Karakorum temperature out of phase with hemispheric trends for the past five centuries

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Received: 17 September 2014 / Accepted: 22 May 2015
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Abstract A systematic increase in global temperature since the industrial revolution has been attributed to anthropogenic forcing. This increase has been especially evident over the Himalayas and Central Asia and is touted as a major contributing factor for glacier mass balance declines across much of this region. However, glaciers of Pakistan's Karakorum region have shown no such decline during this time period, and in some instances have exhibited slight advance. This discrepancy, known as the 'Karakorum Anomaly', has been attributed to unusual amounts of debris covering the region's glaciers; the unique seasonality of the region's precipitation; and localized cooling resulting from increased cloudiness from monsoonal moisture. Here we present a tree-ring based reconstruction of summer (June–August) temperature from the Karakorum of North Pakistan that spans nearly five centuries (1523–2007 C.E.).

The ring width indices are derived from seven collections (six—*Picea smithiana* and one—*Pinus gerardiana*) from middle-to-upper timberline sites in the northern Karakorum valleys of Gilgit and Hunza at elevations ranging from 2850 to 3300 meters above mean sea level (mean elevation 3059 m asl). The reconstruction passes all traditional calibration–verification schemes and explains 41 % of the variance of the nested Gilgit–Astore instrumental station data (Gilgit—1454 m asl, 1951–2009; Astore—2167 m asl, 1960–2013). Importantly, our results indicate that Karakorum temperature has remained decidedly out of phase with hemispheric temperature trends for at the least the past five centuries, highlighting the long-term stability of the Karakorum Anomaly, and suggesting that the region's temperature and cloudiness are contributing factors to the anomaly.

Keywords Karakorum Anomaly · Temperature · Dendroclimatology · High Asia · Glaciers

Electronic supplementary material The online version of this article (doi:[10.1007/s00382-015-2685-z](https://doi.org/10.1007/s00382-015-2685-z)) contains supplementary material, which is available to authorized users.

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Fig. 1 Map showing the study sites outlined in Table 1 (Chaprot, Bagrot, Harmosh, Kargah, and Jutial) where samples were collected. The red box in the smaller inset highlights the area shown on the left. Mount K2 and Nanga Parbat are peaks above 8,000 m in elevation

1 Introduction

The Karakorum Mountain range of northern Pakistan is one of the most remote areas of the Himalayas, and maintains a place in history as home to several of the world's highest, most technically difficult, and most storied mountains for ascent. Adding to the Karakorum's mystique is that little research of any kind has been conducted in this region, particularly with regard to its paleoclimate. Dendroclimatology (tree-ring-based climate analysis) has been applied to analyze large-scale climate over High Asia (Cook et al. 2013a), and over several regions of the Himalaya, for example Cook et al. (2003), in Nepal; Dey and Kumar (1983), Douville and Royer (1996), Li and Yanai (1996), in the Indian Himalaya; Krusic et al. (2015), in Bhutan; and Ahmed et al. (2011), Cook et al. (2013b), Esper (2000), Esper et al. (2002), for parts of Pakistan. Here we present a calibrated and verified reconstruction of summer temperature (June–August) derived from seven tree ring records from the valleys of Gilgit and Hunza (Fig. 1), the first such calibrated and verified reconstruction from the Karakorum. Zafar et al. (2010), and Ahmed et al. (2013) first published these same tree ring records as an assessment of the dendroclimatic potential from the Karakorum, and Cook et al. (2013a), included them as part of a large ensemble (585 records) in a reconstruction of mid-to-high latitude Asian temperature over the past millennium. However, while the Cook et al. (2013a) reconstruction clearly shows the hemispheric scale warming over Asia, our regional record illustrates the out-of-phase nature of the Karakorum, as will be discussed later (Fig. 2).

Global temperature has steadily increased since the industrial revolution, markedly so over the Himalayas and Central Asia (Cook et al. 2013b; D'Arrigo et al. 2006; Davi et al. 2015; IPCC 2014; PAGES 2k Consortium 2013).

While this warming trend has contributed to glacier mass balance declines across most of 'High Asia', the glaciers of the Karakorum have either remained stable or advanced during this same time period, and this has become known as the 'Karakorum Anomaly' (Bolch et al. 2012; Gardelle et al. 2012; Hewitt 2005; Hewitt et al. 2011; Kapnick et al. 2014; Kumar et al. 2015; Minora et al. 2013).

