AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER

10.1002/2015GL063566

Key Points:

- First multicentennial temperature reconstruction from Bhutan
- Temperature variations suggest influence of solar and volcanic forcing
- Scare temperature data from the region makes reconstructions difficult

Supporting Information:

- Figures S1–S6

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Citation:
Krusic, P. J., E. R. Cook, D. Dukpa, A. E. Putnam, S. Rupper, and J. Schaefer (2015), Six hundred thirty-eight years of summer temperature variability over the Bhutanese Himalaya, *Geophys. Res. Lett.*, *42*, doi:10.1002/2015GL063566.

Received 19 FEB 2015
Accepted 25 MAR 2015
Accepted article online 27 MAR 2015

Six hundred thirty-eight years of summer temperature variability over the Bhutanese Himalaya

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Abstract High-resolution tree ring reconstructions from the Himalaya provide essential context for assessing impacts of future climate change on regional water reserves and downstream agriculture. Here we evaluate a small network of tree ring chronologies from Bhutan to produce a 638 year summer temperature reconstruction, from 1376–2013 (Common Era) C.E. Relative to the 1950–2013 C.E. average summer temperature three prominent cold periods stand out, two in the midfifteenth century, and one in the late seventeenth century. The warmest period began in the first decade of the 21st century coinciding with the timing of general glacier recession in the eastern Himalaya that continues to the present. The Bhutan temperature reconstruction exhibits a significant correlation to known volcanic eruptions ($p = 97\%$) and anomalously cold periods appear to align with solar irradiance minima in the fifteenth, late seventeenth, and early nineteenth centuries, implying a link between solar variability and decadal-scale temperature variability.

1. Introduction

Development of long-term, high-resolution proxy climate reconstructions are important for discriminating among factors that drive climate change in remote parts of the planet where instrumental records are sparse and short. One such region is the southern slope of the Himalayan arc, where the effects of climate change are predicted to have widespread natural, socioeconomic, and sociohazard impacts [*National Academy of Sciences*, 2012]. The Himalayan Kingdom of Bhutan, located in the eastern monsoonal Himalaya, faces two important and immediate challenges related to climate change. Foremost among these threats are altered precipitation patterns and accelerated glacial melt that together trigger mass-wasting events such as landslides, as well as glacial lake outburst floods, endangering life and cultural heritage [*Komori*, 2014; *Richardson and Reynolds*, 2000; *Ageta et al.*, 2000; *Ives*, 1986]. Second, increasing variability and unpredictability in stream discharge creates challenges for hydropower generation—which threatens the foundation of Bhutan's economic security [*United Nations Development Program* (*UNDP*), 2014].

Atmospheric temperature and precipitation play a fundamental role in modulating runoff from precipitation and snow/glacier melt in the high Himalaya supply water. A large fraction of Earth's human population depends on mountain runoff in the Greater Himalayan Watershed [*UNDP*, 2014; *Bajracharya et al.*, 2014]. Yet the numbers of continuous, high-resolution, well-calibrated, long-term climate reconstructions from this region are few. Furthermore, most extant reconstructions from the Himalaya are concentrated in the western reaches from Pakistan to Uttarakhand, India [e.g., *Borgaonkar et al.*, 1996; *Yadav et al.*, 1997; *Treydte et al.*, 2006; *Singh et al.*, 2009; *Yadav*, 2009], and the southeast corner of the Tibetan Plateau on the north slopes [e.g., *Bräuning*, 2001; *Yang et al.*, 2010; *Ze-Xin et al.*, 2010; *He et al.*, 2013]. Moving eastward from the border between India and Nepal, along the southern flank of the Himalaya, the number of calibrated tree ring reconstructions drops dramatically, e.g., *Cook et al.* [2003] and *Sano et al.* [2005, 2012] in Nepal and *Bhattacharyya and Chaudhary* [2003] in Arunachal Pradesh, India. A cohesive picture of past climate variability over the Himalaya is additionally hampered by the fact that from those regions where more than one multicentennial reconstruction does exist, the reconstructions are rarely of the same climate variable making any robust assessment of synoptic climate patterns over the Himalaya difficult to summarize.

