilis* in the Langtang National park, central Nepal and they found that its growth was positively correlated with March precipitation and negatively with May temperature.

The potential to develop the long-term tree-ring chronologies was confirmed by using living trees and archaeological wood in western Nepal. Bräuning et al. (2011) analyzed tree-ring samples of *Pinus wallachina* from the living trees and 14C-dated historic wood samples from western Nepal, and demonstrated the potential of radiocarbon wiggle-match dating for the historic tree-ring materials. They also pointed out the possibilities for the development of more than a millennium long tree-ring chronology by connecting the samples from the historic objects (e.g. Schmidt et al. 1999, 2001; Gutschow 2001).

Taken together, most dendrochronolgical studies from the Himalayas have focused on coniferous species, and the application of broadleaf trees species were very limited. In comparison with the western Himalayas, to date, little dendrochronological work has been done in the central Himalayas.

Chapter Three: Linkages of climatic records along an altitudinal gradient in the southern slope of the Nepal Himalayas

3.1. Introduction

Proxy data, such as tree rings, play an important role in understanding past climatic change (Bradley and Jones 1992). Data from these archives are generally calibrated with instrumental climatic records to quantify their climatic sensitivities and were subsequently used to reconstruct variations of climate prior to the instrumental era (Fritts 1976). Instrumental climatic records remained a lack at high elevations, such as the Himalayan region, a climate-sensitive area. In the Himalayas, most of the meteorological stations are located in the low river valleys, whereas climate-sensitive forest sites are always located at high elevations. As a result, it is very difficult to develop climate vs. tree-ring calibration model to reconstruct past climate in the Himalayas (Cook et al. 2003; Sano et al. 2005; Yadav et al. 2011; Dawadi et al. 2013).

The steep S-N gradient and complex topography results in higher variations of climate within a short distance in the southern slope of the central Himalayas. Several researchers (Nayava 1980; Dhar and Nandargi 2005; Putkonen 2004; Barry 2008) found an increase in precipitation with increasing altitude up to certain elevation and then start to decrease with increasing elevation. However, the altitude of the maximum precipitation belt varies from eastern to western Nepal. For example, the maximum precipitation belt is located around 1000-1700 m a. s. l in western Nepal (Kansakar et al. 2004; Dhar and Nandargi, 2005), 3200 m a.s.l in west central Nepal (Putkonen 2004), 1600-2600 m a.s.l in the Langtang region of central Nepal (Fujita et al. 2006) and at 1400 m a.s.l in Kanchanjangha area of eastern Nepal (Dhar and Nandargi, 2000). Conversely, winter precipitation increases with increasing elevation (Putkonen 2004). Barros et al. (2000) as well as Lang and Barros (2002) noted significant spatial variability in monsoon precipitation (4 times differences within 10 km distance). These results confirmed the spatial, temporal and altitudinal variations of precipitation, which may influence the seasonal temperature trends in Nepal (Shrestha et al. 1999).

In temperature analysis along an elevation transect from 72-3705 m a.s.l, Shrestha et al. (1999) found a higher rate (0.06^{o}C/year) of changes in the maximum temperature at higher elevations whereas no trend or even cooling trend at lower elevations, such as in the Terai and Siwalik. Sharma et al. (2009) also reported the greater warming trend at higher elevations of the Himalayas. The rate of warming in the Himalayas is greater than the global average (Shrestha et al. 2012) and the significant increase of temperature occurred in high-elevation eco-regions. The impact of warming is already observed in many fields such as glacier, river discharge and others (Shrestha and Aryal 2011). Recently, Kattel and Yao (2013) showed varied trends of temperature increase at the different altitudes of Nepal, however, higher rate of warming in the recent decades (1997-2009) is common among the most stations. The marked altitudinal range of the country has resulted in significant spatial variation of temperature in Nepal (Shrestha and Aryal 2011). To date, however, few efforts have been made to test the representativeness of the various patterns of meteorological records (temperature and precipitation) from lower to higher elevations where climate proxy sources exist.

The objective of this paper is to determine/quantify the linkages of climatic records along an altitudinal gradient from 130 m a.s.l to 5050 m a.s.l in the south-central Himalayas. We hypothesized that temporal variations in temperature at different elevations have good homogeneity, while precipitation displays large spatial heterogeneity. Our results will show insight on the reliability and robustness of using weather station data at lower elevations to calibrate paleoclimatic proxies at higher elevations in the central Himalayas.

3.2. Material and Methods

3.2.1. Study areas.

Nepal with an area of 147181 km^2 in the central Himalayas occupies one fourth of the total expanse of the Himalayas and bordered with India on three sides and Tibet of Peoples Republic of China to the north. The country is situated between 26°22′ to 30°27’N and 80°04’ to 88°12’E, orienting roughly parallel to the axis of Himalayas. The east-west length is approximately 800 km, while the north-south width varied from east to west at 200 km on average. Altitude varies from 60 m above the sea level to 8848 m at Mt. Everest, the highest point in the world.

Nepal is divided into five major physiographical regions:

I. Terai (60-300 m): The Terai is a flat and valuable stretch of fertile agricultural land in southern Nepal, which forms a part of the alluvial Gangetic plain. This region extends nearly 800 km from east to west and 30-40 km north to south and covers 14% of the total area of the country. This region has a subtropical climate usually very hot in summer.

II. Siwalik Hills (700-1500 m): The Siwalik Hills rise abruptly from the Terai plain and extend from east to west, being wider in western regions than the eastern (8-12 km width). This region covers nearly 13% of the total area of the country and characterizes by low terraces with steep topography and subtropical climate.

III. Middle Mountains (1500-2700 m): Running parallel to north of the Siwalik range, the middle Mountains (also known as the middle hills) extend throughout the length of the country. The mid hill region covers ~30% of the total area of the country. It is the first great barrier to the monsoon winds that produce the highest precipitation on its southern slopes due to orographic effects. The climate of this region ranges from sub-tropic in the valley bottom to cool temperate on the higher ridges.

IV. High Mountains (2700-4000 m): The High Mountain region lies further north of the Middle Mountain range and covers about the 20% area of the country. It has an average width of 50 km and extends from east to west. Steep slopes and narrow valleys with cool alpine climate characterize this region.

V. High Himalayas (4000-8848 m): This region is along the northern boundary of the monsoon climate and geo-political border between Nepal and China. This zone is an area of rocky, ice-covered massifs, rolling uplands, snowfields, alpine glaciers, and sweeping meadow-lands. Eight of the ten highest peaks exceeding 8000 m on earth, including the Mt. Everest (8848 m.), were located in the high Himalayas. Alpine and Tundra climate exists in this region and covers ~ 23% of the total area of the country.

In this study, four observational stations in Simara, Kathmandu, Kyangjing and Pyramid earth station were selected (Fig 3.1) on the basis of the following criteria: (a) representatives to different physiographical regions of Nepal, (b) altitudinal differences more than 1000 m and (c) the AWS data available during the period 2005-2009 AD. The climate is characterized by strong summer monsoon from mid-June to last September and by the westerlies in the winter (D, J, F). Precipitation in the form of snow is common at high altitudes during winter. Monthly variations of temperature and precipitation data based on the long-term averages are illustrated (Fig 3.2).

July is the wettest except in Pyramid (August) and the hottest except in Simara (June). The annual average temperature ranges from 14.5^{o}C to 29.7^{o}C in Simara, 11^{o}C to 23.8^{o}C in Kathmandu, -2^{o}C to 10.4^{o}C in Kayngjing and -8.5^{o}C to 3.5^{o}C in Pyramid. With increasing elevations, annual precipitation is 1903 mm, 1533 mm, 681 mm, and 406 mm from Simara, Kathmandu, Kyangjing to Pyramid, respectively. These regions receive the highest precipitation (>78%) during the monsoon season (June-September) and the least (<4%) in winter (December-February)

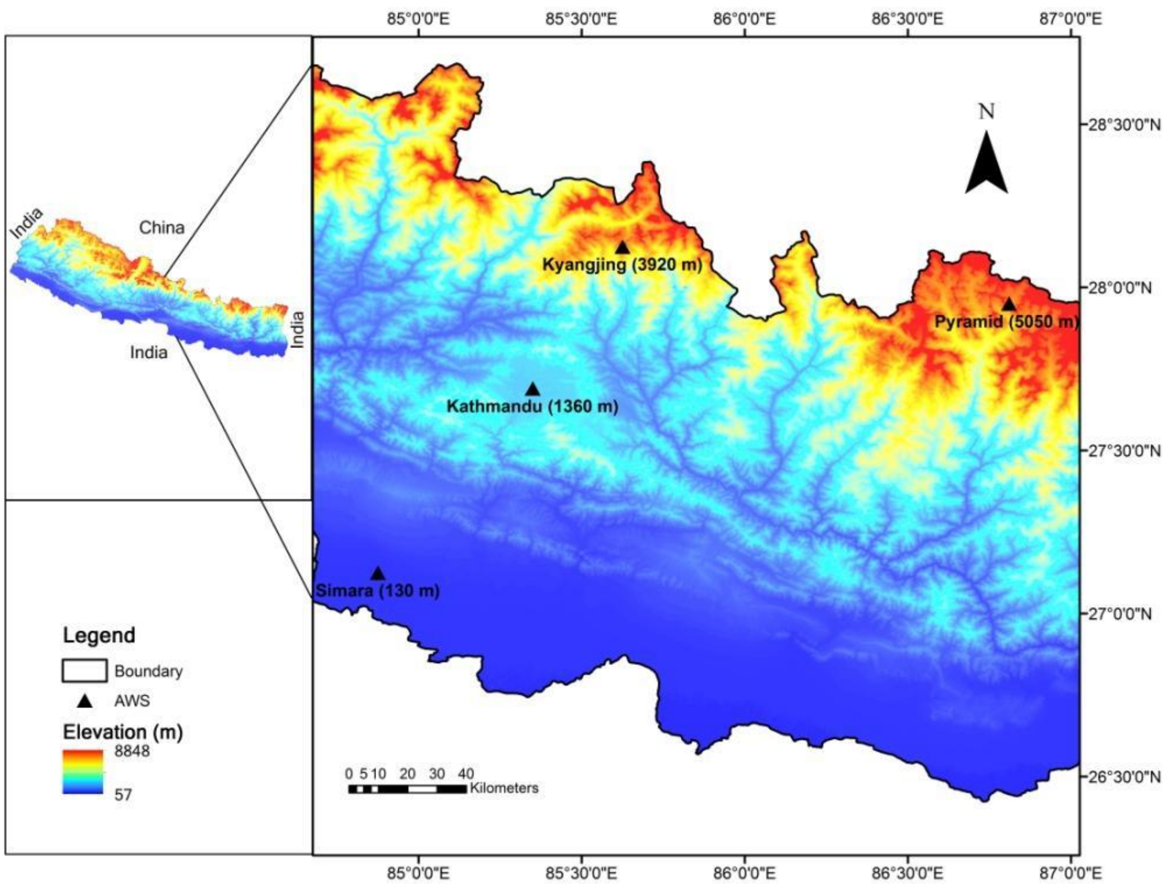

Fig3. 1 Map of Nepal (inset) showing the automatic weather stations (AWS) in physiographical regions

3.2.2. Data source and methods

The temperature data were checked extensively for the irregular and missing values. More than one missing value for the 5-days, two for 10-days and five for the 30-days in the data series were excluded for the further analysis. The daily, 5-day, 10-day and monthly records of the mean temperature and sum of precipitation from the AWSs at the different meteorological stations were compared to each other during the period of January 2005 to December 2008. Pearson's correlations are used to measure the strength of the relationships among the temperature/precipitation records, as shown in other similar studies (Bhutiyani et al. 2007; Liang et al. 2011).

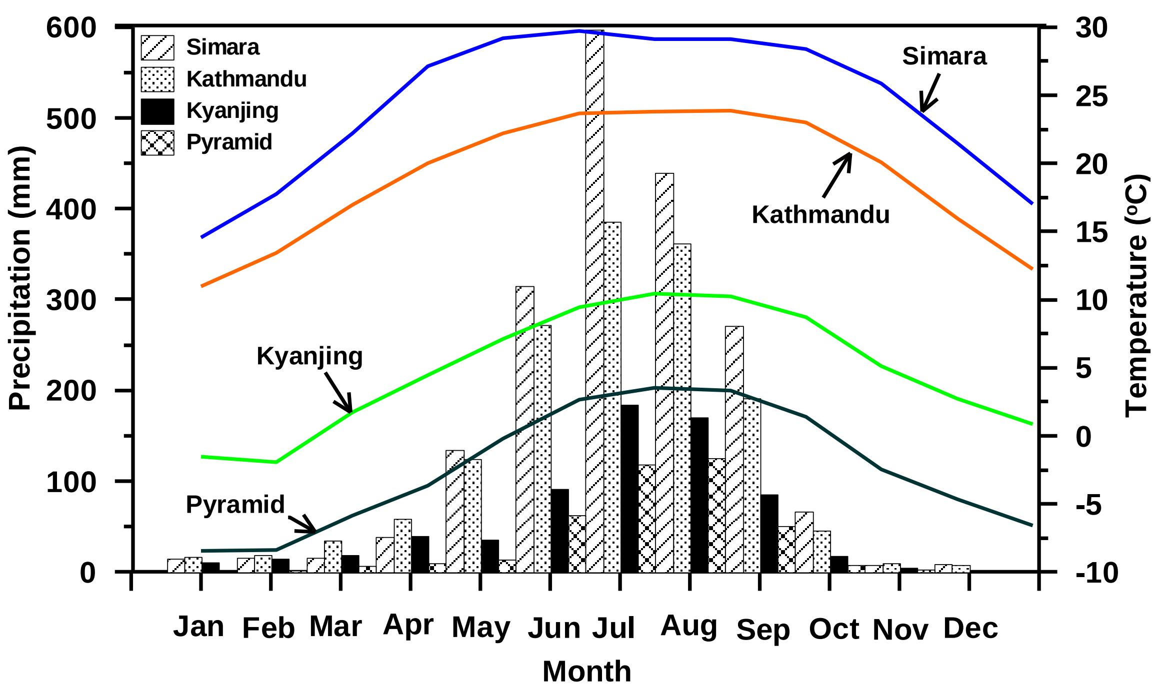

Fig3. 2 Variations of the monthly mean temperature and sum of precipitation in different stations (1994-2009). Vertical bars and lines represent temperature and precipitation

To quantify the relationships of climatic records between low and high elevations, regression analyses were performed on the daily mean temperature and daily precipitation by months. The intercepts and slopes of the regression models, together with the R^2 values, are used to evaluate the physical meanings and quality of the regression models, as shown by Liang et al. 2011. To confirm the patterns seen in the daily data, we also performed the regression analyses on the 5-day/10-day/monthly mean temperature and total precipitation data. In order to understand the magnitude of monthly/seasonal co-variation in average temperature and sum of precipitation among the stations at different elevations, we pooled data from 5-day mean/sum of temperature/precipitation for the individual month/season. The four seasons are divided as winter (December of the previous year, January and February) pre-monsoon (March-May), monsoon (June-September), post-monsoon (October-November).

3.3. Result

3.3.1. Temperature differences along the elevation transect

Temperature differences between the stations are the highest in April except for Kathmandu-Kyangjing in March and all the stations show the least temperature difference in December except for Simara-Kathmandu in November. The temperature difference is the highest in the pre-monsoon season whereas a minimum in early winter season (Fig. 3.3). It increases from December to May and gradually decreases with increasing cloudiness.

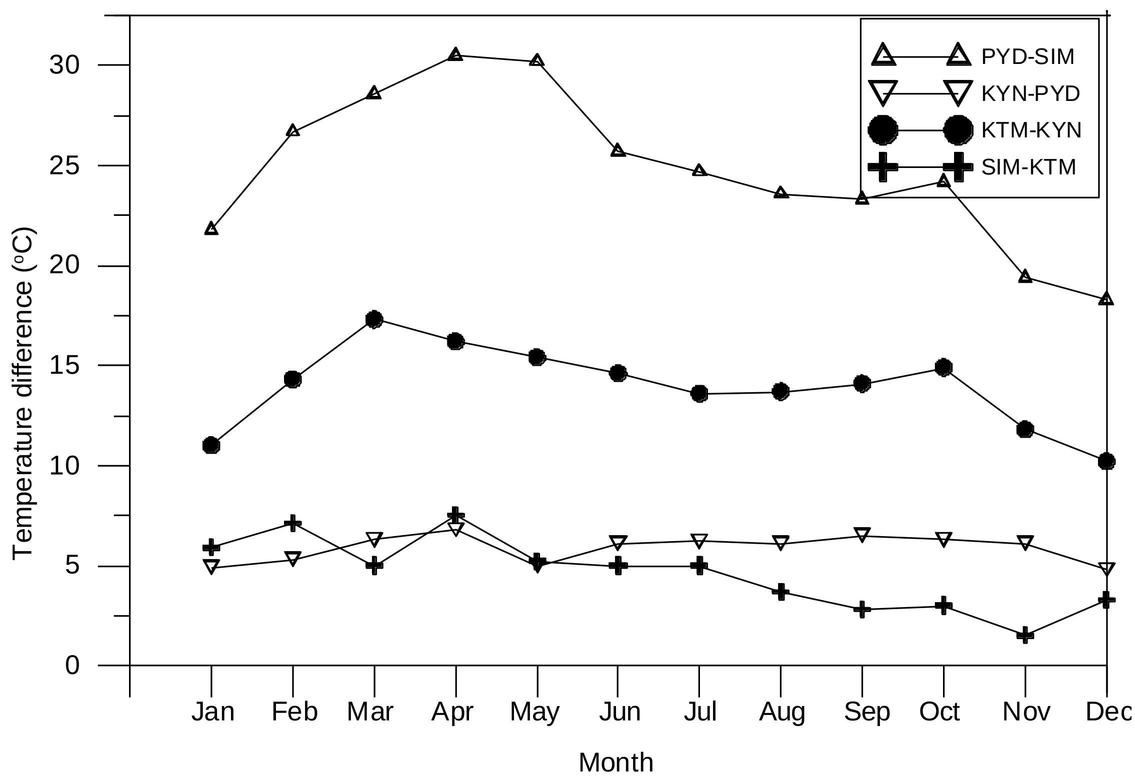

Fig3. 3 Differences of the monthly mean temperature between stations

In spite of differences at their absolute values, variations of temperature records at different elevations seem to be consistent. The standard deviations of the daily (N=1258-1397), 5-day (N=265-281), 10-day (N=134-139) and monthly (N=43-46) mean, maximum and minimum temperatures at different elevations are almost identical (Table 3.1).

