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Article

Strong link between large tropical volcanic eruptions and severe droughts prior to monsoon in the central Himalayas revealed by tree-ring records

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A B S T R A C T

Large tropical volcanic eruptions can cause short-term global cooling. However, little is known whether large tropical volcanic eruptions, like the one in Tambora/Indonesia in 1815, cause regional hydroclimatic anomalies. Using a tree-ring network of precisely dated Himalayan birch in the central Himalayas, we reconstructed variations in the regional pre-monsoon precipitation back to 1650 CE. A superposed epoch analysis indicates that the pre-monsoon regional droughts are associated with large tropical volcanic eruptions, appearing to have a strong influence on hydroclimatic conditions in the central Himalayas. In fact, the most severe drought since 1650 CE occurred after the Tambora eruption. These results suggest that dry conditions prior to monsoon in the central Himalayas were associated with explosive tropical volcanism. Prolonged La Niña events also correspond with persistent pre-monsoon droughts in the central Himalayas. Our results provide evidence that large tropical volcanic eruptions most likely induced severe droughts in the central Himalayas prior to monsoon.

***Keywords*:** Tree ring; drought; tropical volcanic eruptions; Central Himalayas

1. Introduction

Strong volcanic eruptions are natural driving forces of climatic variability [1]. Eruptions of tropical volcanoes cause large-scale surface cooling by altering the Earth’s radiation balance [2]. One of the more explosive tropical volcanic eruptions in the last 500 years is the Tambora eruption of April 1815, which resulted in the so-called “year without summer” in many locations around the world in 1816 [2]. At the same time, variations in response to shortwave radiative forcing, such as those induced by volcanic aerosols, are considered to be more effective than changes in the amount of greenhouse gases in altering precipitation [3]. As shown by observations and model simulations, large eruptions of tropical volcanoes may act as a trigger in causing exceptional drought or precipitation decline in the Asian monsoon area, including the Himalaya region [4,5]. The Himalayas would then be a prime region to test influences of large tropical volcanic eruptions on hydroclimatic anomalies. Hypothetically, these studies suggest that the largest tropical volcanic eruptions in the past 500 years, namely the 1809 and 1815 eruptions, would have caused droughts in the central Himalayas. However, a lack of precipitation records with high temporal resolution in the central Himalayas prevents this model simulation from being rigorously tested.

Annual and pre-monsoon precipitation in the central Himalayas increases from the southern plain areas up to 2,000-3,000 m elevation. Above 2,000-3,000 m, however, precipitation decreases with increasing elevation [e.g. 6]. With central Himalayan timberline located between 3,900 and 4,200 m, it is not unreasonable to consider that moisture availability could be an important limiting factor on tree growth. We recently developed a tree ring network at timberline in Nepal that reflects this relationship: growth of timberline Himalayan birch trees was limited by moisture availability [6]. As a result, our network offers a rare opportunity to reconstruct past precipitation for the region and then to test the hypothesis that the Tambora eruption and other large tropical explosive events caused severe droughts in the central Himalayas.

2. Materials and methods

The study sites are located in three remote, high-elevation nature reserves (Sagarmatha, Langtang, and Manasulu) along three valleys in central Nepal. These reserves are close to well-known mountain peaks, such as the Mount Everest (8,848 m a.s.l.), Langtang Lirung (7,246 m) and Manasulu (8,150 m) (Fig. 1). Annual precipitation is around 780 mm at Kyangjing (3,920 m) close to site LT1 in the Langtang National Park, and 343 mm from 2005 to 2008 at the Pyramid meteorological station (5,050 m) in the Sagarmatha National Park [6]. As derived from a regional mean from averaged CRU gird point data, the study area is characterized by dry winter and pre-monsoon seasons, and an annual mean temperature of 7.2 °C (Fig. S1 online).