Here we present the first multicentennial tree ring based summer (June–August: JJA) temperature reconstruction for Bhutan. Well-calibrated and verified tree ring reconstructions of Himalayan climate are largely constrained

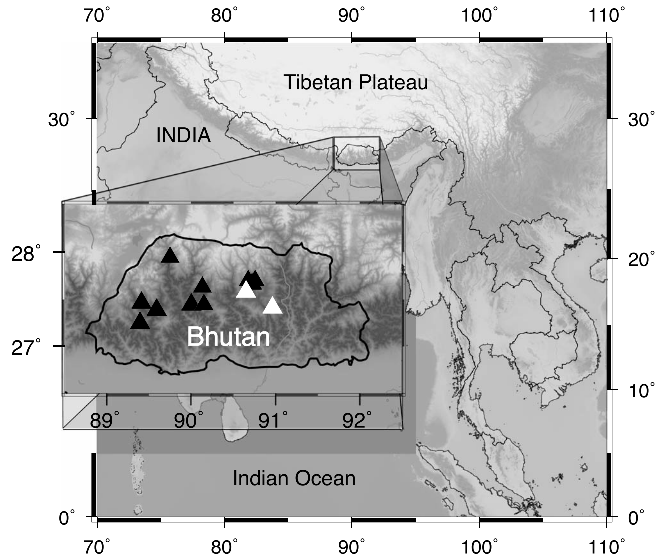

Figure 1. The current Bhutanese tree ring network. The two white triangles locate the Dhur (northmost) and Ura Himalayan spruce (*Picea spinulosa*: Griffith) sites used in this study.

by the scarcity, distribution, and integrity of suitably long instrumental climate records for modeling the tree-growth and climate relationship. Respectable successes in meeting these challenges has been made in the aforementioned examples, and those employing large networks of chronologies and interpolated climate data fields [*Cook and Krusic*, 2008; *Cook et al*., 2010, 2013; *PAGES 2k Consortium*, 2013]. However, the significance of these latter reconstruction efforts has come at the cost of a degraded spatial resolution due to the relatively coarse level (2–2.5°) of climate fields used for reconstruction [e.g., *Cook et al*., 2010, 2013]. The negative consequences of using coarse resolutions can be most acute in the extremely complex orographic conditions of the Himalayas. Here we used the updated (nondegraded) 0.5° × 0.5° Climatic Research Unit (CRU) TS3.22 grid point temperature data set [*Harris et al*., 2014], and an improved tree ring standardization method [*Melvin and Briffa*, 2008], to optimize the tree ring reconstruction of JJA temperatures over Bhutan. Our reconstruction provides a significant contribution to ongoing efforts in modeling the annual to multidecadal sensitivity of Himalayan glaciers, fluvial, and ecological systems to changes in atmospheric temperature. The summer temperature reconstruction can be compared to the variability in regional glacier changes, placing historical glacier dynamics in the context of climatic change.

2. Data and Methods

2.1. Tree Ring Data

With 72.5% of its land covered by forests [*Gilani et al*., 2015] there are few places left in the Himalaya that still retain as much old-growth forest as Bhutan. Thus, Bhutan is an ideal location to search for ancient trees suitable for paleoclimate reconstruction. Since 2002 C.E., we have established a network of 21 tree ring width chronologies from 12 locations in Bhutan. The network contains chronologies from eight tree species, six of which are Himalayan spruce (*Picea spinulosa*: Griffiths). In 2013 C.E. two of the longest spruce chronologies, originally collected in 2002 C.E. and 2003 C.E. (Ura: 90.96°E, 27.42°N, 3440 m (above sea level) asl and Dhur: 90.6509°E, 27.592°N, 3096 m asl) (Figure 1), were updated adding 10 and 11 years, respectively, to each. The common period of the two data sets is 1457–2013 C.E. Following the updates both sites displayed, an improved positive correlation with summer temperatures, and evidence for accelerated warming. This relationship was further improved after combining both chronologies' data into an updated "Dhur-Ura" composite chronology.