Table3. 1 Standard deviation of daily, 5-day, 10-day and monthly maximum, minimum and average temperature

	Maximum temperature				Minimum temperature				Average temperature			
	Daily	5-day	10-day	Mon-thly	Daily	5-day	10-day	Mon-thly	Daily	5-day	10-day	Mon-thly
SIM	5.16	4.83	4.75	4.44	6.44	5.87	5.68	5.45	6.61	5.91	5.41	5.32
KTM	4.76	4.38	4.23	3.99	6.48	6.29	6.26	6.18	5.44	5.31	5.24	5.14
KYN	4.29	3.98	3.84	3.64	5.72	5.57	5.56	5.46	4.90	4.75	4.69	4.54
PYD	4.46	4.10	3.90	3.75	5.29	5.13	5.05	5.02	4.70	4.52	4.37	4.92

3.3.2. Association of temperature records between meteorological stations

The correlations of the monthly mean temperatures between the stations range from 0.47 to 0.91 for daily, 0.55 to 0.96 for 5-day, 0.59 to 0.97 for 10-day and 0.70 to 0.97 for monthly mean. The correlation strength increases with increasing time window. All correlations are statistically significant at 0.001 levels for our analysis period.

The highest correlation (r = 0.97) was observed for the 10-day and monthly mean temperatures between Kyangjing and Pyramid. In spite of their large differences in altitude (2560 m), significant correlation for the monthly mean temperature ($r = 0.91$, $p < 0.01$) between Kyangjing and Kathmandu was also evident (Fig 3.4).

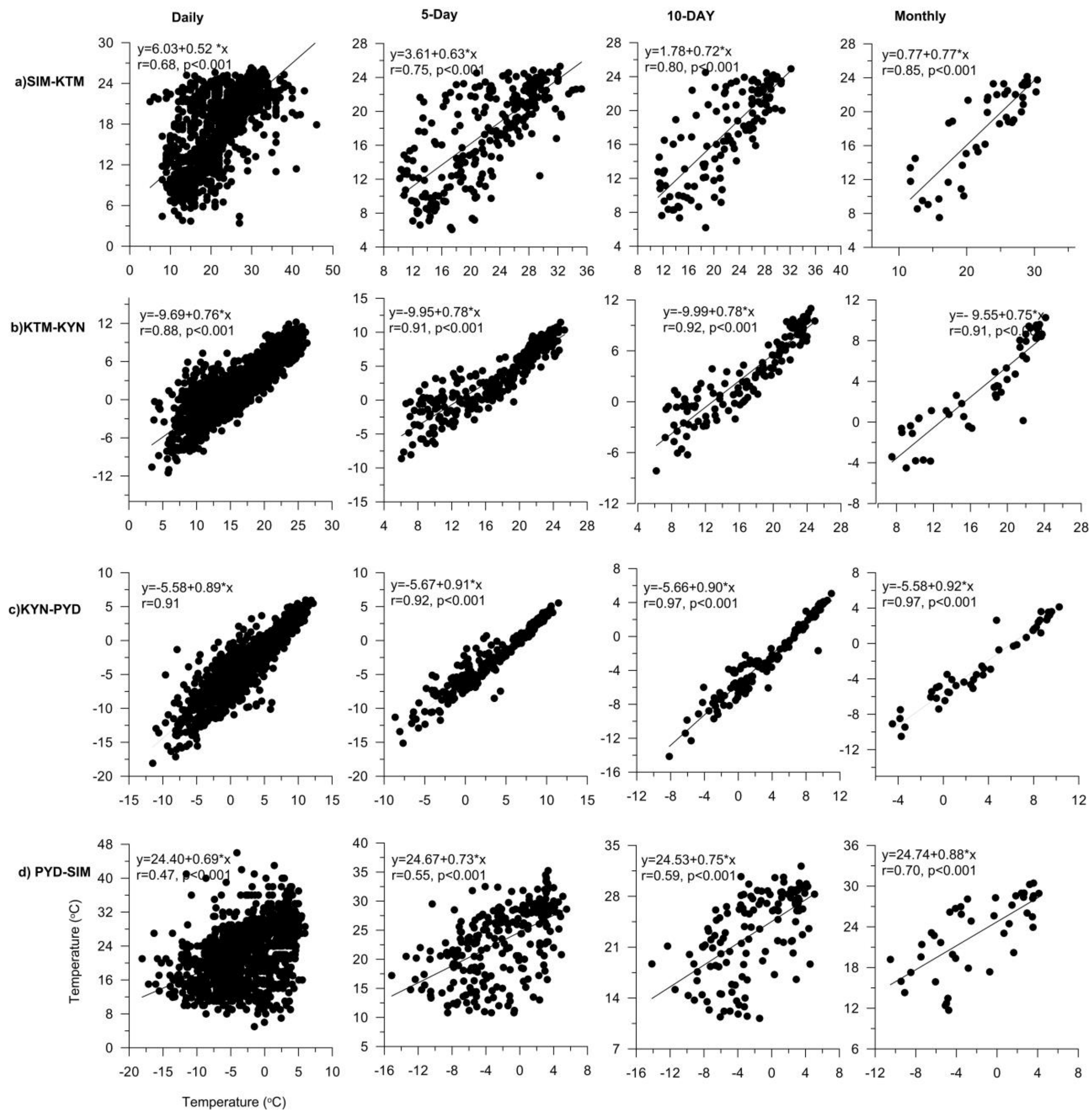

Fig3. 4 A scatter plot for the daily, 5-day, 10-day and monthly mean temperature between stations (a) Simara and Kathmandu, (b) Kathmandu and Kyangjing (c) Kyangjing and Pyramid (d) Pyramid and Simara

3.3.2.1 Seasonal correlation of temperature records along the elevation gradient

The seasonal analysis of temperature between the stations in the mid hills, high Mountains and high Himalayas showed strong and significant correlation (r=0.54-0.97, $p < 0.01$) for all seasons (Table 3.2). There is strong co-variation of temperature between the stations in the high mountains and high Himalayas (r=0.81-0.97, $p < 0.01$) in all the seasons during the period of our analysis. The mid hills and high mountains also have a strong and significant correlation (r=0.54-0.91, p<0.01) in the different seasons. However, weaker correlation exists between Terai and mid hills/High Himalayas (Table 3.2)

Table3. 2 Seasonal correlation of temperature between the stations; Sim, Ktm, Kyn, Pyd represent the name of station as Simara, Kathmandu, Kyangjing and Pyramid respectively

Season	Sim-Ktm (Cor/n)	Ktm-Kyn (Cor/n)	Kyn-Pyd (Cor/n)	Pyd-Sim (Cor/n)
Winter(D,J,F)	*0.33/62	**0.54/76	**0.88/74	*0.28/62
Pre-Monsoon(M,A,M)	**0.53/71	**0.91/72	**0.97/70	**0.45/70
Monsoon(J,J,A,S)	**0.38/92	**0.62/80	**0.95/80	0.13/94
Post-Monsoon(O, N)	**0.66/40	**0.86/43	**0.81/42	**0.45/40

Significant correlations are indicated at **p<0.01 and * p< 0.05

3.3.2.2 Correlations of temperature by months along the elevation gradient

The temperature in most months shows very strong and significant correlation (r= 0.50-0.92, p<0.01) between Kathmandu-Kyangjing (except for June, r= 0.29) and Kyangjing-Pyramid (r=0.85-0.97, p<0.01) (except for November, r= 0.40). Simara-Kathmandu shows comparatively stronger correlations only in April (r= 0.53, p<0.01), June and October (r= 0.45-0.52, p<0.05). Between Pyramid and Simara, higher correlation exists in April and May (r= 0.44-0.45, p<0.05) than other months (Table 3.3).

Table3. 3 Correlations of the monthly mean temperatures between the stations; Sim, Ktm, Kyn, Pyd represent the stations of Simara, Kathmandu, Kyangjing and Pyramid, respectively

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Sim-Ktm	-0.12	0.28	0.11	**0.53	0.33	*0.52	0.22	0.35	0.23	*0.45	0.17	-0.34
Ktm-Kyn	**.50	**.90	**.79	**0.69	**0.80	0.29	**0.76	**0.71	**0.73	**0.92	**0.71	**0.57
Kyn-Pyd	**0.87	**0.85	**0.87	**0.93	**0.97	**0.95	**0.91	**0.86	**0.93	**0.88	0.40	**0.87
Pyd-Sim	-0.40	0.27	-0.09	*0.44	*0.45	0.04	0.22	0.03	0.17	0.24	0.26	-0.35

**Significant at 0.01 and * at 0.05

3.3.2.3. Using low-elevation temperature data to represent those at high elevations

Based on the results of regression (Fig 3.5), it is clear that the variations in the daily and seasonal temperatures at lower elevations are excellent representatives for their counterparts at higher elevations nearby, supporting our hypothesis. The intercept of the regression model indicate a hypothetical 'base temperature' at higher elevation when the corresponding lower elevation temperature is 0°C (Liang et al., 2011a). The slopes of the models, however, showed the amount of temperature changes at higher elevation per °C measured at the corresponding lower elevation.

It is interesting to note that for every 1^{o}C change of temperature in Kathmandu, change by 0.56 to 1.14^{o}C in Kyangjing except for June (0.29^{o}C). During the winter season, the change rate of Kyangjing temperature in correspondence to Kathmandu temperature is >0.84/1^{o}C whereas comparatively lower (<0.64/1^{o}C) in the monsoon season. R^2 values of the regression model are relatively high (>0.50) except for January, December, and June. Temperature between Kyangjing and Pyramid (High Himalayas) showed almost similar range of fluctuation throughout the year. For 1^{o}C change in Kyangjing there is 0.77 to 1.18^{o}C change in temperature in Pyramid except for November (0.49^{o}C). Higher slopes (>1.0) in January, April, May, August and September indicated higher fluctuations of temperature in Pyramid in comparison with Kyangjing. R^2 values of the regression model are also high (>0.64) excluding November (0.16). The model is not statistically significant in November due to reduced sample size. However, the temperature data in Simara can not present well of those in Kathmandu- Pyramid.

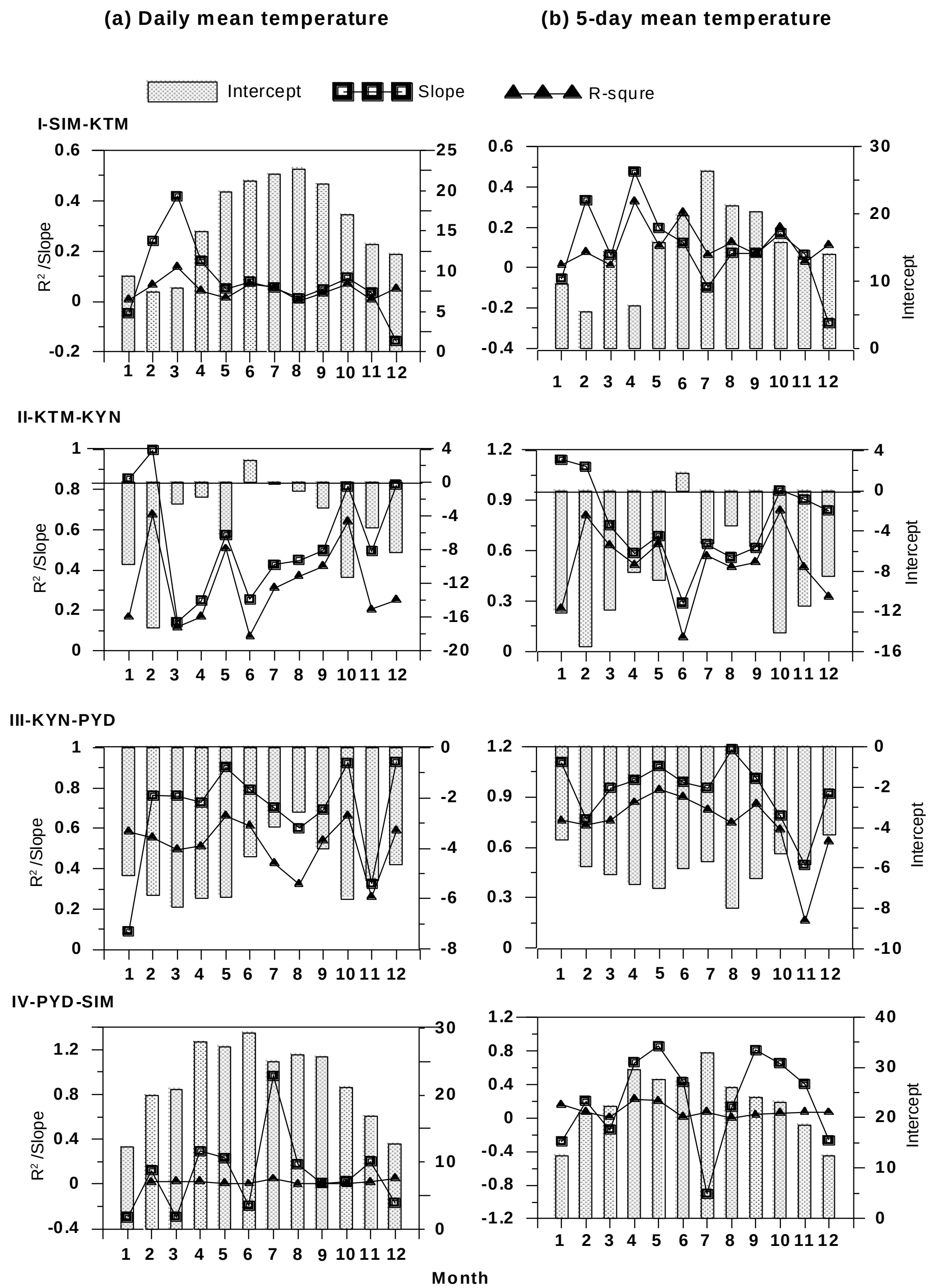

Fig3. 5 Intercepts, slopes and R^2 values of regression models by months between the different stations, Regression models using the (a) daily mean temperature (b) 5-day mean temperature. SIM, KTM, KYN, PYD represent the stations Simara, Kathmandu, Kyangjing and Pyramid, respectively

3.3.3. Comparison of precipitation along the altitudinal gradient

Precipitation shows spatial and temporal variability along the altitudinal gradient. The daily, 5-day, 10-day and monthly sum of precipitation is significantly different between the stations and decreases with increasing elevation along the S-N transect (Table 3.4). However, they are significantly correlated to each other. Their correlations increase with increasing time window from 0.28-0.55 for daily data to 0.54-0.81 for monthly sum of precipitation ($p < 0.001$) (Fig. 3.6).

Table3. 4 Daily, 5-day, 10-day and Monthly sum of precipitation (mm) at different stations during the period of January 2005- December 2008

	Daily	5-day	10-day	Monthly
Simara	3.4	43.1	76.8	168.4
Kathmandu	2.3	15.2	30.7	98.6
Kynjing	0.9	10.7	21.5	66.4
Pyramid	0.9	4.1	8.9	28.6

The correlation of precipitation between the stations in the mid hills, high mountains and high Himalayas are positive and significant ($p < 0.05$) to each other for all the seasons (Table 3.5) except for Kyangjing-Pyramid in the monsoon season. However, precipitation from the plain area (Simara) to the mid hills and high Himalayas is negatively correlated in the winter season and non-significant except for Simara-Kathmandu in the monsoon and post-monsoon seasons. There is a weaker correlation of monthly precipitation between stations and non-significant for most cases (not shown).