Himalayan birch (*Betula utilis* D. Don) is an endemic tree species in the Himalayas. Undisturbed and pure Himalayan birch forests form abrupt treelines within a belt between 3,900-4,200 m where the forest coverage is more than 30%. We collected increment cores from upper timberline Himalayan birch in the Sagarmatha (4 sites) and Langtang (2 sites) National Parks, and Manasulu (3 sites) Conservation Area to create a network of nine sites across the central

Himalayas [6]. These sites are located in the rain shadow on southwest- or west-facing slopes. At each site, 15-30 dominant birch trees were selected and one or two increment cores were taken from each tree. Altogether, 292 cores were collected from 211 trees.

Tree-ring data were processed by standard dendrochronological methods. After visual crossdating, the tree-ring widths were measured to an accuracy of 0.01 mm using a LINTAB measuring system (Rinntech, Heidelberg, Germany). Tree-ring boundaries were easily distinguished when the core surface was kept moist. Crossdated measurements were verified using the COFECHA program [7]. Tree-ring width data were standardized using the program ARSTAN [8] to remove growth trends related to age and stand dynamics while retaining the common signal. A smoothing spline of 67% of the series length was applied for detrending the individual tree-ring series because some trees grew in a fairly dense forest and showed evidence of endogenous disturbance [9]. Standardized individual tree-ring series were then averaged into standard site chronologies.

To determine the climate–tree growth relationships, bootstrapping correlations were calculated between the nine standard chronologies and monthly climate data obtained from the CRU TS 3 at 0.5° spatial resolution [10] from 1960-2009 (Fig. 1). An average of eight grids was used to present variations in regional temperature and precipitation at high elevations in the central Himalayas. Based on signal strength of pre-monsoon precipitation [6], and significant correlations between the chronologies (Fig. S2 online), a regional mean chronology (RC) derived from six standard birch tree-ring chronologies was used to reconstruct variations in pre-monsoon precipitation by linear regression (Fig. 2). The record of pre-monsoon precipitation (1960-2009) was split into two sub-periods for independent validation. To test the stability of the model over the entire record, we calibrated the regional chronology using two different 30-a periods (1960-1989 and 1980-2009), and then verified on the remaining 20 years for each calibration. Pearson's correlation coefficient (r) as well as the reduction of error (RE), coefficient of efficiency (CE) and sign test statistics were applied to validate the reconstructed time series [9].

Superposed epoch analysis (SEA) [11] was used to evaluate the influence of explosive volcanic eruptions on the hydroclimate in the central Himalayas. The statistical significance of the temporal relationships between drought events and volcanic eruptions was tested by a conventional bootstrapped resampling with replacement [11] where confidence intervals are calculated by repeating the SEA using repeated (n = 10,000) random draws of pseudo - "event" years from the available time span. Significance is then evaluated by comparing percentiles from the random draw to the composite mean of the real data. The SEA was performed in the R version 3.1.3 using package dplR (R Development Core Team 2015, R: A Language and Environment for Statistical Computing. http://www.R-project.org/. R Foundation for Statistical Computing, Vienna, Austria.). The input data included tree-ring based pre-monsoon precipitation reconstruction, large tropical volcanic events from Fischer et al. [12] and the reconstructed eastern tropical Pacific SST (sea surface temperature) since 1650 [13].

3. Results and discussion

3.1 Pre-monsoon precipitation reconstruction in the central Himalayas

All nine chronologies correlated positively and significantly with March-May (pre-monsoon) precipitation. Of these, four were also negatively and significantly correlated with March-May mean temperature [6]. Our findings were supported by other work in the central Himalayas where the growth of *Abies spectabilis*, *Pinus roxburghii*, *Pinus wallichiana* and *Picea smithiana* was also limited by pre-monsoon precipitation [14-16]. It seems likely that these results differ from studies in cold biomes in the Northern Hemisphere [e.g.,17-19] because of the reduction of precipitation in higher elevation in the central Himalayas and that most of our sites are in rain shadow locations. Further, work in high elevation mountains in the American west indicate that upper timberline trees in some locations were more limited by moisture than cool temperatures [20,21]. Additionally, weekly xylogenesis monitoring at drought-prone forest sites indicates that spring drought stress can delay the onset of cambial cell division, cause the occurrence of locally missing rings, or restrict radial growth during the growing season [22-24], highlighting the critical role of precipitation in controlling tree growth, even at high elevation. Indeed, a high frequency of locally missing rings of Himalayan birch in our research sites was associated with dry and warm pre-monsoon conditions [6]. Finally, the treeline-shift rates of Himalayan birch were primarily mediated by spring precipitation [25]. Taken together, spring moisture controls the growth and survival of Himalayan birch at timberlines and hence its ring width will be a promising proxy to spring precipitation.