The first step in building a chronology is to remove the nonclimatic trend in the radial measurements of each tree that is largely due to the geometric consequence of adding a new layer of wood to a stem of ever increasing diameter (in the sense of *Fritts* [1976] and *Cook and Kairiukstis* [1990]). The attention paid to the "detrending" of ring width measurements is particularly important when working with trees growing in highly productive, ecologically, and geologically active, environments such as the subtropical mountain forests of Bhutan. In these environments, nonclimatic factors affecting tree growth can impose transient extremes of low- and high-frequency variation that are difficult to remove without also removing or dampening the imprint of low-frequency climate variations [*Cook and Peters*, 1981; *Cook*, 1985; *Cook and Kairiukstis*, 1990]. The detrending of each ring width series from Dhur and Ura began with an initial power transformation (PT) of the ring width measurements to stabilize the variance in the series [*Cook and Peters*, 1997]. For each PT ring width series, dimensionless indices of tree growth were computed as residuals from

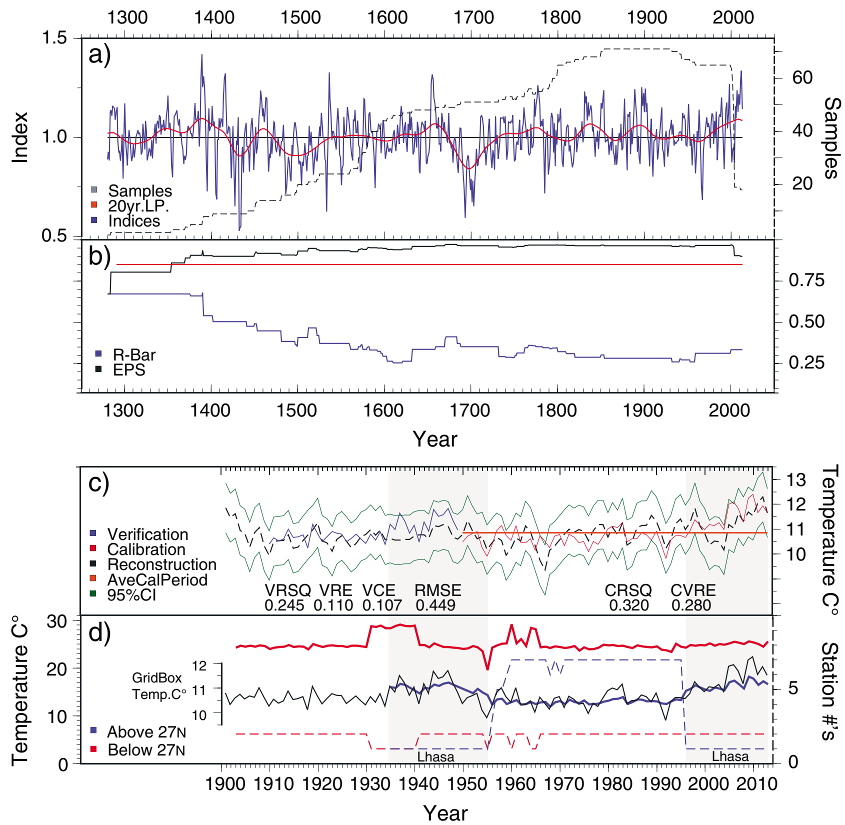

Figure 2. (a) The Dhur-Ura composite chronology with medium-pass smoothing and sample depth. (b) Chronology EPS and constant sample size (50 years) RBAR. (c) The CRU TS3.22 four grid-cell, average annual JJA calibration and verification period temperatures, together with the reconstruction and the reconstruction's 95% confidence interval. (d) The average annual CRU TS3.22 JJA temperatures for all stations above 27 N (solid blue) and below 27 N (solid red), together with the annual changes in their respective numbers of reporting stations (dashed blue: above 27 N and dashed red: below 27 N) from 1901 to 2010. The average CRU TS3.22 four-cell, JJA grid box temperature series used for climate modeling (black: with scale) is plotted over the 27°N average to illustrate the degree to which the Tibetan Plateau stations influence the Bhutan grid box mean.