Table3. 5 Correlation of precipitation between the stations between different seasons. Sim, Ktm, Kyn, Pyd represent the stations Simara, Kathmandu, Kyangjing and Pyramid, respectively

Season	Sim-Ktm(Cor/n)	Ktm-Kyn(Cor/n)	Kyn-Pyd(Cor/n)	Pyd-Sim(Cor/n)
Winter	-0.07/55	*0.55/76	*0.63/76	-0.08/55
Pre-monsoon	0.16/70	*0.26/72	*0.30/71	0.16/70
Monson	*0.21/94	*0.22/95	0.12/95	0.17/94
Post-monsoon	*0.38/40	*0.84/43	*0.42/48	0.25/40

* Significant at $p<0.05$

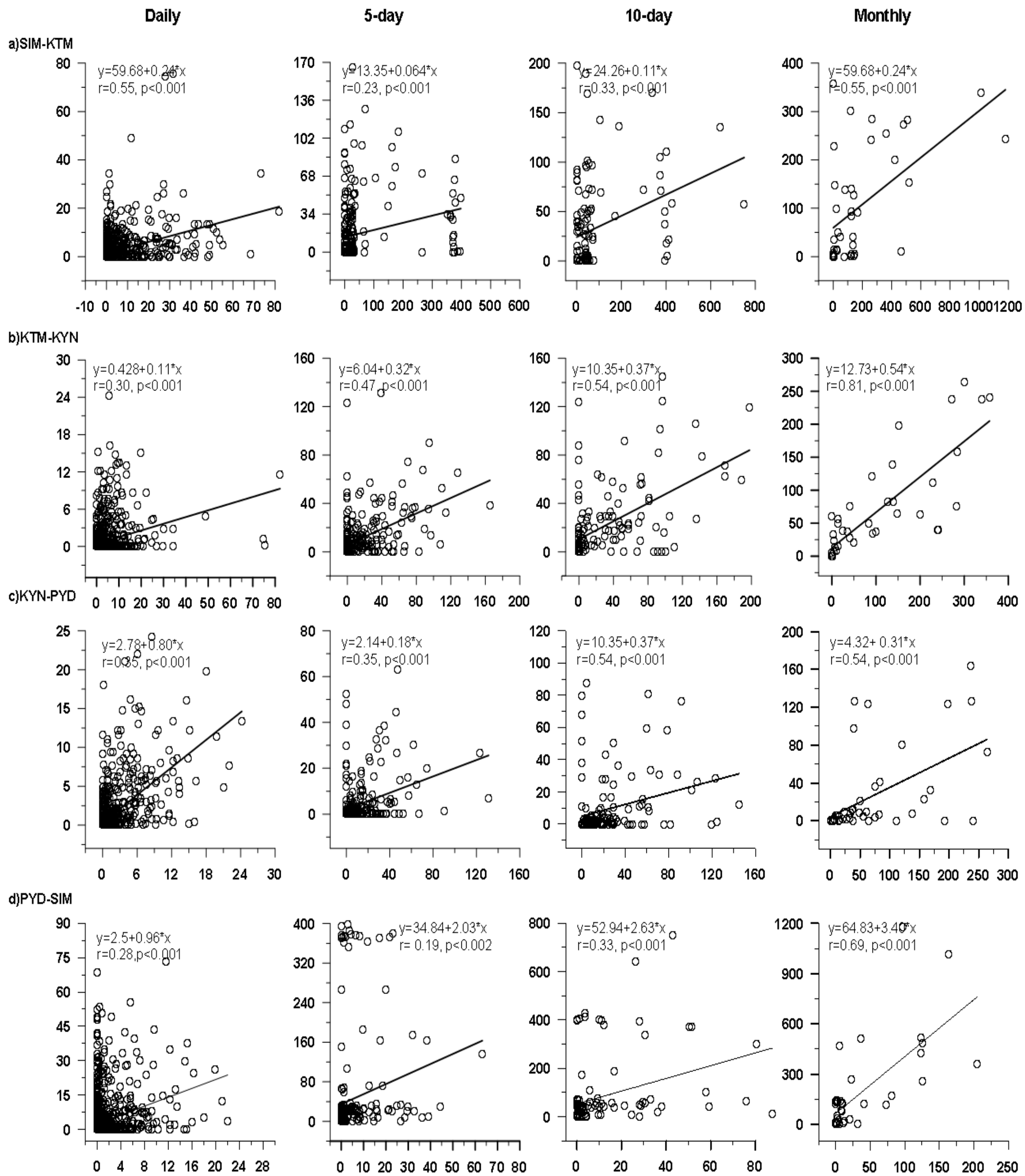

Fig3. 6 A scatter plot for the daily, 5-day, 10-day and monthly sum of precipitation (mm) between stations. (a) Simara and Kathmandu, (b) Kathmandu and Kyangjing (c) Kyangjing and Pyramid (d) Pyramid and Simara

3.4. Discussion

3.4.1. Association of temperature records between meteorological stations

Strong correlations between high-elevation stations might be due to their similarities in topographical condition, cloud cover, snow cover and wind pattern (Pepin and Norris, 2005). Ueno and Aryal (2008) reported that snow cover in the complex topography of Himalayas alters the surface energy balance at the local scale and affect the temperature. In general, the heating of the atmosphere induces a valley wind over the slope of a mountain, generate horizontal pressure gradient and creates the local level inversion. However, the plain areas have a wide variety of weather throughout the year, with cold winter and very hot summer causes a weaker correlation in temperature between the plain areas with those hill or mountain areas.

3.4.2. Seasonal and monthly associations of temperature between stations

Strong and significant correlations were observed between the mid hills and the high Mountains as well as between the high Mountains and high Himalayas except for June and November. At high elevations, temperature variability is closely related to snow cover in the beginning of the winter season (Ueno and Aryal, 2008). At the high Himalayas (Pyramid), there is always snow cover but in Kyangjing (High Mountain), the temperature never reaches to 0^{o}C in November (Fig 3.5 low value of slopes and R^2), resulting their weaker relationship in November. The mid hills are the first great obstacles for the summer monsoon that often onsets in mid June. Thus, the onset of monsoon and associated cloudiness in the south and comparatively dry and fair weather in the north might be the reason for weaker correlation of temperature in June between the stations in mid hills and high Mountains (Kathmandu-Kyangjing**)**. In the mountain region, when the sun is shining, it may be quite warm, even in winter, but if a passing cloud blocks the sun, the temperature drops rapidly. The thin and clean sub-alpine air does not hold heat well and allows a larger magnitude of solar radiation back and forth to the surface (http://snobear.colorado.edu/Markw/Mountains/03/mtn_04DRAFT2.doc). This might be the reason for the high degree of fluctuation in temperature in the winter season in the high Mountains and high Himalayas in comparison with low-elevation stations (Fig 3.5).

Extreme climatic events, such as extreme dry winter (precipitation 30% below the normal) from November 2005 to January 2006, could weaken the linkage of temperature records between low and high elevations in the Nepal Himalayas. Such a dry climate caused less snow cover. A reduction in snow cover at high elevations will change the surface albedo of the region, and hence increase the surface air temperature (Ueno and Aryal, 2008). As a result, the average temperature became positive for the third time since the observation (1989) in Kyangjing in February 2006. Another case is wetter winter from February to March 2007, bringing a light snowfall on February 14 for the first time in the past 62 years in Kathmandu (DHM, 2007). Such climatic events during our analysis period caused weaker correlations between the snow-covered areas and snow-free areas (Kathmandu-Kyangjing, Pyramid-Simara) as well as the valley and plain areas (Simara-Kathmandu).

The pre-monsoon and post-monsoon seasons are characterized by clear sky and gradually increase/decrease in temperature throughout the country. Therefore, these two seasons showed significant and stronger correlations between the stations than other seasons (Table 3.2). Monsoonal circulations influence the seasonal temperature in Nepal (Shrestha et al. 1999). The summer monsoon is more active in the southern part but other weather systems like western disturbances are also as effective as monsoon in giving rainfall in the high Himalayan region (Shrestha, 2000). Therefore, there are comparatively weak linkages between temperature records in the north and south areas in the monsoon seasons.

3.4.3. Precipitation variation between stations

Precipitation of a place depends upon several factors such as topography, strength of moisture-bearing wind, the orientation of the mountain range with respect to the prevailing wind direction. A large change in elevation within a relatively short distance caused a great difference in precipitation in Nepal (Higuchi et al. 1982; Shrestha et al. 2000; Lang and Barros 2002). Many studies (Singh and Kumar 1997; Barros et al. 2000; Kansakar et al. 2004; Anders et al. 2006; Ichiyanagi et al. 2007) concluded that the orography and the spatial arrangement of topographic gradients may control the precipitation patterns over Nepal and their effects are more pronounced in summer

(Shrestha, 2000; Barros et al. 2004). In the high-elevation Himalayas, annual precipitation is much lower in lee-side rain shadows than in windward side (Kansaker et al. 2004; Putkonen 2004; Dhar and Nandargi 2005). Increase in total/summer precipitation from lower to higher elevation up to certain point (Nayava 1980; Dhar and Nandargi 2000; Putkonen 2004) and than decrease with increasing elevation (Barry 2008) whereas increase in winter precipitation with increasing altitude (Putkonen 2004), making wide variation in precipitation between the stations at different elevations. Along with these factors, occasionally occurring extreme climatic events (as described in 4.2.1) weakened the association of precipitation between different elevations and not stronger as the case for temperature.

3.5. Summary

The quality of the paleoclimatic reconstructions depends on the successful calibration of proxy sources with instrumental climatic data, usually obtained from weather stations lying at lower elevations. To test the linkages of climatic records from 2005 to 2008 under different topographic conditions, we examined observational climatic data from four automated weather stations (AWSs) at different elevations, ranging from 130 m a.s.l to 5050 m a.s.l on the southern slope of the Nepal Himalayas. In spite of different elevations, variations in the temperature records across different time windows are consistent. However, precipitation data show weaker correlations (but significant for most cases) in comparison with temperature. Significant linkages of temperature and precipitation data at different elevations [except for the Terai (low elevation) to the mid hills and the high Himalayas to the Terai] showed the possibilities to use lower-elevation climatic data to represent ones at higher elevations for paleoclimatic calibration.

Chapter Four: Dendroclimatic potential of Himalayan birch (*Betula utilis*) from the high hills of the central Himalayas

4.1. 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 (Esper et al. 2002; Borgaonkar et al. 1996, 2011; Bräuning and Mantwill, 2004; Yadav et al. 2004; Bhattacharyya and Shah, 2009; Liang et al. 2009, 2011b; Cook et al. 2010; Lv and Zhang, 2011; Yadav, 2011; Zhu et al. 2011a), the application of broadleaf 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; Takahashi et al. 2005; Yu et al. 2005; Bräuning, 2004; Bhattachryya et al. 2006; Levanič and Eggertsson, 2008).

In the Himalayan region, there are large areas of natural Himalayan birch (*Betula utilis* D Don) forests. It is long-lived (more than 400 years old) (Bhattachryya et al. 2006) with the promise for developing long tree-ring chronologies. Unfortunately, to date, little is known about its dendrochronological potential (Bräuning, 2004; Bhattachryya 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) (Bhattachryya et al. 2006). Taking its wide distribution in High Asia into account, continuous efforts are needed to be made to investigate its potential to develop a long, high-elevation tree-ring chronology at higher elevations, 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 dendroclimatic potential in central Nepal. We hypothesized that the radial growth of Himalayan birch at timberline may show a positive response to summer temperature, as reported from timberline conifer trees and an alpine rhododendron shrub on the southeastern Tibetan Plateau (Bräuning and Mantwill, 2004; Liang et al. 2009; Liang and Eckstein, 2009; Lv and Zhang, 2011; Wang et al. 2012; Zhu et al. 2011b).

4.2. Site description

The study areas, Kyangjing Gompa and Langtang Villages, are parts of the Langtang National Park. They are located on a west-facing slope of the Langtang Valley (Fig. 4.1), approximately 55 km north of Kathmandu and about 15 km south of the Tibetan border, China.

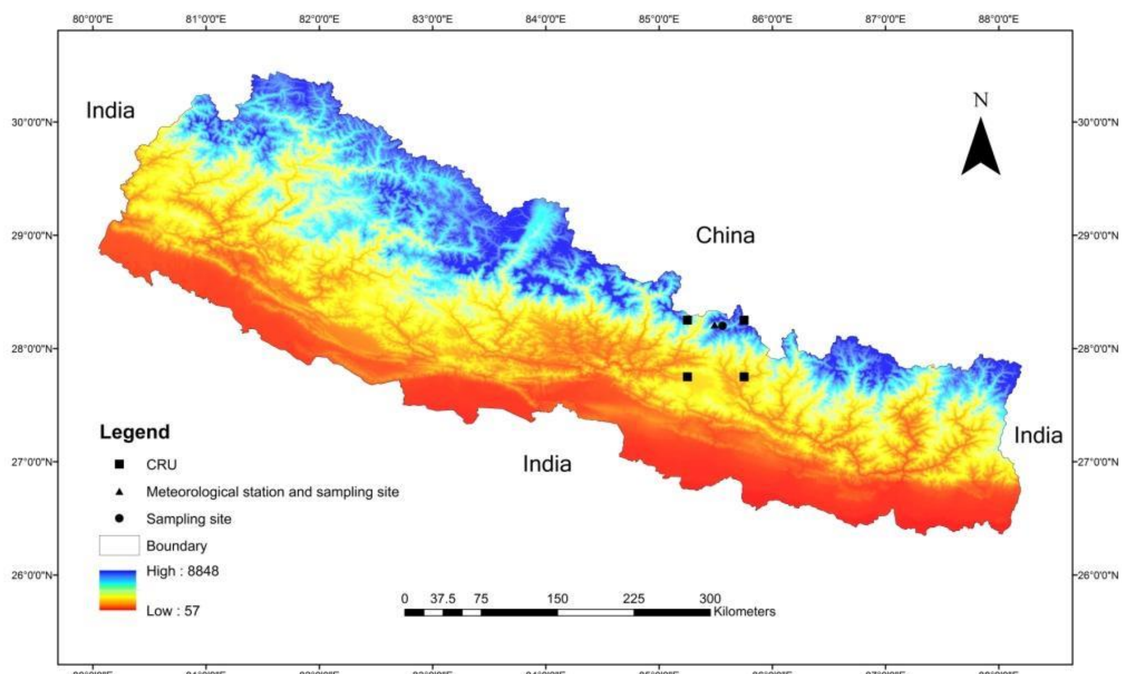

Fig4. 1 Map of Nepal showing the study area with the tree-ring sampling sites, a local meteorological station at Kyangjing and four CRU grid points

The local meteorological station at Kyangjing is ca. 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 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. 4.2).

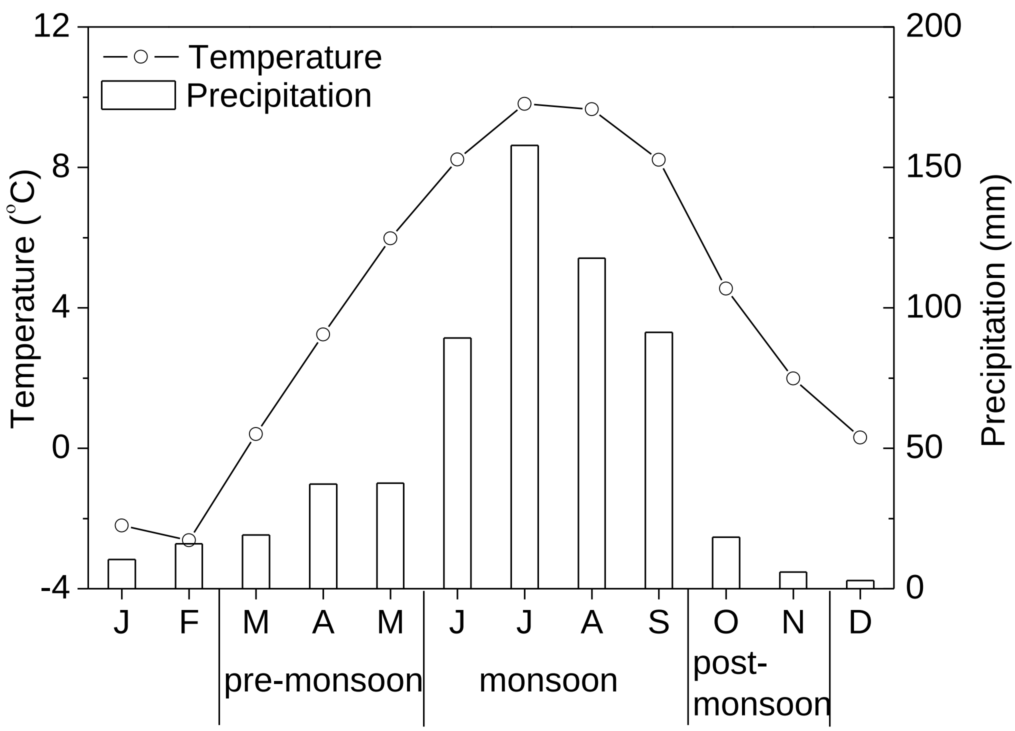

Fig4. 2 Variations of monthly mean temperature and sum of precipitation at Kyangjing (3920 m a.s.l.) based on the average from 1989 to 2008. The annual mean temperature is 4.0°C and sum of annual precipitation is 604 mm

4.3. Research species

Himalayan birch is an endemic species in the Himalayas growing up to 20 m tall at a variety of substrates from sandy to heavy clay soils. It grew to an elevation of 1800 m a.s.l. during the Pliocene when was characterized by the cooling and drying of the global environment, but it now grows above 3000 m a.s.l. (Vishnu-Mittre 1984). It was firstly described and named by botanist David Don in his Prodromus Florae Nepalensis (1825), from specimens collected by Nathaniel Wallich in Nepal in 1820. The white, paper-like bark of the tree was used in ancient times for writing Sanskrit scriptures and texts (Müller, 1981). It is still used as paper for the writing of sacred mantras, with the bark placed in an amulet and worn for protection. It is widely distributed in high Asia, growing closer to glaciers than other tree species. Himalayan birch in general grows on the north-facing slope in the rain-shadow areas, receiving less precipitation in comparison with the windward south-east facing slopes. Mixed forest of *Betula utilis-Abies spectabilis* at lower elevation (3500 to 3900 m) had young tree ages (less than 30 years as we observed in the Langtang valley), and might develop after clear cutting of large *Abies spectabilis* trees (Shrestha et al. 2007).