Hewitt (2005) suggests that the apparently anomalous glacial stability of the Karakorum is in response to greater transport of summer monsoonal moisture that causes increased snowfall at high altitudes—a synoptic pattern that also results in increased cloudiness and summertime cooling in the region's valleys, such as Gilgit and Hunza in Pakistan's Karakorum. Two-thirds of high-altitude snow in the Karakorum accumulates in the winters and is caused by synoptic westerly disturbances, while the remainder accumulates during the summer months under the influence of the Indian Monsoon (Benn and Owen 1998; Bookhagen and Burbank 2010; Hewitt et al. 1988; Hewitt 2005; Palazzi et al. 2015). Similarly, Gardelle et al. (2012) and Farhan et al. (2015) also argue that the anomaly is a result of a combination of the region's unique precipitation and temperature dynamics. Both studies show that Karakorum summer mean temperature decreased between 1980 and 1995 (albeit increased since 1996, as also seen in our reconstruction, concurrent with an increase in winter precipitation). Alternative explanations have been offered by Minora et al. (2013) suggesting that high debris loading on regional glaciers serves to insulate them from the effects of warming, and Kapnick et al. (2014) who reason that the cause of the Karakorum Anomaly is the higher contribution of non-monsoonal wintertime snowfall compared to what is primarily monsoon-season snowfall in the Himalayas. The latter authors concluded that the unique precipitation

Fig. 2 Three-panel plot showing z-scores of (top) Cook et al. (2013a) and Pages 2k Consortium (2013) High Asia summer (June–August–JJA) temperature reconstruction; (middle) Gilgit–Astore (JJA) temperature reconstruction from this study, (bottom) both reconstructions bandpassed to extract 20–40 years periodicity and superimposed to illuminate the out of phase nature of the two reconstructions. Note the different y axis scale for the bottom plot

seasonality of the Karakorum serves to insulate the region from the broad scale glacial retreat that has been observed over the remainder of Himalayan and Central Asian glaciers.

In this paper we generate and analyze June through August (JJA) temperature trends for the Karakorum for the past five centuries based on crossdated tree-rings of spruce and pine. We conclude that the unique summer temperature dynamics of this region are strongly influenced by local cloudiness, and this is a contributing factor to the Karakorum Anomaly.

2 Materials and methods

2.1 Tree ring data

We used standard dendrochronological techniques and protocols for the collection, preparation, measuring and processing of samples obtained for this study (e.g. Cook and Kairiukstis 1990; Fritts 1976; Stokes and Smiley 1968). Zafar et al. (2010), Ahmed et al. (2011) and Ahmed et al. (2013) describe details for the seven site collections used in our study, the locations of which are shown in Fig. 1. Cross-dating was performed under a microscope by matching patterns of narrow and wide rings between cores, and accounting for locally absent (i.e. “missing”) and “false” rings for each core. The measurements of each ring were made to

0.01 mm accuracy. We evaluated the accuracy of the cross-dating for all sites using the statistical tree-ring quality control software COFECHA (Holmes 1983). After assuring that trees were accurately crossdated, ring-width measurements were standardized to remove and reduce non-climatic influences on tree growth by using the program ARSTAN (Cook 1985; Cook and Kairiukstis 1990). Prior to standardization, we employed the methodology of Cook and Peters (1997) where an adaptive power transform is performed, based on the local spread vs. level, in order to ensure homoscedasticity or stable variance through time. We used the ‘Friedman Super Smoother’ ($\alpha = 6$) for standardization (Buckley et al. 2007, 2010; Friedman 1984). The expressed population signal (EPS) statistic was used to interpret the quality of each individual chronology, using $\text{EPS} > 0.85$ as the standard accepted threshold (Wigley et al. 1984) and this value along with all pertinent chronology statistics are included in the Supplementary Online Material (SOM).