the fitted growth curve estimated by age-dependent splines [*Melvin et al.*, 2007]. The composite chronology (1280–2013 C.E.) is produced using an implementation of the "signal-free" method [*Melvin and Briffa*, 2008; *Cook et al.*, 2013] with variance stabilization [*Osborn et al.*, 1997; *Frank et al.*, 2007]. The final stabilized, signal-free chronology used to reconstruct summer season temperatures; along with two measures of chronology common signal strength, the average correlation between series (RBAR) and the Expressed Population Signal (EPS) [*Wigley et al.*, 1984], are shown in (Figures 2a and 2b). An EPS above a 0.85 is a rule-of-thumb threshold for determining the portion of a chronology (1376–2013 C.E.) with acceptable common signal strength [*Wigley et al.*, 1984].

2.2. Climate Data

Continuous instrumental records of climate from Bhutan longer than 35 years do not yet exist (Meteorology Section, Hydromet Services Division, Department of Energy Thimphu, Bhutan: www.hydromet.gov.bt). The paucity of long meteorological records in Asia has been a matter of concern [*Cook et al.*, 2003, 2010, 2013] and is the sole motivation for using in their place high-quality interpolated reanalysis products. Of those available the CRU TS3.22 [*Harris et al.*, 2014] has the highest spatial resolution (0.5° × 0.5°) and time span (1901–2013 C.E.) sufficient for calibrating and verifying the new Dhur-Ura updated chronology. We determined which CRU TS3.22 grid cells had the highest correlation with tree growth by first extracting monthly mean temperatures from 32 grid cells covering all of Bhutan and its immediate surroundings. For each grid cell the correlation between the Dhur-Ura updated chronology and mean monthly temperature from the previous March to the current October was calculated. Results from testing the tree ring/climate response revealed that the current year's JJA mean monthly temperature was the most statistically significant season for reconstruction (supporting information Figure S1). The spatial distribution of both prewhitened (serial autocorrelation removed) and non-prewhitened (serial autocorrelation retained) correlations reveals the average interpolated JJA temperatures at grid point #28 (90.25°E, 28.25°N) produce the highest non-prewhitened correlation ($r = 0.540$), and the average JJA temperatures at grid point #26 (89.25°E, 28.25 N) produced the highest prewhitened correlation ($r = 0.472$), both significant at the 99% level.

The spatial distribution of the 32, JJA correlations suggests the temperature signal best captured by the new composite chronology is directionally biased to the north of Dhur and Ura. This northern bias is a likely reflection of the contributions by the high-elevation, high-latitude Tibetan Plateau stations (above 27°N) to the CRU TS3.22 grid point interpolations versus the contributions by the southern subtropical Indian stations (below 27°N) (supporting information Figure S2). On the basis of the individual grid point correlations and giving consideration to the directional bias found in their distributions, we used the mean JJA temperatures of the four grid points just north of the average latitudes and longitudes of the two spruce sites to calibrate and verify the final reconstruction (supporting information Figure S1d, blue box).

2.3. The Reconstruction

To reconstruct mean-annual JJA temperature, we used a modified version of the Point-by-Point Regression (PPR) method [*Cook et al*., 1999, 2010, 2013]. The PPR methodology is sufficiently flexible that it can be used in small-scale experiments where there is a single predictor (a chronology) and a single predictand (a temperature record). Used in this manner the method estimates a simple linear regression model that transforms the tree ring time series into units of the climate time series. For calibration purposes the mean JJA temperatures from 1950 to 2013 C.E., of the four grid points described above, were used in regression to model the tree ring/climate relationship. The four grid point JJA average temperatures from 1910 to 1949 C.E. were withheld from the modeling phase and used to evaluate the skill of the model. The grid cell values from 1901 to 1910 C.E. were not used in this experiment owing to their demonstrably poor representation of summer temperatures over Bhutan (supporting information Figure S3).