Himalayan birch occupies an upper forest belt from 3500 to 4200 m a.s.l. forming natural abrupt treeline without the *krummholz* zone in the central Himalayas. Pure Himalayan birch forest (with understory *Rhododendron campanulatum*) was mature, with high basal area at high elevation (3900 to 4200 m a.s.l.), and it is relatively undisturbed due to difficult access. Above the abrupt treeline, *Rhododendron anthopogon* and *Cassiope fastigiata* were dominant. In this study, undisturbed pure Himalayan birch forests at high elevations are our research target.

4.4. Material and Methods

4.4.1. Tree-ring sampling

The tree-ring cores of Himalayan birch were collected in May 2010 from the timberlines at Kyangjing (28.20°N, 85.56°E, 3950 m a.s.l.) and Langtang villages (28.21°N, 85.49°E, 3780 m a.s.l.) in the Langtang National Park, central Nepal (Fig. 4.1). 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 firewood. Dominant trees without obvious signs of crown or root damage were selected for sampling. In most of the cases one increment core per tree at breast height, was collected because opposite side was not approachable owing to a steep slope. In total, 49 cores from 41 trees growing on moderate to steep slopes.

4.4.2. 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 crossdating technique (Stokes and Smiley, 1968). The ring widths were measured to an accuracy of 0.01 mm using the measuring system LINTAB (Rinntech, Heidelberg, Germany). The tree-ring borders in birch are faint, delineated by a light line of terminal parenchyma. Thus, crossdating and measurement of ring widths require careful examination. The quality of crossdating and measurement was checked using the COFECHA program (Holmes, 1983). The cores for which errors appeared were reexamined to evaluate the sources of the errors, and corrections were made. COFECHA was run again on the corrected measurements to check occurrence of any further errors. Out of 11014 rings counted and measured, 138 (1.25%) were missing.

4.4.3. 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 1900-2000 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.

4.4.4. Climate data

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; Liang et al. 2011a; Yadav, 2011). Our remote sampling sites likewise did not have respective nearby long-term meteorological records. The local meteorological station at Kyangjing has temperature/precipitation data available from 1989/1988 to 2008 with some gaps, being too short for dendroclimatological calibration. Therefore, we used high-resolution gridded monthly temperature and precipitation data for the period of 1950-2009 from CRU TS 3 at 0.5° spatial resolution (Mitchell et al. 2005). Large differences in climatic conditions can occur over a small difference of latitude in the Himalayan region, since grid points can shift from vegetated surfaces to glacier regions and vice versa. Therefore, we merged the monthly mean temperature and precipitation data sets 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) by simple arithmetic averaging. The merged monthly mean temperature and precipitation data are higher correlated with the locally observed data at Kyangjing (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 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.

4.4.5. 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.

4.5. Results and discussion

4.5.1. Chronology statistics

We developed a 458-year tree-ring standard chronology from AD 1552 to 2009 (Fig.4.3). 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. Higher values of mean sensitivity and standard deviation are the indicators of high dendroclimatic potential of the species (Fritts, 1976). Mean sensitivity(MS), a measure of the mean percentage change from each measured yearly ring value to the next, is found to be moderate (0.19) and the correlation among all radii (RBAR) is 0.26 (Table 4.1), being comparable to alpine rhododendron with a medium signal strength (Liang and Eckstein, 2009). The chronology statistics are lower than of Himalayan birch in the western Himalayas (Bhattacharyya et al. 2006) and *Betula ermanii* in the Changbai Mountains, northeast China (Yu et al. 2005). Generally, as compared with arid sites, trees in subalpine-temperate regions have lower MS and RBAR (Gou et al. 2005; Liu et al. 2009; Liang et al. 2009; Shao et al. 2010; Lv and Zhang, 2011). As reported, trees growing in the western (Borganokar 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. Autocorrelation is the association between ring width for the year (t-1) and the subsequently formed ring t, (t+1) to (t + k). The moderate value (0.45) of autocorrelation indicates that growth during prior years have moderate influence on the growth during the subsequent years.

Table4. 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*	0.93
Signal-to-noise ratio*	12.87
Variance in first eigenvector*	30%
Correlation among all radii*	0.26

* for the common interval from 1900-2000.

Expressed population signal (EPS) is a measure of the correlation between the mean chronology derived from the core samples and the population from which they are drawn. EPS show the usefulness of the chronologies for past climate signal. Though the ring-width chronology (Fig. 4.3) 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.

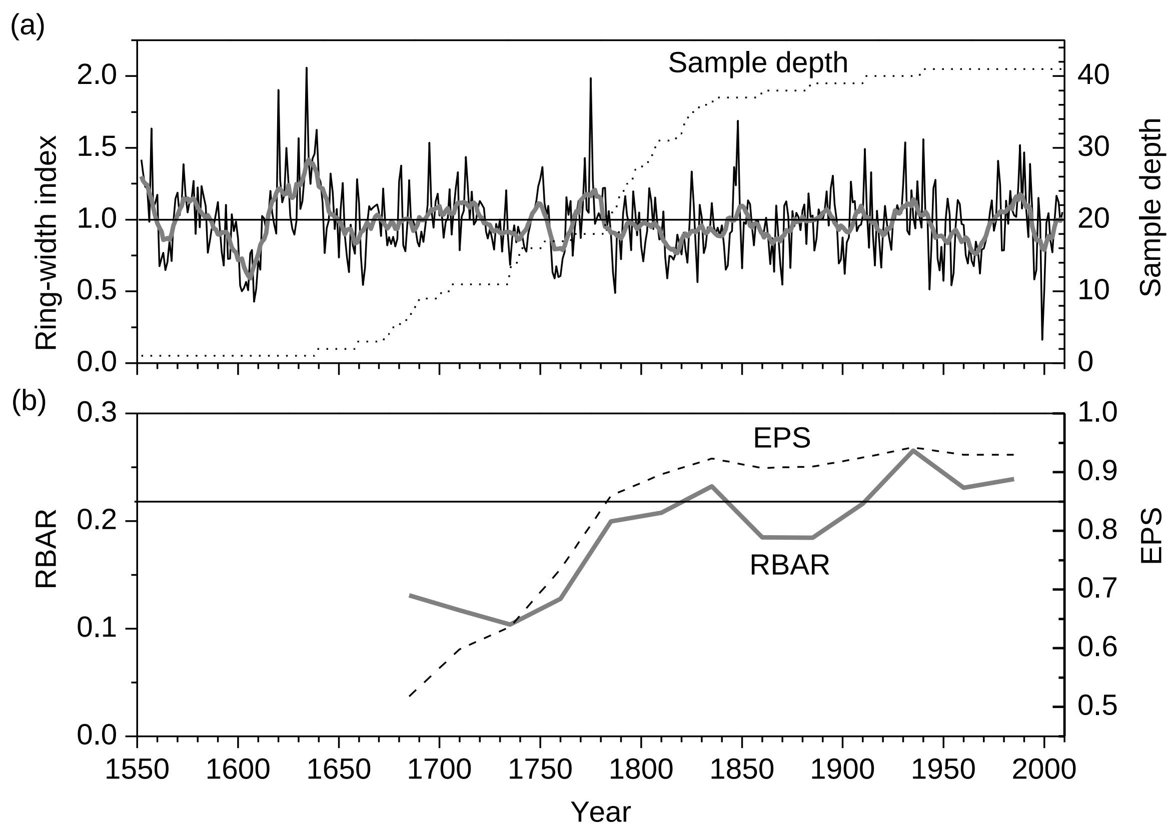

Fig4. 3 (a) Tree-ring width chronology with a 10-year moving average curve superimposed (thick solid line) and sample depth (number of trees) (dashed line); (b) Variation of RBAR and EPS over time; the horizontal line marks EPS=0.85

4.5.2. 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. 4.4). Thus, cool/wet conditions during the pre-monsoon season favor the growth of Himalayan birch in central Nepal, contrary to our hypothesis that growth would positively respond to higher temperature.

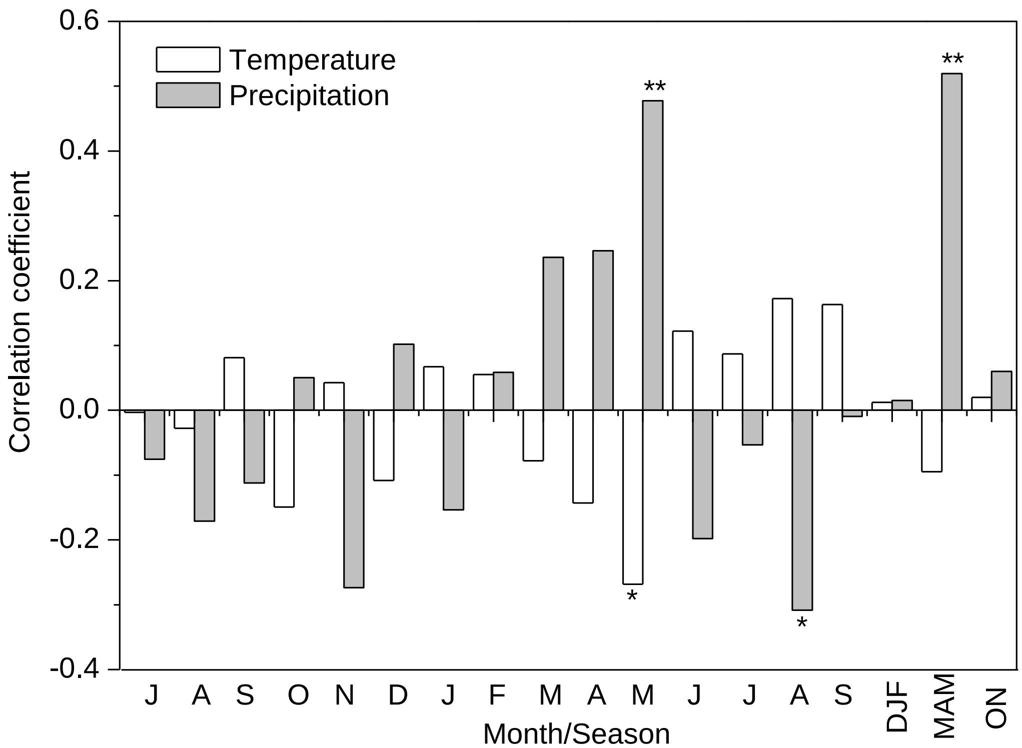

Fig4. 4 Correlations between the standard ring-width chronology and the merged gridded CRU temperature and precipitation data from July of the previous year to September of the current year. DJF, MAM and ON represent winter, pre-monsoon and post-monsoon seasons, respectively. Statistically significant relationships are indicated by * ($p < 0.05$) and ** ($p < 0.01$)

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 (Bhattachryya et al. 2006) in the western Himalayas, *Betula 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 regions. Alpine juniper trees and shrubs on the southeastern Tibetan Plateau exhibit similar climate vs. growth relationships as Himalayan birch (Zhu et al. 2011a; Liang et al. 2012).

The significant and negative correlation between Himalayan birch and August precipitation is similar with *Betula erminii* 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 brings about a reduction in photosynthesis of plants and hence tree growth decline (Takahashi et al. 2005).

4.6. Summary

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 long chronology (back to AD 1552) was developed. To date, it 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.

Chapter Five: Precipitation-limited Himalayan birch growth at the timberline: a global comparison with other timberline species

5.1. Introduction

It is generally accepted that treeline/timberline formation is directly or indirectly related to temperature (Tranquillini 1979; Steven and Fox 1991; Holtmeier 2003; Körner 2003; Wieser and Tausz 2007; Nagy and Grabherr 2009). Based on a line of worldwide dendroclimatic and dendroecological studies, tree growth at the treeline/timberlines was dominated by low temperature (i.e. Payette et al. 1985; Hughes et al. 1999; Jacoby et al. 2000; Mäkinen et al. 2000; Cook et al. 2003; Esper et al. 2003; Frank and Esper 2005; Liang et al. 2009). Apart from low summer temperature, winter desiccation could also be a growth-determining factor at the timberline (Oberhuber 2004; Mayr et al. 2006). In the recent decades, warming-induced drought stress became a limit for timberline trees, causing the divergence of tree growth response to temperature (i.e., Briffa et al. 1998; Barber 2000; Wilkming et al. 2005; Wilson et al. 2007; D'Arrigo et al. 2008; Büntgen et al. 2008). However, the divergence phenomenon at the timberline is a different issue with the tree growth-climate relationship at high-elevation subtropical timberlines where tree growth was fundamentally controlled by precipitation or moisture availability (Leuschner 2000; Binodi 2001; Moreas et al. 2004). Unfortunately, to date, a few cases were presented to challenge a general agreement that tree growth at the natural treeline/timberlines was primarily limited by temperature from extra-tropical mountains.

As the third pole, the Tibetan Plateau and the Himalayas has the world's highest natural treeline and timberline. Based on dendroecological and dendroclimatic studies at the timberlines in the recent decades, it could be summarized that tree growth at the upper timberlines across the Tibetan Plateau was limited by temperature in winter season prior to tree growth or/and summer season of the current year (Bräuning A. 1999, Gou et al. 2008; Shao et al. 2010; Zhu et al. 2011a). In particular, tree growth at the timberlines (around 4400 m a.s.l.) is primarily limited by summer temperature in semi-humid and humid areas in the southeast Tibetan Plateau (Bräuning A. 1999; Liang et al. 2008, 2009; Fan et al. 2009; Zhu et al. 2011b) and by winter temperature prior to the growing season in the semi-arid and arid areas (natural timberline is located around 4200 m a.s.l.) of the northeastern Tibetan Plateau (Liu et al. 2005; Gou et al. 2008; Zhu et al. 2008; Shao et al. 2010). It is the same case for high-elevation forest in the Himalayas where tree growth was limited by temperature in winter season prior to the growing season or early summer (Cook et al. 2003). As reported recently, a dwarf juniper shrub at an extremely high elevation up to 4800 m a.s.l in central Tibet was dominated by moisture availability in early growth season (May-June) (Liang et al. 2012), being different with the dwarf shrubs surrounding the northern pole where their growth is strongly limited by temperature of the warmest month the year (July) (Forbes et al. 2009; Hallinger et al. 2010; Rayback et al. 2012; Weijers et al. 2012). Given the high elevation (beyond the maximum precipitation belt) and decreasing precipitation with increasing elevation in the third pole, tree growth at the timberlines theatrically could also be limited by precipitation, as showed by Wilson juniper dwarf shrub (Liang et al. 2012). However, still little is known whether precipitation can be a dominant factor for tree growth at the natural timberlines in the third pole.

To date, most studies focused on coniferous forest timberlines in the third pole and it is essential to expand the present studies to broadleaf timberlines. Birch is a widespread broadleaf treeline species at high-latitude and high elevations (Bhattachryya et al. 2006; Dawadi et al. 2013). In comparison with coniferous timberlines, birch treeline is less studied, except for the high latitudes (Eckstein et al. 1991; Kullman, 1993). As reported, birch growth at alpine timberlines is primarily controlled by temperatures (Eckstein et al. 1991; Kullman, 2001; Takahashi et al. 2005; Yu et al. 2005), being similar with other coniferous timberline species (Liang et al. 2009). Among them, Himalayan birch (*Betula utilis* D. Don), native to the Himalayas, is the only broadleaved angiosperm tree species in the Himalayas that dominates an extensive area at subalpine altitudes (Stainton, 1972; Zobel and Singh 1997). Due to poor accessibility of remote birch timberline sites and difficulties in tree-ring crossdating, to date, little was known about timberline Himalayan birch growth performance and climatic factors in controlling its growth (Bräuning 2004; Bhattacharyya et al. 2006; Dawadi et al. 2013).

The objectives of this study are to initiate a tree-ring network of Himalayan birch at the timberlines in the central Himalayas, and to identify the determent climatic factors for timberline birch growth. Based on decreasing precipitation with increasing elevation above 2000-3000 m a.s.l. (Putkonen 2004; Ichiyanagi et al. 2007), we proposed that tree growth at the natural birch treeline/timberlines, had more chance to be limited by moisture availability rather by low temperature as reported from a tree-ring network around 3000 m a.s.l in the central Himalayas (Cook et al. 2003).

5.2. Material and Methods

5.2.1. Study area and climate

The south Himalayas are deeply dissected by large valleys. The study areas are located in three high-elevation nature reserves (Sagarmatha, Langtang and Manaslu) along three valleys in central Nepal. Several mountain peaks, such as Mount Everest (Qomolangma) (8848 m), Langtang Lirung (7246m) and Manasulu (8150m) close to the research areas (Fig 5.1). After possible transport by the jeep or small airplane, it took another 4-6 days by climbing to reach the highest birch forest through the valleys.