Based on our analyses here and previous results [6], we developed a spring precipitation-sensitive regional tree-ring width chronology of Himalayan birch. Excluding three records from the southeast facing slopes where birch growth is less limited by moisture [6], the regional average chronology of the remaining six sites shows a significant correlation to pre-monsoon precipitation (r=0.61, P<0.001, 1960-2009) (Table 1, Fig. 2a), and a non-significant correlation to mean temperature of the pre-monsoon season (r=-0. 23, P>0.05; 1960-2009) (Fig. 2). Together, the positive correlation to precipitation, and negative correlation to temperature represents the classic drought-stress signal in trees, although the weak temperature correlation indicates that precipitation more strongly controls the regional growth of birch. When we combine all series from the network into a regional chronology, the resulting chronology has five trees present at 1650 and an EPS>0.85 since 1700. The creation of this record enables a multi-centennial and annually resolved reconstruction of pre-monsoon precipitation for the eastern-central Himalayas (Fig. 3).

The ability of the regional chronology in estimating pre-monsoonal moisture is confirmed by statistical tests of the reconstruction models, such as the Pearson's correlation coefficient (r), reduction of error (RE), coefficient of efficiency (CE), sign test statistics [9], and returned significant values for all periods (Table 1). Over the entire instrumental period, the linear regression model captured 37% (P<0.001) of the total variance. Our pre-monsoon precipitation reconstruction is spatially representative for the central Himalayas and northeastern India along the prevailing pattern of atmospheric moisture transport from the Bay of Bengal (Fig. S3 online). The statistically-verified reconstruction allows us to evaluate the coupling between major tropical volcanic eruptions and hydroclimatic conditions in the central Himalayas.

Our reconstruction contains several well-documented drought events in southeast and south Asia, such as the Strange Parallels drought (1756-1767), the East India drought (1790-1795) [26], and sustained droughts in Nepal during the last 60 years (1954-1971 and 1995-2004) (Fig. 3). However, it did not show the late Victorian Great Drought (1876-1878) that occurred during one of the most severe El Niño events [26]. The response of the trees in our network to the recent drought events helps to underscore the accuracy of our reconstruction (see Fig. 2 – overlay of RC and instrumental record of precipitation).

3.2 Coupling between drought and large tropical volcanic eruptions

In examining our reconstruction, we found that 11 large tropical volcanic eruptions (eight in Southeast Asia and three in tropical America) since 1650 were associated with dry conditions or a decline in precipitation in the central Himalayas. Of the eight large tropical volcano eruptions in Southeast Asia determined by Fischer et al. [12], six were linked to droughts (defined here as >1.0 standard deviation less than the long-term average since 1650). One weak eruption in 1831 corresponds to 0.35 standard deviations below the average in precipitation based on our reconstruction (Fig. 3b). While we did not find a significant drought in the central Himalayas after the Krakatau eruption in 1883, precipitation did decline following the Krakatau event (Fig. 3b). Three volcanic eruptions in tropical America, 1835, 1902, and 1982, correspond to a precipitation decline of 0.35-1.1 standard deviations below the long-term mean. These results support model predictions that dry conditions would follow explosive volcanism [27]. Similarly, superposed epoch analysis suggests that dry conditions can occur after a volcanic eruption (Fig. 4a).