Despite the lack of contribution by any Bhutanese meteorological station data to the gridded CRU TS3.22 interpolated temperature field, the JJA Bhutan temperature reconstruction has a statistically acceptable level of fidelity. The calibration period R^2 (CRSQ = 0.32) and the cross validation reduction of error (CVRE = 0.28) (functionally equivalent to Allen's PRESS [*Allen,* 1971]) are each significant at the 90% level. Over the verification period measures of explained variance by the prediction, the square of the Pearson correlation (VRSQ = 0.245), the reduction of error (VRE = 0.110), and the coefficient of efficiency (VCE = 0.107) are all positive indicating the tree ring model has reconstruction skill (Figure 2c). That the spruce trees in Dhur and Ura only capture 25% to 30% of the annual variation of the interpolated JJA temperatures is not necessarily surprising given the environmental conditions under which the trees are growing and the degree to which the CRU TS3.22 grid box values accurately represent average JJA temperature over the two sites. This uncertainly extends not only across the region but also through time as the number of high-latitude, high-elevation stations contributing to the four-cell grid box average over Bhutan varies from a maximum of eight (1960–1995 C.E.) to as low as 1 from 1935 to 1945 C.E. and 1996 to 2013 C.E. (Figure 2d).

We examined in more detail the relationship between the Dhur-Ura reconstruction and the CRU TS3.22 grid box average JJA temperatures using the Kalman filter (KF) [*Van Deusen*, 1987; *Visser and Molenaar*, 1988]. In this context the KF serves as a dynamic regression-modeling tool. It uses maximum likelihood estimation to objectively test for significance in the statistical association between two time series and in so doing explicitly evaluates their association for the presence of time dependence. The KF provides theory-based uncertainties on the regression coefficients as they evolve over time, thus allowing for the objective detection of time dependence in the association. See *Visser and Molenaar* [1988] for details. Our KF results find the dynamic regression model relating the Dhur-Ura reconstruction to CRU TS3.22 grid box average JJA temperatures is statistically significant at the ±2 standard error limit from 1940 to 2013 C.E. but becomes marginally nonsignificant prior to 1935 C.E. (supporting information Figure S3). This performance suggests the Tibetan Plateau stations, in particular Lhasa (275 km north. 3649 m asl.), are the most influential stations affecting the grid box mean during the calibration period (Figure 2d). Since there are no Tibetan Plateau stations contributing information to the CRU TS3.22 grid box average prior to 1935 C.E., we assume the spatial