The Himalayas are situated in the interface between temperate and subtropical mountains. The valleys in the central Himalayas exposes to the southeast monsoon flow and characterized by an increasing-decreasing south-north gradient in monsoonal precipitation (Kansaker et al. 2004; Putkonen 2004; Ichiyanagi et al. 2007). Despite a lack of climatic stations at high elevations, the precipitation radar on the Tropical Rainfall Measuring Mission (TRMM) enable to show a general spatial patter of precipitation in the Nepal Himalayas (Fig. 5.2). Annual precipitation increases from low-elevation plane areas up to some limiting elevation (around 2000 m a.s.l) and then decrease northward with increasing elevation. Annual precipitation is above 2000 mm around the mid-elevation belt (2000-3000m in elevation), and ranges from 750 to1000 mm at 4000 m in elevation in our study area. Lower annual precipitation at higher elevation above 2000-3000 m a.s.l was also confirmed by instrumental observations (Putkonen 2004). Precipitation varies considerably on a local scale in relation to location on windward/leeward slopes, as a result of the local wind circulations (Barry 2008). In the high-elevation Himalayas, annual precipitation is much lower in lee-side rain shadows than in windward side (Kansaker et al. 2004; Putkonen 2004).

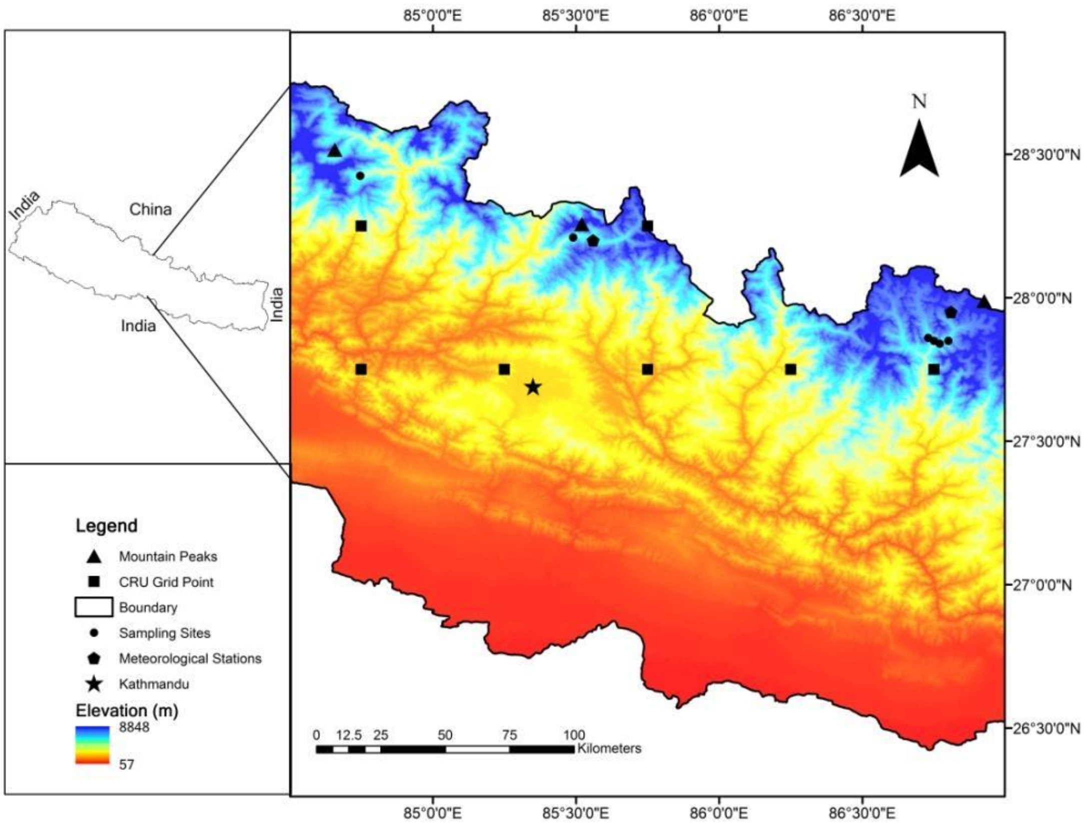

Fig5. 1 Map showing location of Himalayan birch sites and CRU gridded data as well as two high-elevation meteorological stations at Kyangjing of the Langtang valley and Pyramid of Mt. Everest areas in the central Nepal Himalayas. Triangles showed the world's 8^{th} highest peak Mt. Manslu, Mt. Langtang Lirung and the world's highest peak Mt. Everest (from the left)

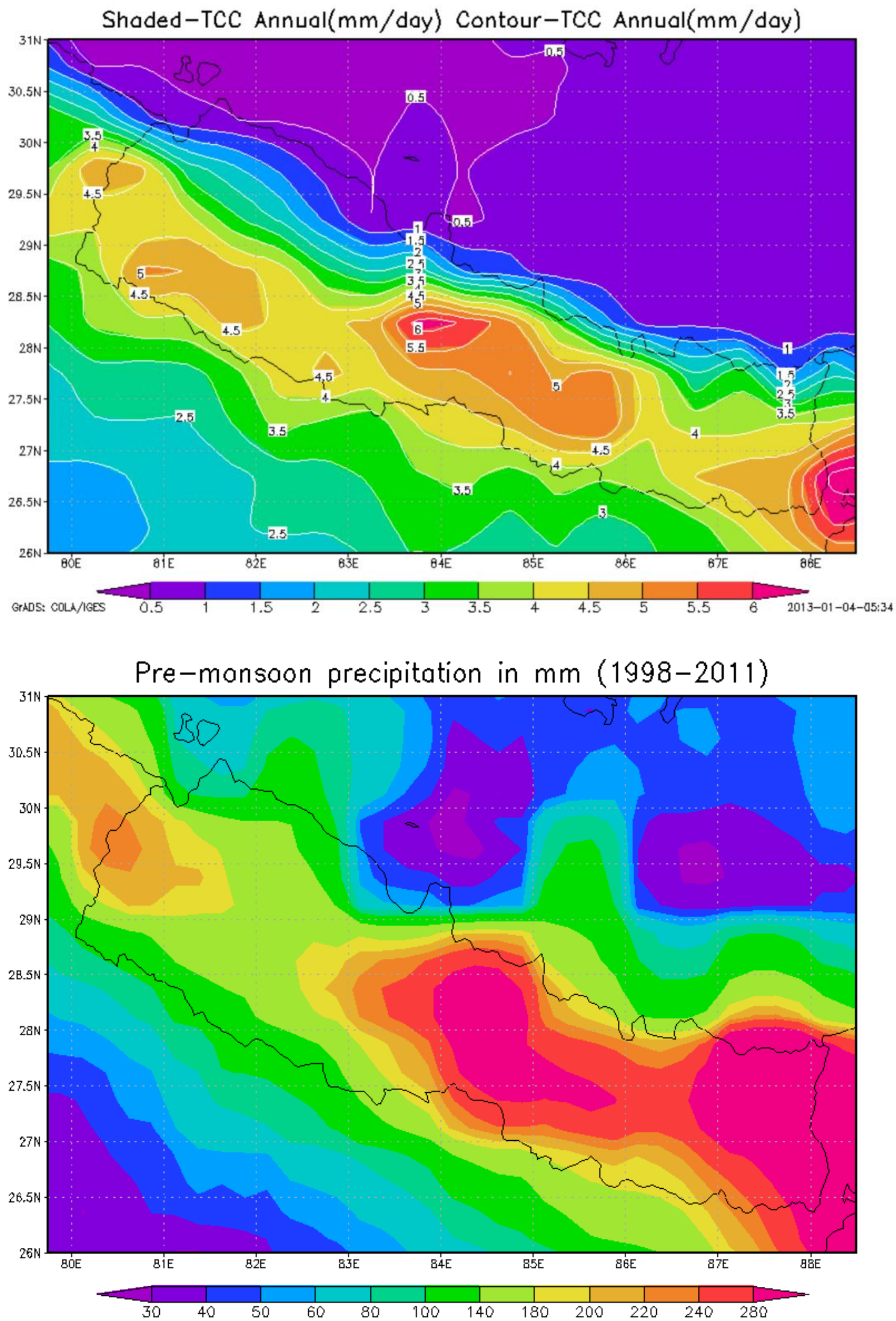

Fig5. 2 TRMM data show spatial variations of annual precipitation (by mm/day) and pre-monsoon precipitation

In spite of a lack of instrumental climatic records in the Manasulu Nature conservation, instrumental observations in the Langtang and Sagarmatha valley confirm a general picture in altitude-dependent precipitation. In the Langtang valley, annual total precipitation is around 3500 mm at elevations of 1600-2600m (Dhar and Nadargi, 2000), while around 604 mm (from 1989 to 2008) at Kyangjing (3920 m a.s.l) close to our birch timberline sampling. At Kyangjing, annual maximum, mean and minimum temperature is around 9.4, 3.7, -0.2 °C, respectively. The warmest month (July) is around 9.8°C, being close to the 10°C isotherm during the warmest month for estimating treeline position (Tranquillini 1979).

More meteorological data were available in the Mt. Everest area. South of Mt. Everest at 2600 m a.s.l. annual totals of precipitation range from 2300 to 2600 mm, and then decrease to 1000 mm or less at 3450-3850 m a.s.l. At Namche Bazar (3450 m 25 km southwest of Mt. Everest) the annual precipitation is about 1000 mm (Miehe et al. 2007) while on the Khumbu Glacier (5300) is only 450 mm (Dhara and Nandargi, 2000). As recorded by the high-altitude Pyramid meteorological station (5050 m) (12 km southwest of Mt. Everest, annual precipitation averaged only 465 mm for 1994-1999 (Bollasina et al. 2002) and 404 mm for 1994 - 2008 with very small amounts from December to April.

Due to a paucity of long-term instrumental climatic records, high-resolution gridded monthly temperature and precipitation data for the period 1950 to 2009 from CRU TS 3 at 0.5° spatial resolution (Mitchell and Jones, 2005) were used for the analysis (Fig. 1). An average of 7 grids was used to present variations in regional temperature and precipitation at high elevations in central Himalayas. The mean gridded monthly mean temperature and sum of precipitation show high correlation with the instrumental records at Pyramid ($r = 0.92$ and $r = 0.82$, $n=180$) and Kyangjing ($r = 0.90$ and $r = 0.71$, $n = 240$) respectively. Thus, the average regional gridded temperature and precipitation data are representatives of variations in climatic conditions in the study areas, as showed in southeast Tibet (Liang et al. 2011).

5.2.2. Tree-ring sampling, crossdating and standardization

Tree-ring cores were taken from 7 Himalayan birch timberline sites ranging from 3900 to 4200 m a.s.l. in Manaslu (1 site), Langtang (2) and Sagarmatha (4) Nature Conservations (Table 5.1).

Table5.1 The Himalayan birch tree-ring chronologies from central Himalayas and their major chronology statistics

SN	Site	Sample ID	Lat (N)	Lon (E)	Alt (m)	Slope (°)	Orientation	MS	RBAR	EPS >0.85
Sagarmatha National Park										
1	Pangboche	SKB1	27.86	86.8	4158	20-25	North west	0.18	0.32	1710
2	Deuboche	SKB2	27.84	86.77	3867	15-20	West	0.2	0.35	1785
3	Dole	SKB3	27.87	86.73	4110	20-25	Northeast	0.23	0.33	1790
4	Portshe	SKB4	27.85	86.75	3920	20-25	South west	0.22	0.32	1930
Langtang National Park										
5	Kyangjing	LT1	28.2	85.56	4050	20-25	West	0.19	0.28	1835
6	Langtang	LT4	28.21	85.49	3880	20-25	South west	0.25	0.31	1815
Manaslu Conservation Area										
7	Prok	Man1	28.5	84.8	3856	20-25	North east	0.25	0.31	1805

Apart from one site (SKB3) at a southeast facing slope in the Sagarmatha national park, other sites are located in the rain shadow in the south-west facing slopes (Fig 5.3). At each site, 15-30 dominant birch trees at or close to the upper treelines/timberlines were selected. One or two increment cores were taken from each selected trees. All tree-ring cores were fixed in wood supports and smoothing.

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. We found that tree-ring boundary was easily distinguished when the core surface keep moist. With this technique, we can successfully crossdate most tree-ring cores. The quality of crossdating and measurement was checked using the COFECHA program (Holmes, 1983).

Fig5. 3 Landscape view of birch forest with clear abrupt treeline. (a) SKB1 site with Mt Everest in the back, (b) tree line in the Sagarmatha national park (c) Sampling site in the Langtang national park near Kyangjing (d) Sampling site in the Manaslu conservation area

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 (Cook et al. 2003) was applied for the detrending birch tree-ring series of each site. The standardized tree-ring series of the individual samples were then averaged into the standard chronologies at different sites (Fig 5.4). To evaluate the chronology signal, a common interval from 1900 to 2009 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.

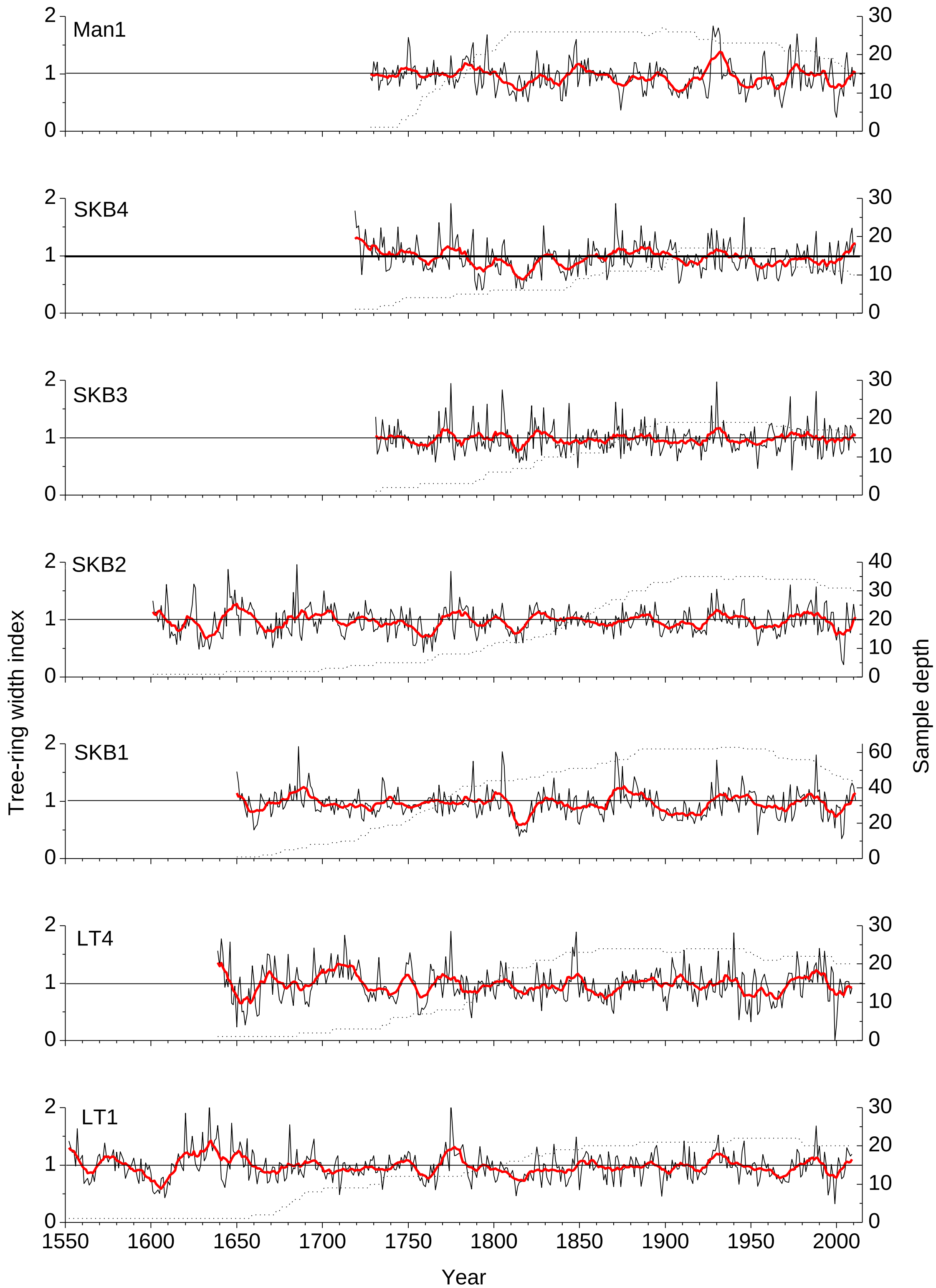

Fig5. 4 Standard tree-ring width chronologies for Himalayan birch in the Langtang (LT1, LT4), Sagarmatha (SKB1, SKB2, SKB3 and SKB4) and Manaslu conservation areas (Man1) in the central Himalayas

5.3. Results

Himalayan birch at the timberlines has a lower annual growth rate, as indicated by a mean ring-width of 0.80 mm among 250 investigated tree-ring cores. As shown by COFECHA output, the inter-series correlation between the measured ring-width series ranged from 0.50-0.56 at each site, showing a confidence crossdating. In addition, tree growth show synchronous patterns between different sites in the three conserve areas, as shown by a higher inter-series correlation (r= 0.50) between tree-ring series (250 series) along all sites. In particular, extreme narrow rings occur in the same years such as 1710, 1790, 1816, 1898, 1954, 1999, 2003 and 2004, providing a useful clue for crossdating. In the Langtang and Sagarmatha Nature conserves, we found birch trees more than 400 years old. Most sampled trees were more than 200 years old.