Our results indicate that large volcanic events may reduce moisture availability in the central Himalayas. These findings support early work using a tree-ring width network developed from 11 tree species in Nepal where widespread growth suppressions were evident in the early 1800s [28]. These growth suppressions corresponded with the most severe drought in our reconstruction that occurred from 1809-1823. Over this same period, there were three large volcanic eruptions: an unknown eruption in 1809, the Tambora eruption in 1815, and an eruption in 1822 in Southeast Asia. Long-term changes in high-elevation tree-ring δ^{18}O record showed a trend of weakened Asian summer monsoon intensity since 1820 in the central-western Himalayas [29]. The volcanic eruptions in 1809 and 1815 induced substantial global cooling [2,30-32], especially cooling in the Himalayas and the Tibetan Plateau [33-36]. Ice cores on the Tibetan Plateau show a strong signal from the influence of the Tambora [36]. Because of the negative correlation between temperature and the growth of Himalayan birch in our network, a period of cooling or a cool year should increase growth. However, we did not find such a response. It stands to reason that the dampened growth response of these trees during this period is the result of reduced precipitation. Drought-sensitive tree-ring records in the western Himalayas [37], northeastern Tibetan Plateau [38-42], and parts of Monsoon Asia [5] indicate drier conditions around this period.

Apart from the signals of the Tambora eruption, we observed fingerprints of other large tropical volcanic eruptions (Fig. 3b). In particular, drought events occurred after the eruptions in 1963, 1982, and 1991. Following the 1991 Pinatubo eruption, Nepal and northern India had an exceptionally dry year in 1992 and a remarkable cooling covered the Tibetan Plateau at the same time [43]. As observed by Trenberth and Dai [4], there was also a substantial reduction in the strength of the global hydrological cycle after the Pinatubo eruption. The eruption of El Chichon in April 1982 coincided with a significant drop in precipitation in Nepal, India, and a slight drop in temperatures on the Tibetan Plateau [43]. Although these dry conditions were not as severe as those after the 1809+1815 double eruptions, our precipitation reconstruction reveals reduced precipitation following all 11 large tropical volcanic eruptions since 1650.

3.3 Forcing for eruption-related drought

A strong coupling seems to exist between drought events and not only large tropical volcanic eruptions but also the cold phase of ENSO. The millennial simulations showed the cooling in the tropic Pacific and decreases in precipitation in the tropical and subtropical regions (including the central Himalayas) after large volcanic eruptions [44]. As shown by spatial correlation analysis (Fig. S4 online), pre-monsoon drought in the central Himalayas is strongly linked with cold SSTs from previous October to February in the eastern tropical Pacific. However, it still remains inconclusive as to whether or not there is a causal link between volcanic activity and the ENSO events [1,45,46]. A recent study based on proxy data and model simulation, however, clearly showed that a La Niña-like state occurred in the second year after large tropical volcanic eruptions during the past 1500 years [47]. The cold SSTs in the East Pacific may have caused the Asian drought from 1998 to 2001 [48]. Our reconstructed pre-monsoon precipitation series shows that several drought periods were associated with prolonged La Niña events. As an example, a part of the widespread mid-latitude drying, the 1998-2004 drought period in central Nepal coincided with a protracted cold phase of ENSO (La Niña) from 1999-2002 [49]. The strongest La Niña years 1999 (March-May), 1995, and 2010-2011 were indeed in phase with droughts in Nepal. During the 20th century, La Niña conditions spanning three consecutive years (1908-1910, 1954-1957, and 1973-1975) [49] corresponded with severe droughts in our study area. A superposed epoch analysis also confirms a significant coupling between drought events since the early 20th century and cold SST in the eastern tropical Pacific [13] (Fig. 4b).

A long-lasting effect of tropical volcanic eruptions may be related to a persistent cooling of eastern tropical Pacific SST [50-52]. Pre-monsoon drought in the central Himalayas is also coupled with cold SST of the Indian Ocean (Fig. S4 online). On the other hand, the aerosol-induced energy imbalance between the northern and southern hemispheres can slow down the tropical atmospheric circulation [53]. As a result, the rain belt may have not risen to its altitude during boreal late spring and early summer in the central Himalayas. Other effects may include increased stability of the atmosphere, reduced evaporation, and 'spin-down' of the local Hadley cell circulation, all of which would have weakened the Indian monsoon [50]. It showed that the Hadley circulation is usually weaker for La Nina than El Niño events [54]. In addition, pre-monsoon drought in the central Himalayas showed the teleconnection with Atlantic Multidecadal Oscillation [14] (Fig. S4 online). However, this study cannot answer why large volcanic events reduced pre-monsoon precipitation at high altitudes in the central Himalayas rather than in other regions. It is necessary to have further modelling studies to investigate the coupling mechanism between large tropical volcanic eruptions and pre-monsoon drought in the central Himalayas.