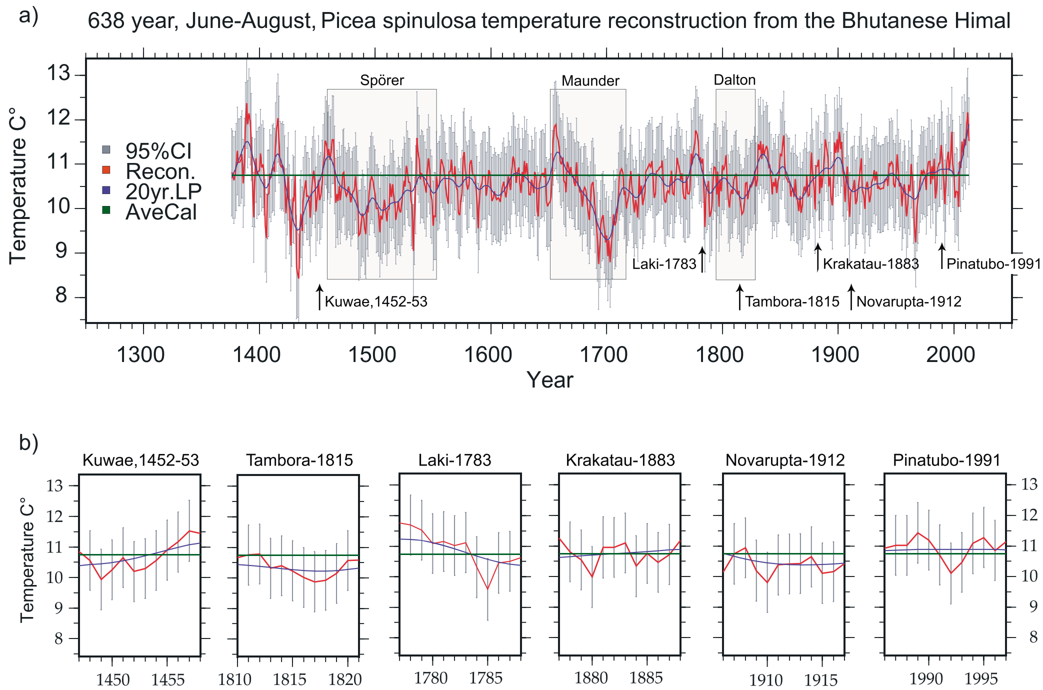

Figure 3. (a) The new, updated Dhur-Ura, Bhutan, June–August temperature reconstruction with 20 year low-pass filter and 95% prediction intervals, along with the calibration period mean. Overlayed above the reconstruction are the relative time spans of the Spörer, Maunder, and Dalton solar minimums, and the years of the six volcanic eruptions used in the SEA experiment. (b) The lower six panels provide exploded views of the reconstruction values in Figure 3a surrounding the same six eruptions.

interpolation of information from neighboring Indian stations to the south and west dominates the verification period (1910–1935 C.E.) grid box values. Thus, a reasonable explanation for the weaker verification period results may be supported by this shift in station contribution.

3. Results

Despite the less-than optimal composition of the calibration and verification-temperature record, the Dhur-Ura updated reconstruction captures a reasonable degree of annual to multidecadal temperature variations across a large portion of southeast and central Asia (supporting information Figure S4). Evidence of the reconstruction's spatial significance can be found in the correlations between the reconstructed JJA temperatures over Bhutan (this study) and interpolated JJA temperatures from two, but not fully independent, gridded temperature data sets covering much of southern and central Asia. In all experiments, the highest correlations are centered over Bhutan, confirming the reconstruction's local signal strength, while at the same time suggesting that the reconstruction may have sufficient skill to estimate summer temperatures across much of the eastern Himalaya.

Examination of the final reconstruction (Figure 3) reveals that the number of predicted values falling below the calibration period average JJA temperature (10.75°C) by two or more standard deviations is more numerous than those rising above the mean. The most significant short-term negative (i.e., cold) departures occur in the years 1431–33 C.E. and 1533–35 C.E. Over Bhutan, the 20 year period from 1690 to 1710 C.E. was among the coldest episodes of the past 600 years, coinciding with anomalously cold conditions reported in Europe [*Miller et al.*, 2012] and central Asia [*Jiang and Xu*, 1985; *Xu et al.*, 2008; *Yang et al.*, 2010]. At multidecadal to multicentennial timescales, summer temperatures during much of the fifteenth to eighteenth centuries were below the calibration period average, containing deep departures that coincide with minima in solar energy output [*Usoskin et al.*, 2002, 2003]. The warmest period occurs within the most recent decade, 2004–2013 C.E.; however, this period is not statistically unprecedented compared with earlier warm periods, e.g., in the 1650s and late fourteenth century.