For the standard chronologies, the mean sensitivity ranging from 0.18 to 0.25 and RBAR ranging from 0.27 to 0.35 show its potential for dendrochronological studies. In particular, tree-ring standard chronologies from different sites show high correlations, with a correlation coefficient from 0.18-0.70 ($p<0.001$). The first principal component (PC1) from the seven chronologies with a common period from 1731 to 2009 can explain 52.2% variations so that it was taken to evaluate the relationship between tree growth and climate. The secondary and third principal components (PC2 and PC3) explain 16.31% and 9.6% of the total variance, respectively.

Across all sites, the missing rings were dated. In the past 300 years, the occurrence of missing rings was confined to the recent decades, such as 1954 (5.8%), 1995 (7.8%), 1999 (13.5%), 2003 (23.6%) and 2004 (22.0%) [Fig 5.5]. We found trees older than 80 years and 200 years both have produced missing rings in the extremely drought year. Age-dependent occurrence of missing rings may be not very strong. In particular, at extremely high sites, for example, SKB1 (4100 m a.s.l) and SKB2 (4000 m. a.s.l.) have more occurrence of missing rings in percentage, in comparison with other sites.

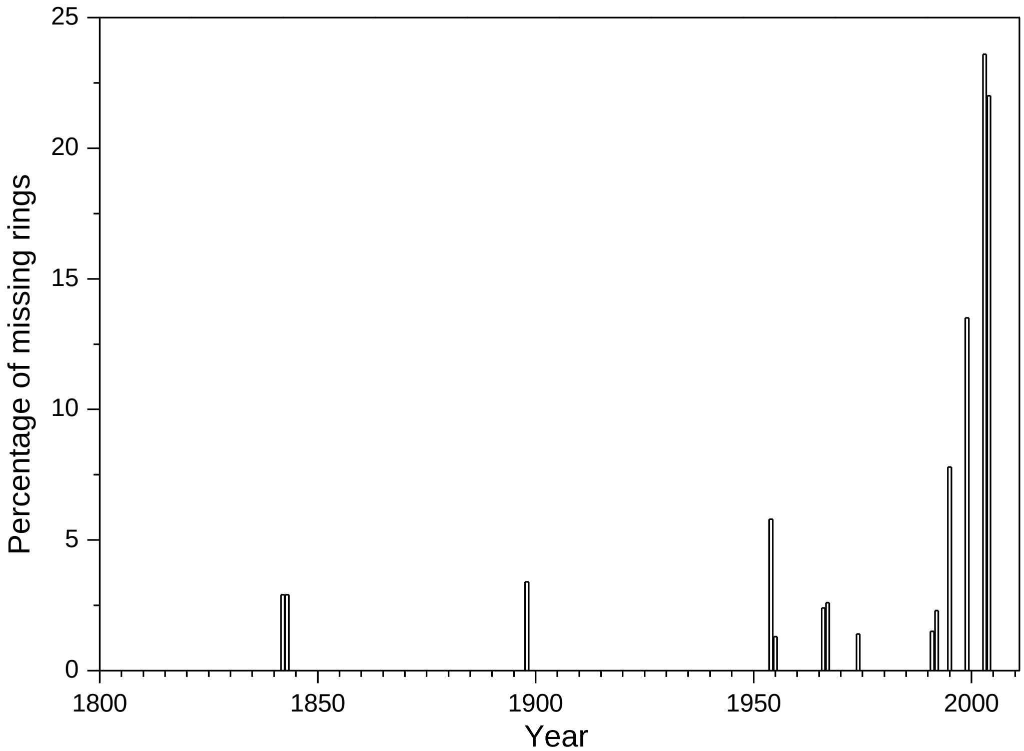

Fig5. 5 Occurrence of missing rings since AD 1800 at all sites

Birch growth is dominated by pre-monsoon moisture availability, as showed by positive correlation with precipitation in March, April and May with significant correlation ($p<0.05$) at least for one month of them. All chronologies display a significant correlation with sum of precipitation in March-May, with a less significant signal force ($p<0.05$) for SKB3 in windward southeast-facing slope in comparison with other chronologies at leeward southwest-facing slope ($p<0.001$). All the chronologies show negative correlation with temperature in March, April and May, with significant correlation coefficients for May at LT4, April at SKB2, and March-April at SKB3 (Fig 5.6).

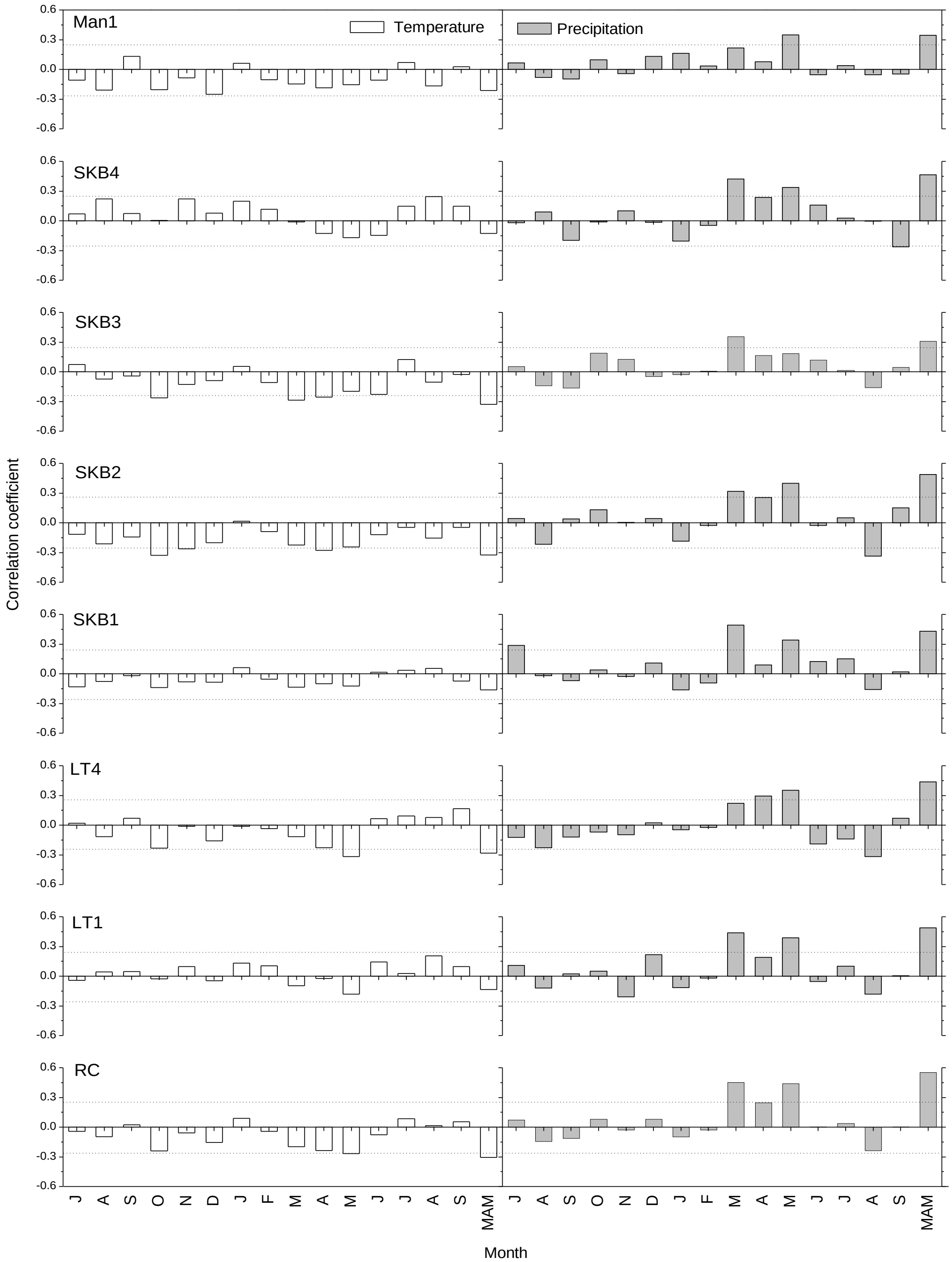

Fig5. 6 Tree growth and climate relationships of Himalayan birch at each site and their regional average tree-ring chronology (RC). The horizontal solid and dotted lines represent 95% confidence level.

5.4. Discussion

Timberline birch growth-climate relationships, characterized by positive correlations with precipitation and negative correlation with temperature (high temperature-induced evaporation) in March-May, represented an enhancing forcing for moisture stress for birch growth. Such a climatic response is similar with other forest in semi-arid or arid areas (Sheppard et al. 2004), where precipitation in early growing season or prior to the growing season is a determinant factor for tree growth. In comparison with tree growth at most alpine timberlines where it is primarily limited by temperature in the growing season and winter season prior to tree growth (Zhu et al. 2008; Shao et al. 2010), precipitation-controlled Himalayan birch growth at timberlines is closely related to its eco-physiological trait and elevation precipitation variations in the central Himalayas.

A tree growth response to climate is dependent on water-thermal balance. Precipitation in the central Himalayan decrease with increasing elevation above 2000-3000 m a.s.l. Himalayan birch usually grows in the rain shadow, where receives much less annual precipitation (Putkonen 2004). As recorded by the Pyramid meteorological station close to Mt. Everest, pre-monsoon precipitation is around 24 mm, accounting for 7.0% of annual precipitation. Most alpines timberlines are located under or in a maximum precipitation belt where moisture availability is not a limit for tree growth. Reasonably, tree growth at such timberlines is fundamentally controlled by temperature. For example, the maximum precipitation on the northeastern Tibetan Plateau is around 4600 m a.s.l. (Wang et al. 2010). Under a semi-arid macroclimate on the northeastern Tibetan Plateau, the typical natural treeline of Qilian juniper reach an elevation around 4200 m a.s.l., where its growth was strongly determined by winter (prior to tree growth) and summer temperatures (Zheng et al. 2008; Zhu et al. 2008; Shao et al. 2010). However, it is limited by precipitation at its low-elevation distribution around 3850 m (Zheng et al. 2008; Shao et al. 2010). It is partly similar with subtropical timberline (Leuschner 2000; Binodi 2001; Moreas et al. 2004) where receive less precipitation in association with a strong solar radiation and evaporation. Himalayan birch at the timberline also share the similarity with Wilson juniper shrub whose growth is strongly limited by moisture in early growing season despite an extremely high elevation up to 4800 m a.s.l in central Tibet (Liang et al. 2012).

Moisture was considered to play an important role in spatial distribution of Himalayan birch. As observed, Himalayan birch often descends down to the valley floor along moist watercourses in the Mt. Everest area, proving an evidence support for precipitation-driven birch distribution. Growing at north-facing slopes, its growth and regeneration are largely dependent on spring snow melting (Shrestha et al. 2007). As observed from Kyangjing and Pyramid earth station from 2005 to 2008, snowfall or precipitation in the pre-monsoon (March-May) season accounted for 85-90% from November to May. Reasonably, dry pre-monsoon environmental conditions are a critical factor in controlling Himalayan birch growth. Thus, Himalayan birch growth show a distinguish difference in its growth responses to climate with high elevation coniferous trees (Cook et al. 2003; Sano et al. 2005).

The occurrence of missing rings is an indicator that drought stresses reach the survival limit of Himalayan birch growth. However, across a temperature-sensitive high-elevation coniferous tree-ring network in Nepal, Cook et al. (2003) and Sano et al. (2005) did not reported the occurrence of missing rings. High percentage of missing rings occurred in 1964, 1999 and 2003, in which extremely pre-monsoon drought events was evident in Nepal (Sigdel and Ikeda 2009; WMO 2011). The southwest-facing slope (such as birch site LT4) receives more solar radiation and hence stronger evaporation in comparison with west-facing slope (such as LT1). As a result, LT4 produce higher frequency of missing rings than LT1. In the recent decades, there is strong evidence that precipitation decreased and glacier retreat in the Himalayas (Yao et al. 2012). Taking consideration that the recent 50 years may be the warmest period in the last 600-1000 years (Thompson et al. 2006; Zhu et al. 20011, Cook et al. 2012), increasing missing rings in the recent decades may be partly related to warmer-induced moisture stress in dry years based on the significant and negative correlation between Himalayan birch and pre-monsoon temperature. The occurrence of missing rings in the years with dry pre-monsoon seasons provide a reasonable and strong support for precipitation-controlled Himalayan birch growth at the timberlines, being basically different in growth-limiting factors with other temperature-sensitive timberlines.

The intervals with great tree growth decline of Himalayan birch before the instrumental period were in phase with well-recorded extreme historical drought events in south Asia. For example, Himalayan birch in the central Himalayan birch show clearly growth declines during the periods for 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), and other drought events 1810-1820 (Duan et al. 2004). In a long-term view, Himalayan birch growth at the timberlines is sustained limited by moisture stress, unlike other divergence phenomenon at latitudinal timberlines (i.e., Briffa et al. 1998, Barber 2000; Wilkming et al. 2005; Wilson et al. 2007; D'Arrigo et al. 2008; Büntgen et al. 2008)

5.5. Summary

We developed a network of seven tree-ring chronologies of Himalayan birch collected from the central Himalayas. All the tree-ring chronologies showed positive correlation with spring (March-May) precipitation and inverse relation with temperature. Himalayan birch usually prefers to grow in the rain shadow region which receives much less precipitation. High percentage of missing rings in the extreme drought year confirmed the growth of Himalayan birch was drought sensitive. The tree-ring series from south-west facing slope gets high frequency of missing rings due to the strong solar radiation in comparison with others. This study confirmed that precipitation variation rather than the temperature, as observed worldwide treeline / timberline (Payette et al. 1985; Hughes et al. 1999, Jacoby et al. 2000; Mäkinen et al. 2000; Frank and Esper, 2005; Liang et al. 2009), controled the Himalayan birch tree-growth in the central Himalayas.

Chapter Six: Pre-monsoon precipitation inferred from Himalayan birch in the Central Himalayas

6.1. Introduction

The climatic reconstructions extending beyond the industrial-era improved our understanding on the earth's climate system (Jones et al. 2009). As shown by the temperature reconstructions, the variability increased by 75% (in comparison with pre-industrial period) due to the recent warming, though regional features and impacts associated with both past and future climate variability are still subjected to considerable uncertainties (IPCC 2007). These uncertainties are particularly large for hydroclimatic change due to its spatial heterogeneity mainly in the region of complex terrains such as the mountain areas (Schiermeier 2010). Due to the lack of empirical and proxy records, the changes of climatic driving forcing were not well understood (Yadav et al. 2011). The technological difficulties in maintaining regular weather stations in the complex terrains of the high Himalayas made this region as a lack of long-term climatic data for understanding climate dynamics. Such information is particularly scare for the central Himalayas in comparison with the eastern and western Himalayas.

The climatology of the central Himalayas is based mainly on the instrumental records, which rarely exceeds 40 years. In order to understand the natural climatic variability, long-term high-resolution proxy records from the central Himalayas are invaluable. Tree rings (Cook and Kairiukstis 1990) are ideal climatic proxy dating back several centuries to millennia. The annual growth rings of trees are a particularly useful climate proxy due to their annual resolution, climate sensitivity and widespread availability (Fritts 1976).

Several coniferous species were confirmed to be potential for the dendroclimatic studies in the Himalayas and surrounding regions (Borganokar et al. 1996; Pant et al. 2000; Cook et al. 2003; Zhang et al. 2003; Bräuning and Mantwill 2004; Sano et al. 2005; Singh and Yadav 2005; Liu et al.2005; Singh et al. 2006; Liang et al. 2008; Singh et al. 2009; Yadav et al. 2009; Liang et al. 2009; Yadav 2011; Zhu et al. 2011a; Zhu et al. 2011b). However, in contrast to a wide distribution of Himalayan birch in the Himalayas, little is known about its dendroclimatic 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). Recently, Dawadi et al. (2013) found that tree growth of the Himalayan birch is positively correlated with pre-monsoon (March-May) precipitation in the central Himalayas. Thus, Himalayan birch at high elevations may provide a possibility to reconstruct hydroclimatic variations in the central Himalayas.

The objectives of this study are (1) to reconstruct pre-monsoon precipitation of the central Himalayas based on a new established tree-ring network; (2) to investigate the possible linkages between the precipitation reconstruction and other regional precipitation indices and environmental events.

6.2. Materials and Methods

6.2.1. Study area and tree-ring chronology

The tree-ring samples in this study are used from the previous chapter (Chapter 5). The correlations among all the six chronologies for the common period AD1731-2009 were shown in Table 6.1. Significant correlations (r =0.37-0.70, p< 0.001) between the chronologies indicated the similarity in variations of tree growth across different sites. Based the above correlations, six sites were selected to make a mean regional chronology (RC) for the climate reconstruction. (Fig.6.1).