In summary, this study shows a significant linkage between large tropical volcanic eruptions and dry conditions during the pre-monsoon season in the central Himalayas. In particular, the most persistent and severest pre-monsoon drought in the central Himalayas since 1650 followed the Tambora eruption, the strongest volcanic eruption in the tropics during the past 500 years. It may relate to a persistent cooling of the eastern tropical Pacific and Indian Ocean after volcanic eruptions. This presents a new case study that can serve to increase a fundamental understanding of Earth's hydrological cycle and its long-term dynamics over the world's largest elevation gradient in the central Himalayas.

Conflict of interest

The authors declare that they have no conflict of interest.

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Author Contributions

E.L. designed research; E.L. and B.D. performed research; all authors analyzed data and wrote the paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/----.

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Table 1. Calibration/verification statistics for the pre-monsoon precipitation reconstruction; the calibration was performed over two 30-year and one 50-year intervals, and the verification over two 20-year intervals.

	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-	38+/12- (P<0.01)

Figure captions:

Fig. 1 Location of the Himalayan birch sites and of the CRU grid points as well as of two high-elevation meteorological stations at Kyangjing in the Langtang valley and at Pyramid in the Mt. Everest area in the central Nepalese Himalayas. Triangles show the peaks of Mt. Manaslu, Mt. Langtang Lirung and the world's highest peak Mt. Everest (from the left).

Fig. 2 Pre-monsoon precipitation signals recorded by the regional chronology. (a) Correlations between the regional chronology and monthly and seasonal temperature and precipitation; (b) comparison between the reconstructed and the CRU gridded precipitation in the pre-monsoon season.

Fig. 3 Tree-ring based pre-monsoon precipitation reconstruction in this study. The years for 11 large tropical volcanic eruptions after 1650 [12] are indicated by dotted vertical lines.

Fig. 4 Coupling between dry conditions, large tropical volcanic eruptions and cold SST. (a) Superposed epoch analysis between pre-monsoon precipitation events derived from a regional Himalayan tree-ring chronology and 11 tropical volcanic eruptions (1673, 1809, 1815, 1822, 1831, 1835, 1883, 1902, 1963, 1982 and 1991) selected by Fischer et al. [12] since 1650; Superposed epoch analysis between dry years in the central Nepalese Himalayas and tropical eastern Pacific SST [13]. (b) Dry conditions since the early 20th century occurred in years and in the year before with significant cold SST; * shows significance at $P<0.05$.