2.2 Climate data

The Gilgit meteorological station (35°55' N, 74°20'E, 1454 m asl) is located in close proximity to most of the tree ring sites (Fig. 1). Although short (1955–2009), it is the longest such record in Northern Pakistan. Astore (35°37' N, 74°00'E, 2167 m) is approximately 115 km southeast of Gilgit and is farther away from our tree-ring locations. Astore’s temperature data span 1960–2013 and agree well

with the Gilgit station data. We therefore made a composite temperature dataset from both stations by preserving the statistical properties (mean, standard deviation) of the Gilgit station subsequent to confirming the homogeneity between the two datasets for each month for the common period (1960–2009). We then calculated the z-scores for both datasets and averaged them for the common period (1960–2009). The averaged z-scores were then converted to degrees Celsius by multiplying with the standard deviation and adding the mean of the Gilgit temperature. Finally, to account for the elevation difference between Gilgit (1454 m) and the mean elevation of our tree sites (3059 m), we used the moist adiabatic lapse rate of $6.5\text{ }^{\circ}\text{C}/\text{km}$ as a conservative estimate of the mean monthly temperature at the field sites to develop a 59-year record that spans from 1955–2013.

The mean annual temperature for the Gilgit–Astore composite is $5.5\text{ }^{\circ}\text{C}$, mean summer (JJA) temperature is $15.7\text{ }^{\circ}\text{C}$, and the mean temperature for the entire period from November through February remains below freezing. Box and whisker plots of mean monthly temperature are presented in Fig. 3, illustrating that summer temperature peaks in July and that January is the coldest month. We used the Gilgit–Astore temperature dataset for all ensuing analyses and for reconstruction of summer temperature from our seven-site tree ring matrix. For this purpose we used the Lamont-Doherty Earth Observatory Tree Ring Laboratory's freeware program PCReg (<http://www.ldeo.columbia.edu/tree-ring-laboratory/resources/software>), which enables users to reduce data to principal components and to select varying parameters for screening predictors prior to regression.

For additional comparison with our tree ring sites and our Gilgit–Astore temperature reconstruction, we used gridded temperature data from the University of East Anglia's Climate Research Unit (UEA CRU), Ts3.21 0.5° lat $\times$ 0.5° lon dataset (Harris et al. 2014), as well as the ASIA 2k temperature reconstruction of Cook et al. (2013a) and the PAGES 2k Consortium (2013). We also compared our reconstruction with the Monsoon Asia Drought Atlas Palmer Drought Severity Index (MADA-PDSI—Cook et al. 2010). For percentage cloudiness we used the diagnostic low-level cloud data from the NCEP/NCAR monthly dataset (Kalnay et al. 1996). All of these data were downloaded from the International Research Institute for Climate and Society and Lamont-Doherty Earth Observatory (IRI and LDEO) Climate Data Library and are available at <http://iridl.ldeo.columbia.edu/>.

2.3 Reconstruction methodology

To develop the reconstruction we first determined the climate season to which the trees were most sensitive by conducting diagnostic comparisons between all tree rings sites and Gilgit and Astore precipitation and temperature

Fig. 3 Box plot of estimated mean monthly temperature at the mean elevation (3059 m asl) of the tree-ring sites based on the Gilgit–Astore station mean temperature (1955–2013). The temperature difference between tree-ring sites and stations was calculated by using a moist adiabatic lapse rate of $6.5\text{ }^{\circ}\text{C}/\text{km}$. Red squares in the figure show outliers, and the black line connects the mean temperature for each month in sequence

(Fig. 4a, Fig. S1–S3). For this purpose we used a 24-month dendroclimatic window, where the 12 calendar months for the year of growth (year t) as well as the year prior to growth (year $t - 1$) were analyzed via point-by-point regression. The prior year was used to account for the tendency of conifers to “carry over” the effects of prior year's growth (Fritts 1976).

To extract the common signal from the seven chronologies we conducted a principal component analysis (PCA—Cooley and Lohnes 1971) based on the common period of 1737–2005. We retained the first two Principal Components (PC1 and PC2) based upon their eigenvalues exceeding the selection criteria of one, and they explain 67.3 and 13.9 % of the total variance, respectively. We then used the ‘PC scores’ to develop a regression model with the Gilgit–Astore temperature series. In order to maximize the timespan of our reconstruction we performed a similar procedure twice more, after dropping the Chera *Picea* (1394–2005) site, and Chaprot *Pinus* (1737–2008) site, and we then combined the three reconstructions to develop the final nested reconstruction that spans the period from 1523–2007. All of the *Picea* time series loaded positively onto PC1, while the lone *Pinus* site loaded onto PC2.