Table6. 1 Correlations between the six tree-ring chronologies for the two common periods AD 1731-2011 and 1950-2009. Values in the brackets are correlations for the recent period 1950-2009. All the correlations are significant at *p*< 0.001 level

	Kyangjing	Langtang	Pangboche	Deuboche	Portshe	Manaslu
Kyangjing (LT1)	1	0.59(0.68)	0.40(0.70)	0.50(0.45)	0.38(0.43)	0.43(0.57)
Langtang (LT4)		1	0.27(0.37)	0.40(0.48)	0.18(0.1)	0.36(0.64)
Pangboche (SKB1)			1	0.54(0.72)	0.61(0.59)	0.37(0.57)
Deuboche (SKB2)				1	0.44(0.31)	0.36(0.57)
Portshe (SKB4)					1	0.30(0.37)
Manaslu (Man1)						1

6.2.2. Climate data

The long-term meteorological records are in general rare in Monsoon Asia (Cook et al. *2010*), including the central Himalayas (Dawadi et al. 2013) and surrounding regions (Borgaonkar et al. 2011; Yadav 2011; Liang et al. 2011). Most stations lie at low elevations and far from tree-ring sampling sites. Our research sites in the remote mountainous areas further added the difficulties to get long-term meteorological data. The local Pyramid Earth station (86.81E, 27.95N, 5050 m a.s.l) near the Mt. Everest has been running since AD1994, which is too short for dendroclimatological calibration. Therefore, we used high-resolution gridded monthly temperature and precipitation data for the period of 1960-2009 from CRU TS 3 at 0.5^{o} spatial resolutions (Mitchell and Jones 2005), as described in chapter 5.

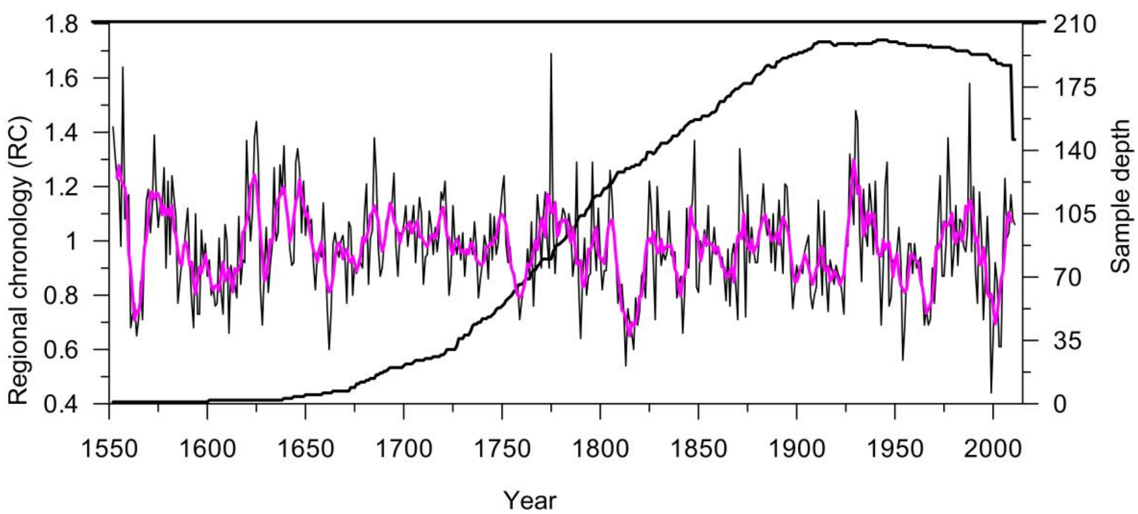

Fig6. 1 The regional chronology (RC) with a 10-year moving average curve (thick line) and sample depth (numbers of cores)

6.2.3. Tree growth and climate relationships

The Pearson correlation was used to determine tree growth and climate (monthly/seasonal mean temperature and sum of precipitation) relationships. The RC shows statistically significant relationship with March and May precipitation ($p < 0.001$) and temperature in October the previous year ($p<0.05$). Among the various seasonal temperature and precipitation data, the RC was most strongly correlated with Pre-monsoon (March-May) precipitation of the current growth year ($r= 0.61$, $p<0.001$)

[Fig.6.2]. The positive relationship between tree growth and pre-monsoon precipitation indicated drought in the early growing season reduced the growth of Himalayan birch, as showed in the semi-arid environment conditions (Fritts 1976).

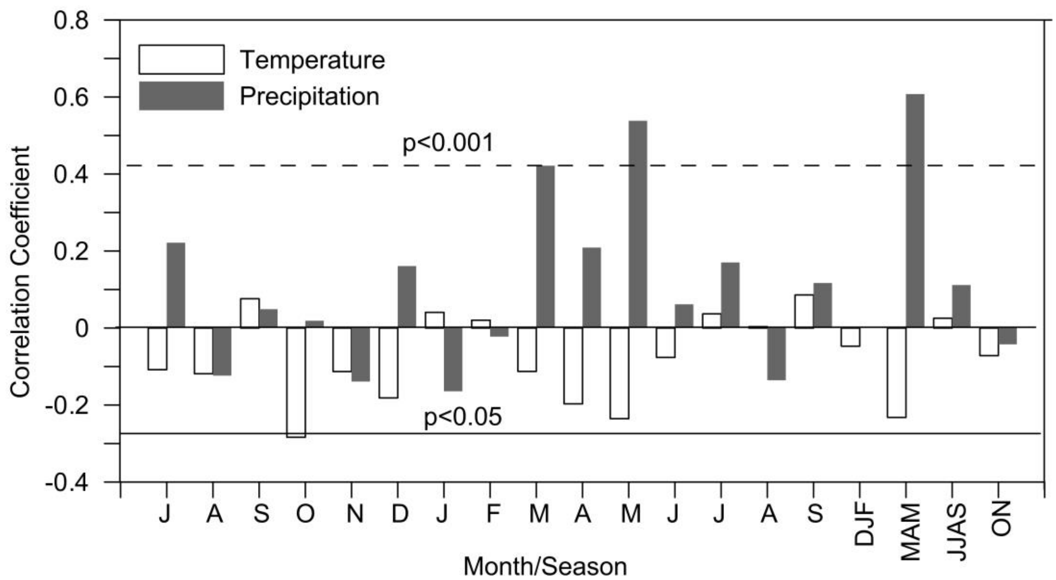

Fig6. 2 Correlations between the regional mean chronology (RC) and the merged gridded CRU temperature and precipitation data from July of the previous year to September of the current year. DJF, MAM, JJAS and ON represent winter, pre-monsoon, monsoon and post-monsoon seasons, respectively. The horizontal solid and dotted lines represent 95% and 99.9% confidence level

6.2.4. Calibration, verification and reconstruction

The strong and significant relationship between pre-monsoon precipitation and tree growth enabled to a dendroclimatic reconstruction. We prepared two calibration models using RC and pre-monsoon precipitation. The climate data from 1960 to 2009 was separated into two sub-periods for correspondingly calibration (1960-1989, 1980-2009) and verification (1990-2009, 1960-1979). The regression model captured 37% of the ($p<0.001$) of the variance in the calibration interval from 1960 to 2009 and is validated by calibration/verification tests (Table 6.2); RE and CE are both positive, indicating the predicative skill of the models. The sign test provides additional evidence for the qualification of the model. We used the whole period (1960-2009) calibration model for reconstruction, as the use of the longer calibration interval enhances the ability of the regression model to capture low-frequency variability in the reconstruction. We, therefore, reconstructed total precipitation from the Pre-monsoon precipitation (M, A, M) using the RC chronology of Himalayan birch. The regression equation for the reconstruction for the reconstruction is as follows.

P = 234RC +17.5

Where P is pre-monsoon season precipitation and RC is the regional chronology of Himalayan birch as derived from section 6.2.2.

The estimated pre-monsoon precipitation using this model showed very close similarity with CRU pre-monsoon precipitation (Fig 6.3a).

Table6.2 Calibration/verification statistics for the reconstructed pre-monsoon precipitation; the calibration and verification was performed over a 30-year interval

	Calibration (1960-1989)	Verification (1990-2009)	Calibration (1980-2009)	Verification (1960-1979)	Full calibration (1960-2009)
r	0.56	0.72	0.60	0.62	0.61
r^2	0.31	0.51	0.36	0.39	0.37
RE		0.37		0.38	
CE		0.36		0.27	
Sign test	21+/9- ($p<0.05$)	17+/3- ($p<0.001$)	23+/7- ($p<0.01$)	14+/6- ($p<0.05$)	38+/12- ($p<0.01$)

6.3. Results and discussion

The pre-monsoon precipitation reconstruction (AD1552-2011) showed annual to multiannual fluctuations (Fig 6.3b). The year 1999, 1813 and 1954 are characterized as the driest years whereas 1775, 1557 and 1988 are the wettest years in the whole period (Table 6.3). As showed by the reconstructed precipitation series, AD1811-1821 and 1995-2005 were the driest decades whereas AD1926-1936 and 1640-1650 the wettest decades (Table 6.4). There are no other high-resolution proxy records of precipitation for the central Himalayas that could be compared with the present precipitation reconstruction. The systematic meteorological observations in Nepal started in the later 1960s (Shrestha 2000), therefore, it is difficult to validate the precipitation variations before this period. Published precipitation reconstructions from the Indian Himalayas and surrounding regions (Borganokar et al. 1994; Singh and Yadav 2005; Singh et al. 2006; Singh et al. 2009; Yadav 2011) were difficult to be used to compare with our precipitation series because of differences in the reconstructed seasons and the nature of higher variability of precipitation in the mountain areas. However, some similarities should be noted, especially at decadal and centennial time scales.

Table6. 2 Ranking of the top ten driest and wettest years in the central Himalayas based on the pre-monsoon precipitation reconstruction (March-May)

Rank	Dry year	Precipitation (mm)	Wet Year	Precipitation (mm)
1	1999	120.5	1775	412.9
2	1813	143.9	1557	401.3
3	1954	148.5	1988	387.2
4	1662	157.9	1930	363.8
5	1817	157.9	1625	354.5
6	2003	160.2	1931	354.5
7	2004	160.2	1552	349.8
8	1790	167.2	1573	342.8
9	1564	169.6	1624	340.4
10	2000	169.6	1685	340.4

Table6. 3 The 10 and 20-year running mean of the reconstructed pre-monsoon precipitation from the central Himalayas

Driest Periods	mm	Wettest Periods	mm
10-year mean			
1811-1821	195.3	1926-1936	279.2
1995-2005	215.9	1640-1650	279.2
1960-1970	217.1	1570-1580	278.0
1600-1610	219.1	1688-1698	265.2
1755-1765	223.6	1980-1990	264.2
20-year mean			
1806-1826	217.0	1630-1650	270.9
1591-1611	223.6	1924-1944	261.1
1950-1970	226.1	1770-1790	257.4

6.3.1. Pre-monsoon precipitation reconstruction and local drought events

As observed with instrumental records, large-scale droughts after 1960 occurred in 1965, 1967-1973, 1975, 1991-1993 and 1999-2001 in Nepal (Sigdel and Ikeda 2010). Based on precipitation data from different sources, such as SPI, NCEP, GPCP, ERA40 and models SMRC (2009), the years 1965, 1966, 1975, 1999 and 2000 are the driest years in Nepal. Several studies (Shakya and Yamaguchi 2007; Attri and Tyagi 2010) reported considerable drought conditions over the region in the same periods. Our reconstruction also showed lower precipitation during these years. Eleven of the last 12 years (1995 to 2006) except for 1996 ranked among the 12 warmest years since 1850. Among them, 2002, 2003 and 2004 were recorded as the 4th, 3rd and 5th warmest years (Trenberth et al. 2007; IPCC 2007). In addition, India, Pakistan and Bangladesh have also witnessed exceptionally harsh pre-monsoonal heat waves in these years (maximum in 2003) (WMO 2011). The increases in temperature will enhance moisture holding capacity of the atmosphere that consequently alters precipitation patterns (Trenberth et al. 2003). Drought conditions in the recent decade (1995-2005) closely related to the warming. In this context, variations in pre-monsoon precipitation in the central Himalayas seem to show that the warming may be associated with the drought conditions in the central Himalayas.

6.3.2. Comparisons with regional hydroclimatic records

The drought events around the 1810s and 1950s were also observed in other proxy sources such as tree rings (Singh et al. 2009; Yadav 2011), stalagmite records (Kotela et al. 2012) and ice cores (Yao et al. 2000; Duan et al. 2004) in the western Himalayas and surrounding regions. In these periods, the reconstructed pre-monsoon precipitation showed the lowest values, confirming its indicator to large-scale pre-monsoon precipitation. The well-documented historical megadroughts, such as the Strange Parallels drought (1756-1768), the East India drought (1790-1796), the late Victorian-era Great Drought (1876-1878) and drought event around 1560s (Cook et al. 2010) appeared to be embedded in much longer drought periods in our reconstruction. In this context, the persistent pre-monsoon droughts in the central Himalayas seem to be harbinger of the megadroughts induced by the South Asian monsoon failure.

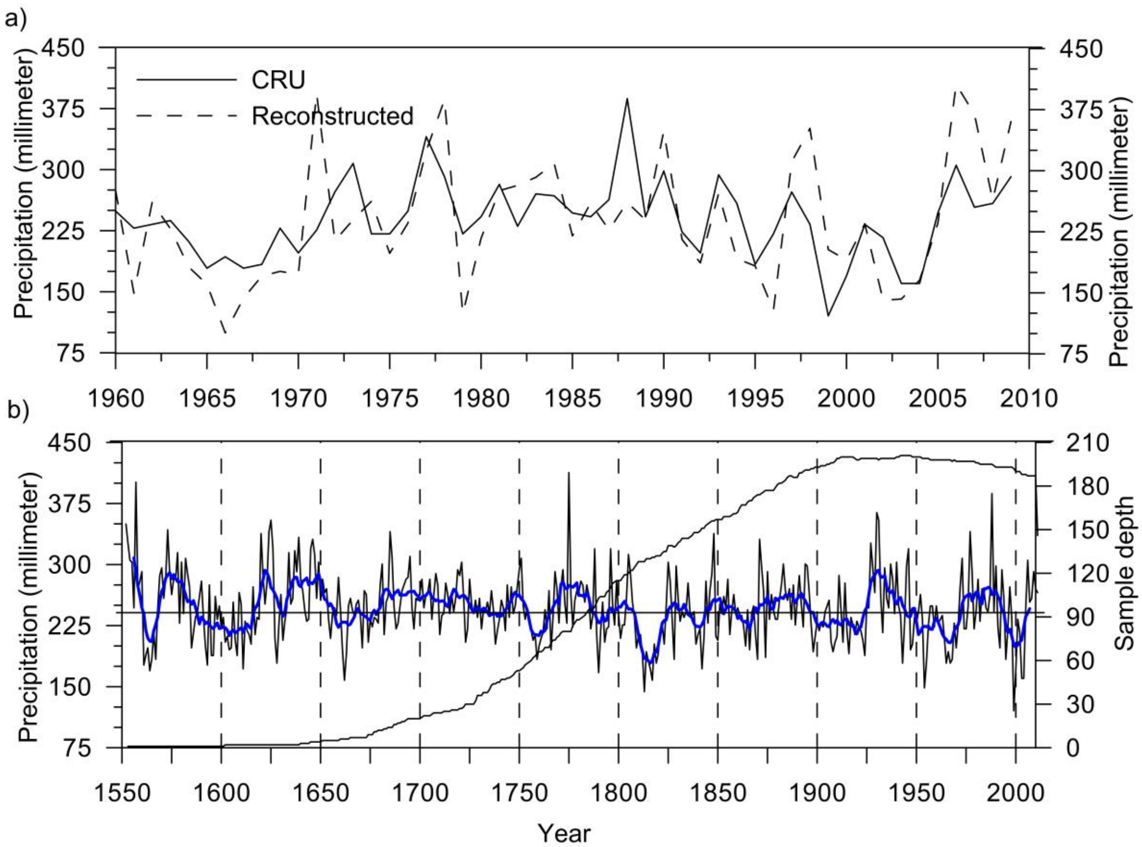

Fig6. 3 (a) Comparison of CRU (solid line) and reconstructed (dotted line) pre-monsoon precipitation (mm). The AD1960–2009 calibration model was used for the reconstruction. (b) The pre-monsoon precipitation reconstruction (AD1552-2009) for the Nepal Himalayas along with 9-year moving average (thick solid line)

6.3.3. The pre-monsoon reconstruction and its linkages with local and regional rainfall indices

The pre-monsoon precipitation from the central Himalayas showed significant correspondence with larger-scale indices that were typically used to represent Indian and south Asian monsoon rainfall. It had higher correlations with the IITM (Sontakke et al. 2008) east Uttar Pradesh March-May rainfall index ($r= 0.23$, $p< 0.06$) and North central India rainfall index ($r= 0.25$, $p< 0.06$), respectively. In particular, the reconstruct had stronger correlation ($r =0.35$, $p< 0.006$, $n=57$) with rainfall index of the northern mountain region of India over the period 1950-2006 than other regions of India. Long-term climatic data in Nepal was available in Kathmandu (85.35E, 27.69N, 1360 m a.s.l.).

The correlation between the reconstructed precipitation and March-May precipitation in Kathmandu is 0.44 from 1950 to 2000 ($p< 0.001$, $n = 51$). The strong and significant correlation of the reconstructed precipitation series with Kathmandu and Indian monsoon regional rainfall indices indicates a possible teleconnections.

6.3.4. The possible linkage between drought events and volcanic eruptions

The ice cores from the Green land and Antarctica (Dai et al. 2009) and Dasuopu (Thomson et al. 2000) showed high concentrations of dust, chloride (CL^-), and nitrate (NO^-_3), sulphite (SO_4^{2-}) during the volcanic eruptions in 1810s. The increase of aerosols can change the concentration of cloud condensation nuclei and in turn alter the hydrological cycle of the atmosphere (Charlson et al. 1992). Aerosols act to inhibit precipitation in the sense that they reduce atmospheric precipitable water, decreases cloud droplet size and prolong cloud lifetime. Periods of reduced precipitation and incident of drought phenomenon are also reported by the historical records of droughts in India during the periods 1790-1796 and 1876-1877 and by high concentrations of dust, chloride and $d^{18}O$ in the Dasuopu ice core from southern Tibet (Thomson et al. 2000).