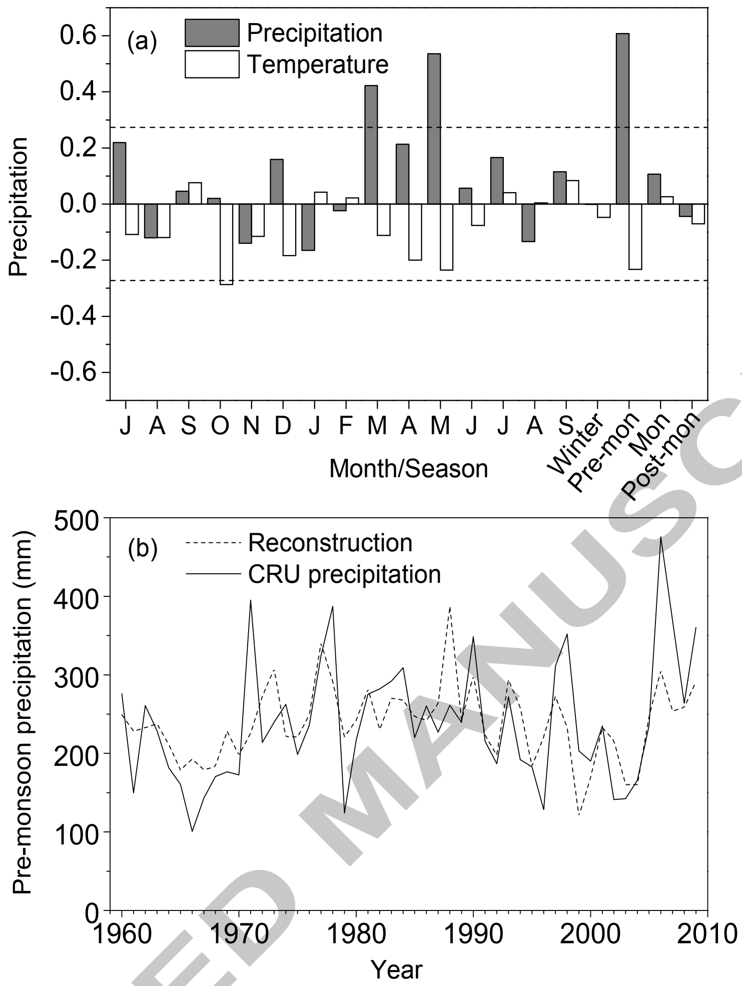
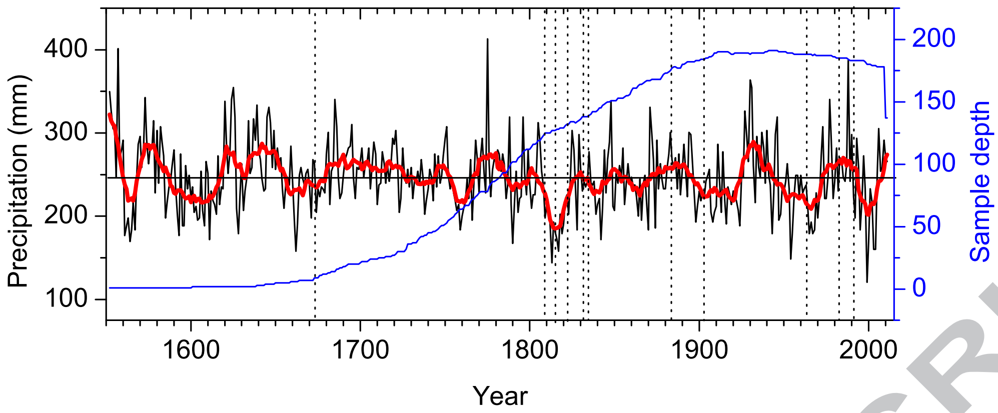

(a)
Precipitation
Temperature
Precipitation
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
J A S O N D J F M A M J J A S Winter Pre-mon Mon Post-mon
Month/Season
(b)
Reconstruction
CRU precipitation
Pre-monsoon precipitation (mm)
500
400
300
200
100
0
1960 1970 1980 1990 2000 2010
Year

Fig. 2



Precipitation (mm)
400
300
200
100
Sample depth
200
150
100
50
0
1600
1700
1800
1900
2000
Year