Apart from the visual (i.e., statistically untested) suggestion of solar forcing, the Bhutan summer temperature reconstruction does contain a statistically robust ($p > 97\%$) association with historic episodes of explosive volcanism. Superposed epoch analysis (SEA) performed on the reconstructed Bhutan summer temperatures, using reported dates for the six largest eruptions (as defined by total sulfate loading) over the past 700 years [*Gao et al.*, 2006; *Oppenheimer*, 2003], detected a significant year $t+1$ cooling response (supporting information Figure S5). Previous studies investigating the impact of volcanism on tree growth in the region have reported similar results [*Cook et al.*, 2013; *Yadav*, 2007]. However, we find following the initial drop in summer temperatures in the year after an eruption there is an equally significant increase in temperature 2–4 years later. Such an expression of climate rebound has also been reported previously [*Esper et al.*, 2013]. Albeit, our results from Bhutan indicate a significant ($p > 95\%$) posteruption warming of ~0.25°C, a level that is in agreement with *Esper et al.* [2013], tends to occur in year $t+2$.

Regional variability of reconstructed Himalayan temperatures is evident on the basis of comparisons between the January–June temperature reconstruction over southeast Tibet by *Yang et al.* [2010], the nearest $2.0° \times 2.0°$ grid box reconstruction of summer temperature by *Cook et al.* [2013], and our new Bhutanese summer reconstruction (supporting information Figure S6). The degree of correspondence between the Bhutanese and Tibetan reconstructions is strongest in the pre-1700 C.E. period. In contrast, comparison between the summer season grid box reconstruction of *Cook et al.* [2013] and the JJA temperatures over Bhutan indicates greater agreement is in the post 1700 C.E. period. We note that both the preupdated Dhur and Ura chronologies were used in the *Cook et al.* [2013] gridded summer temperature experiment, as indicated by the degree to which the two reconstructions express the recent warming trend. Yet despite the shared information between this new Bhutan reconstruction and *Cook et al.* [2013] or the geographical proximity of the *Yang et al.* [2010] reconstruction, neither *Yang et al.* [2010] nor *Cook et al.* [2013] can produce a more skillful reconstruction of the four-cell grid box average JJA temperatures over Bhutan (supporting information Figure S6).

4. Summary

Here we present a new, 638 year long, annually resolved, reconstruction of summer temperature over Bhutan. Although the calibration and verification metrics indicate modest fidelity, the reconstruction has sufficient skill to justify its use in reconstructing past climate change in the Himalaya. Taking into account the instrumental climate data issues described, the indicated reconstruction skill may be significantly underestimated. Our reconstruction captures high-frequency temperature fluctuations following extreme volcanic eruptions, and medium-frequency fluctuations that correspond with the timing of minima in total solar irradiance. Our summer temperature reconstruction over Bhutan sheds light on local and regional climate history of the eastern Himalaya and places recent warming and glacier retreat in a proper long-term context.

Acknowledgments
The authors wish to acknowledge the invaluable help of all past and present staff in the Ministry of Agriculture and Forests (MoAF), Council for Renewable Natural Resources Research of Bhutan (CoRRB) Thimphu, Bhutan, and the current staff of the MoAF, Department of Forests (DoF) in Thimphu and Yusipang, Bhutan. We are especially grateful for the personal assistance of Prem Bahadur Rai (Renewable Natural Resources Research and Development Center, MoAF, Bumthang, Bhutan); Karma Tenzin, Department of Forests and Park Service (DoFPS-Yusipang); Kinley Tenzin (DoFPS-Yusipang); and Andras Darabant, BOKU University, Vienna, Austria. All maps and figures were produced by GMT (http://gmt.soest.hawaii.edu/). All data produced for this study are available from the International Tree Ring Databank (www.ncdc.noaa.gov/data-access/paleoclimatology-data/datasets/tree-ring). A. E. Putnam was supported by a Lamont Postdoctoral Fellowship, the Lamont Climate Center, the Comer Science and Education Foundation, and the Lenfest Foundation. This research was supported by National Science Foundation (NSF) grants EAR-1304351 and EAR-1304397. Lamont-Doherty Earth Observatory Contribution 7887.

The Editor thanks two anonymous reviewers for their assistance in evaluating this paper.

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