Dry conditions ranging between 1 to 5 years following a volcanic eruption were clearly noted in our reconstruction (for example after Tambora and unknown eruption AD1811-1821, Agung eruption 1964-1967 and Pinatubu eruption 1992). The decrease in precipitation actually began before the Tombara volcano (AD1815) which supported that the climatic impact of an unknown eruption in 1809-10, as described by Dai et al. (1991) and Briffa et al. (1998). Such dry events after the volcanic eruptions also have been well demonstrated in other several studies in Nepal (Shrestha et al. 2000), Southeast Asia (Trenberth and Dai 2007; Buckley et al. 2010), Southeast Asia including India (Schneider et al. 2009) and central Asia (Anchukaitis et al. 2010). We compared our precipitation reconstruction with the Myanmar teak chronology (D'Arrigo et al. 2011). During the year with the large-scale volcanic eruptions, both of the series showed decreases in precipitation as well as ring-width indices (Fig 6.4). Shi et al. (2012) also showed the dry conditions during the 1810s in southeastern Tibetan plateau possibly due to impact of the volcanic eruptions on the monsoon flow. Several General Circulation Models (GCMs) also predicted that the large volcanic eruptions should also result in anomalous dry conditions throughout much of monsoon Asia (Oman et al. 2005; Schneider et al. 2009; Fan et al. 2009).

According to large-scale tree-ring based temperature reconstructions, the 1810s is the coldest decade of the past 250 yr to 600 yr in the Northern Hemisphere (Briffa et al. 1998; 2001; Briffa and Osborn 1999; Esper et al. 2002). This cold event was also reported in the Tibetan plateau (Bräuning and Mantwill 2004; Liang et al. 2008, 2009), the Tien Shan Mountains of central Asia (Esper et al. 2002), Japan (Yonenobu and Eckstein 2006) and in the Himalayas (Hughes 2001; Cook et al. 2003; Yadav 2007). A decrease in temperature also reduces the evaporation from the surface and hence decreases the moisture supply, reducing precipitation in the monsoon area and leading to narrower tree rings of Himalayan birch in the central Himalayas.

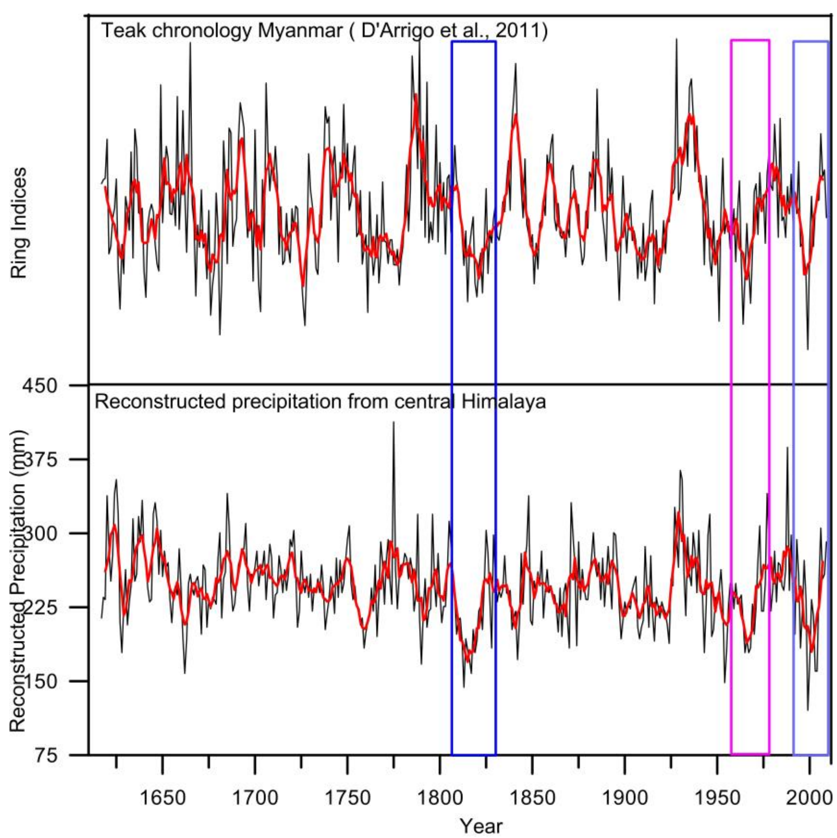

Fig6. 4 A comparison between the reconstructed pre-monsoon precipitation from the central Himalayas and the teak tree-ring chronology of Myanmar (D’Arrigo et al. 2011)

6.3.5. Spectral Analysis

To understand the variability mode in the reconstructed precipitation, the multi-taper method (MTM) (Mann and Lees 1996) spectral analysis was performed over the period AD1700-2009. The spectral analysis showed significant cycles of 3.4, 3.6, 3.9, 26.2, 30, and 42.7, 53.8 years (Fig 6.4). The 3.4-3.9 periodicity falls in the range of ENSO variability (Trenberth 1976) which widely matches with the reconstructed precipitation series from the western Himalayas (Yadav 2011; Singh et al. 2009). The cycle of 42.7 years could be attributed to AMO, which has also been observed in the reconstructed precipitation series from the western Himalayas (Yadav 2011; Singh et al. 2009) and other proxy records (Delworth and Mann 2000; Gray et al. 2004; Hubeny et al. 2006) and model studies (Knight et al. 2005).

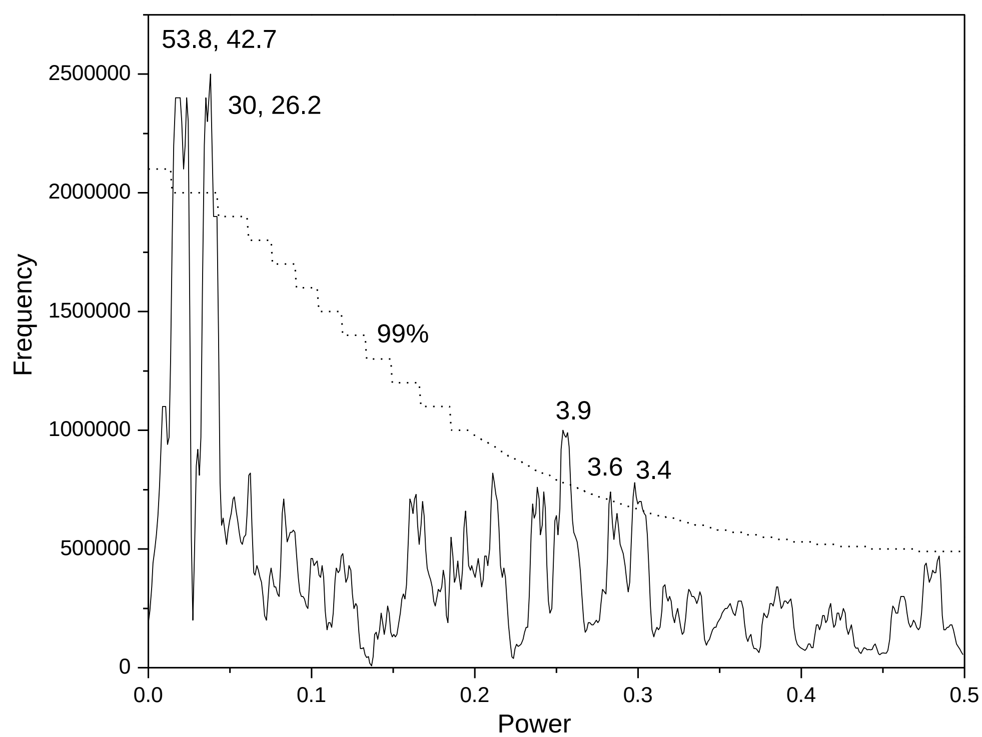

Fig6. 5 MTM Spectral analysis (after Mann & Lees 1996) of the reconstructed pre-monsoon precipitation time series (AD1700-2009). The dotted line indicates 99% significance level

6.4. Summary

We developed a 460-year regional chronology of Himalayan birch collected from timberlines in the central Himalayas. The climate and tree growth relationships demonstrated that the growth of Himalayan birch was an excellent proxy of March-May precipitation, and hence was used for the pre-monsoon precipitation reconstruction. The reconstructed precipitation series showed annual, multiannual to decadal variations. The precipitation reconstruction also revealed dry conditions after the large-scale volcanic eruptions of Southeast Asia. Spectral analysis of the reconstructed series indicated dominant cycles of 3.4, 3.6, 3.9, 26.2, 30, and 42.7, 53.8 years.

Chapter Seven Conclusion and future work

7.1. Major conclusions

7.1.1. Linkages of climatic records along an altitudinal gradient in the southern slope of Nepal Himalayas

In order to investigate climatic linkages between different elevations, we compared the climatic data representing wide range of climatic conditions from sub tropical (130 m a.s.l) to sub-alpine (5050 m a.s.l.) from January 2005 to December 2008. In terms of magnitude of their means and distributions, temperature and precipitation across different altitudes at varying time scales are significantly different to each other. In spite of these differences, the variations of temperature and precipitation are consistent in different altitudes and their agreement increases with lengthening time window. Strong and significant correlation of temperature was observed between elevations [except between low–elevation (plan area) with the mid hills as well as the high Himalayas]. The slopes of the regression model (R^2>0.5) indicated similar changes in temperature between different elevations. As commonly used variable for calibration in dendroclimatic studies, the monthly mean temperature records at lower elevations are better representatives to higher elevations. Precipitation data also showed a similar pattern, although the associations between the stations at different elevations were not as stronger as the temperature, however, significant in most of the cases. In summary, we found that it is possible to use lower-elevation monthly climate records to quantitatively assess those at higher elevations in the central Himalayas. However, variations of climatic records at low-elevation (plane area) can not represent well those in mid hills and the high Himalayas.

7.1.2. Dendroclimatic potential of Himalayan birch from the high hill of central Himalayas

Based on Himalayan birch tree-ring samples from central Nepal, we developed a 458-year chronology that is currently the longest of this species in High Asia. The chronology statistics showed a high dendroclimatic potential. The tree-ring growth of Himalayan birch demonstrated positive and significant ($p<0.001$) response to pre-monsoon precipitation. The growth of timberline trees generally showed positive response to temperature. However, beyond our expectation, tree rings of timberline Himalayan birch provide a unique opportunity to show variations of past pre-monsoon precipitation in the Nepal Himalayas.

7.1.3. Precipitation-limited Himalayan birch growth: a global comparison with other timberline trees

Climate signals derived from tree-ring width of timberline Himalayan birch supported our hypothesis that its growth was primarily controlled by moisture stress rather than by low temperature. Its growth at the timberlines is primarily controlled by moisture availability during the pre-monsoon season, being different with tree growth across the Tibetan Plateau, surrounding polar areas as well as other alpine timberlines. Such a climatic response at timberline is closely related to the world's largest elevation gradient in association with decreasing precipitation with increasing elevation (above 2000-3000 m a.s.l). On the other hand, it is related to the ecophysiological trait of Himalayan birch preferring to grow in the rain shadow. Given a wide distribution of Himalayan birch forest in the Himalayas, its timberline represent an exceptional case to investigate mechanism driving timberline formation.

7.1.4. Precipitation reconstruction for the Central Himalayas

Based on Himalayan birch collected from the Sagarmtha National park, Langtang National park and Manaslu conservation area of the central Himalayas, we developed 460-year regional mean chronology. Based on strong relationship between the regional birch chronology and pre-monsoon (March-May) precipitation, we reconstructed spring precipitation back to 1552AD. This is, to date, the first precipitation reconstruction using this species and the first precipitation reconstruction from the central Himalayas. The reconstructed precipitation series showed annual, multiannual to decadal variations. The years 1999, 1813 and 1954 experienced the driest springs whereas 1775, 1557 and 1988 the wettest years. The reconstructed series showed AD1811-1821 and 1995-2005 are the driest decades. The decrease in precipitation was in phase with the unknown volcanic eruption around 1809/10 and the Tambora eruption, suggesting that the subtropical and tropical volcanic eruptions may cause dry conditions in the central Himalayas. The reconstructed precipitation also showed significant correlation with March-May precipitation in Kathmandu and other large-scale regional indices that were used to represent the South Asian monsoon rainfall.

7.2. Summary

The often cited code in the dendroclimatology is "lack of meteorological data near the sampling site". We found that variations in temperature and precipitation records at lower elevations can be use to represent those at higher elevations and hence can be used for paleoclimatic calibration. Himalayan birch is a broadleaf species, widely distributed in the Himalayan region. However, little was known about its dendrochronological potential. In this study, a timberline Himalayan birch tree-ring network (7 sites) was developed, showing a high dendrochronological potential. Tree growth at all the sites responds positively to pre-monsoon precipitation and inverse relation with pre-monsoon temperature. Thus, its growth at the timberlines is primarily controlled by moisture availability during the pre-monsoon season, being different with tree growth at other alipine and arctic timberlines. High percentage of missing rings in the recent drought years further confirmed that the growth of Himalayan birch is controlled by moisture availability in spite of their high elevations. Except for one birch site at a windward slope, 6 Himalayan birch standard chronologies were averaged to develop a regional chronology, showing significant correlation ($r= 0.61$, $p<0.001$) with pre-monsoon (March-May) precipitation. The reconstructed precipitation series showed annual to decadal variability and captured most of the local and regional drought events. It also exhibited strong and significant correlations with March-May precipitation in Kathmandu and the Indian regional summer monsoon indices for the same season. Several dry years were in agreement with large volcanic eruptions of Southeast Asia [Indonesia (Tombara, Agung) and Philippines (Pinatubo)]. Our precipitation reconstruction showed insights into hydroclimatic variations and their driving forcing in the central Himalayas.

7.3. Future research objectives

This research developed the network of Himalayan birch from the central Himalayas and proved its dendroclimatic potential. Based on this thesis, the following future research plans are purposed.

- Further extend tree-ring network of Himalayan birch in wider geographical areas.
- Explore other species for dendroclimatic studies from the central Himalayas.
- There is a large altitudinal variation within a short S-N transect in central Himalayas. Therefore, tree growth responses to climate along altitude gradients will be interesting topics in the central Himalayas.
- Develop the multi-species chronologies spanning several centuries to millennia from the central Himalayas

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Curriculum Vitae

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ACADEMIC QUALIFICATION

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Post Graduate	Centre for Space science and technology education For Asia and pacific (Affiliated to the United Nation) India.	2009	Satellite Meteorology and global Climate
M.Sc	Tribhuvan University Kathmandu Nepal.	1999	Meteorology
B.Sc	Tribhuvan University Kathmandu Nepal.	1997	Physics, Mathematics, Meteorologgy

AREAS OF MAJOR INTEREST

- Dendrochronology/ dendroclimatology

- Climate change impacts, mitigation and adaptation

PROFESSIONAL EXPERIENCE *(starting with the recent)*

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Sept, 2004-Update	Central Department Of Hydrology and Meteorology Tribhuvan University	Lecturer	Teaching/Research/Supervising graduate student
Dec, 2000 – Aug, 2004	Department Of Environmental Science, Amrit Campus, Tribhuvan University	Assistant Lecturer	Teaching/Research/Supervising undergraduate student
May, 2000 – Nov,2000	Bagmati Integrated Watershed Management Programme. (A joint Project Government of Nepal and European Union)	Hydrology Field Technician	Conducting field Level activities Like meteorological data collection, discharge measurement, Separating Land use pattern Using GPS etc.

PROJECT HANDLED

- Project coordinator "Hydro Climatic reconstruction over Manaslu region, Central Himalaya, Using high altitude Conifer" Under research-grant scheme funded by **Nepal Academy of Science and Technology (NAST), Nepal** (2010-2011)
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- Project coordinator "Studies on Ground Water Contamination by Agro-Chemicals and other anthropogenic sources and its impacts on soils, quality of raw foods and Human Healths" Funded By National Agricultural Research and

Development Fund (NARDF), **Ministry of Agriculture and Co-operatives, Government of Nepal** (2004-2008).

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- **Dawadi** B. 2004 Study of Drought over Nepal Using Water balance Technique, Proceeding of 4^{ith} National Conference on Science and Technology, p1522-1538.

PAPER PRESENTATION IN INTERNATIONAL CONFERRENCES

- "Variability of Pre-monsoon precipitation inferred from Himalayan Birch from the Mt Everest region, Central Himalaya" in 3rd International Asian dendro-chronological Conference, 11-14 April 2013, **Teharan Iran**.

- Climatic records and linkage along an altitudinal gradient in the southern slope of Nepal Himalaya and their implication for paleo-climatology'. International Conference on "Climate Change in High Altitude" 3-6 September 2012. Bjerknes Centre for Climate Research, University of **Bergen, Norway.**
- Relationship between climate change and socio-natural activities in Nepal: Tourism perspective" In International workshop on Climate Change and Sustainable Management of water Resources in the Asia- Pacific region" 22-24 November, 2011, **Islamabad, Pakistan.**
- Dendroclimatic potentiality of Birch (*Betula utilis*) from the high hill of Central Himalaya, Nepal" in 2nd International Asian Dendrochronological Conference, August 20-23, 2011, **Xi'an, China.**

Professional Membership

- Life Member: Society of Hydrologist and Meteorologist Nepal (SOHAM- Nepal)
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