Fig. 3

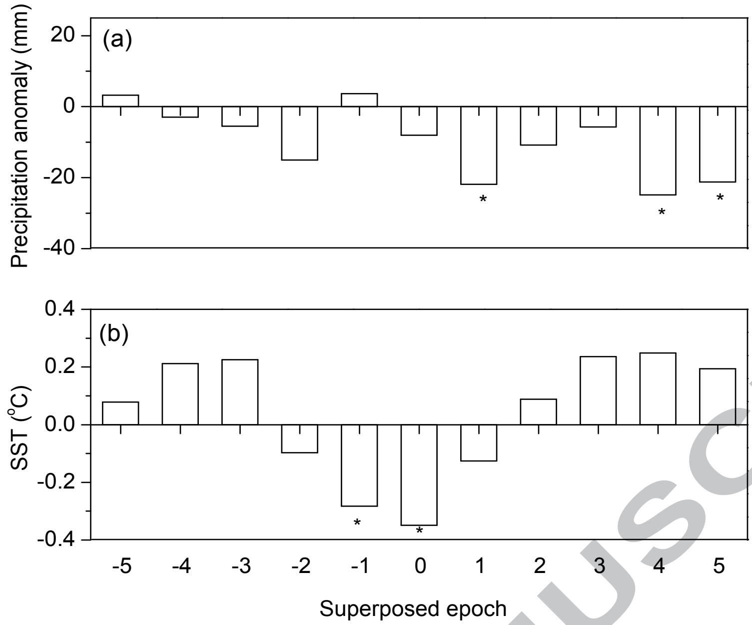
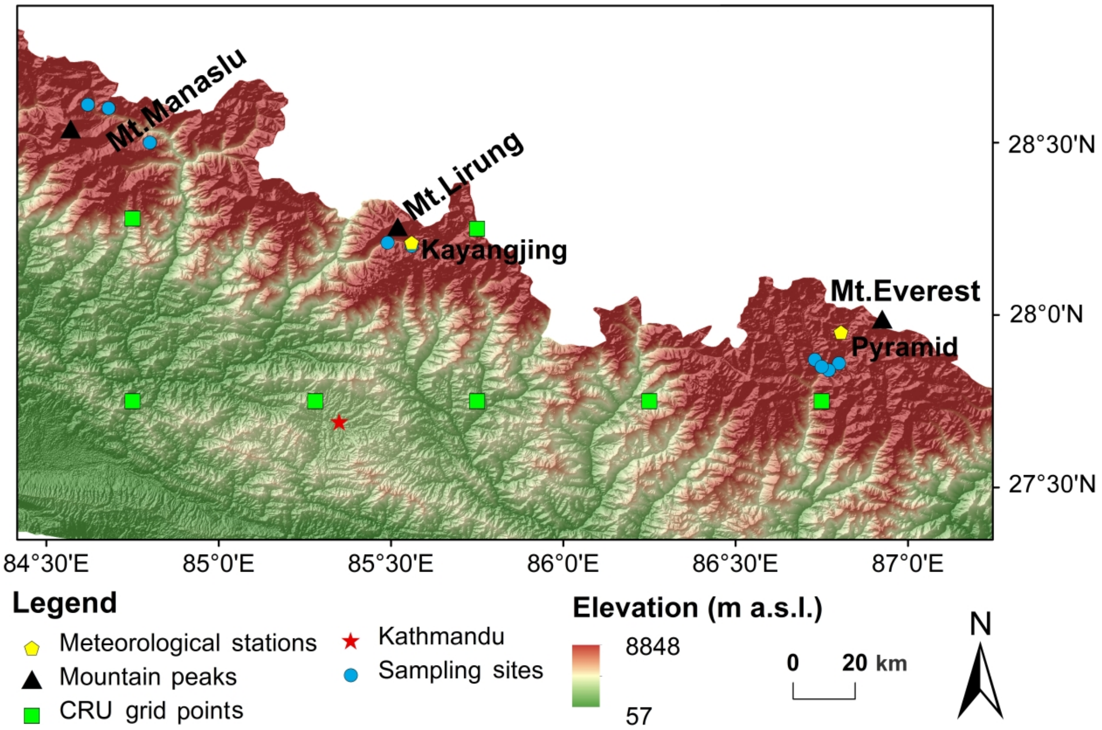


Fig. 4

树轮揭示喜马拉雅山中段季风前干旱与热带火山喷发之间的强关联性

大规模热带火山喷发可以导致短期的全球变冷，然而我们依然不清楚这些火山喷发是否会导致区域性的水文气候异常？此研究基于树轮重建了喜马拉雅山中段 1650 年以来季风前降雨变化，发现季风前干旱的发生与热带火山喷发事件相关联，暗示了热带火山喷发对喜马拉雅山水文气象条件的影响。尤其是，公元 1650 年以来最严重和持续干旱事件发生在坦博拉火山大喷发之后。
关键词：树轮，干旱，热带火山喷发，喜马拉雅山中段


Mt.Manaslu
Mt.Lirung
Kayangjing
Mt.Everest
Pyramid
28°30'N
28°0'N
27°30'N
84°30'E
85°0'E
85°30'E
86°0'E
86°30'E
87°0'E
Legend
Meteorological stations
Mountain peaks
CRU grid points
Kathmandu
Sampling sites
Elevation (m a.s.l.)
8848
57
0
20 km
N