These analyses showed that summer temperature (i.e., the months of June, July and August or JJA) exhibited the most consistent correlation (negative) with our trees for current year and prior year. The strongest correlation for the six spruce sites is concentrated in prior year's temperature and the lone pine site correlates best with current

Fig. 4 Pearson's correlation between monthly Gilgit–Astora temperatures for a 24-month window from the prior year ($t - 1$) January to the current year (t_0) December and tree ring indices. The panel **a** on the *left* shows the correlation between temperature and residual tree-ring indices from each of the seven sites, while on the *right* **b** we show correlation between temperature and first two PC scores from

our chronology network (PC1 and PC2) for the timespan of 1955–2005. The *horizontal solid line* at ± 0.268 represents the 95 % confidence interval for a two-sided Student's t test. This study reconstructs June–August (JJA) temperature using PC1 and PC2, which show highest loading on the six spruce and lone pine sites respectively

year (Fig. 4). Precipitation showed lower correlations than temperature, suggesting that temperature is the dominant limiting factor to tree-growth in this region (Fig. S1–S3). We note, however, that the inverse response to temperature may be interpreted as some form of moisture stress in our trees, so we tested for a relationship between precipitation and growth using both instrumental station records (Gilgit, Astora, Skardu), and gridded datasets (CRU) and still found the relationship to be weaker than that of temperature (not shown).

To verify the fidelity of our reconstruction we applied a split calibration and verification scheme using the Gilgit–Astora meteorological station data (Table 2). Two separate 30-year periods (1955–1985 and 1975–2004) were used, and we determined our reconstruction to be robust during both periods but particularly so when calibrated on the early half of the record. To determine robustness we utilized the Reduction of Error (RE), Coefficient of Efficiency (CE), and the Durbin–Watson statistics, which are commonly used for dendroclimatic reconstruction (Cook and Kairiukstis 1990). RE and CE measure the shared variance between actual and reconstructed temperature, while the Durbin–Watson statistic is used to detect autocorrelation between residuals between the actual and reconstructed temperatures (for more details see Cook and Kairiukstis 1990). Values for RE and CE are, by definition, equal for the calibration periods, but are not constrained to be so for independent verification where CE is notoriously difficult to pass (*ibid.*). Although there is no statistical significance test for CE per se, any values greater than zero

during verification demonstrates model skill. In all cases (using undifferenced data in our verification) CE exceeds zero. The Durbin–Watson statistic in all instances is greater than one, indicating low autocorrelation between residuals, and underscoring the lack of a persistent error bias in our regression. These results establish that our regression model has skill, presents no consistent bias, and therefore the reconstruction is robust in spite of the relatively short length of record. The final reconstruction was developed using the entire period (1955–2009), and explains 41.00 % of the total variance of nested station JJA temperature (Fig. 5, upper left panel), resulting in a 485-year (1523–2007 C.E.) reconstruction of Gilgit–Astora summer temperature (Fig. 5, lower left panel). Each of the individual tree ring indices and sample size are shown in the upper right panel of Fig. 5.

3 Results and discussion

Here we present our reconstruction of Karakorum summer (JJA) temperature for the period 1523–2007 (Fig. 5, lower left panel). To check the validity of our reconstruction over a larger spatial domain we correlated our temperature reconstruction to the CRU gridded temperatures and found that our reconstruction correlates positively ($p < 0.1$, two-sided t test, 1901–2004) with temperature from a broad spatial area that covers the Kashmir regions of Pakistan and India, northern Khyber Pakhtunkhwa (formerly Northwest Frontier Provinces), Tajikistan, Kyrgyzstan, northeastern

Fig. 5 The *upper left panel* shows a comparison between reconstructed June–August (JJA) temperatures (*red dashed line*) and Gilgit–Astore temperature (*solid black line*; $r = 0.6403$, $p < 0.001$, 1955–2004, two-sided t test); the *lower left panel* plots the JJA mean temperature reconstruction for full period 1523–2007 as degrees Cel-

sus; the *upper right panel* is a stack of each of the seven residual chronology indices; the *lower right panel* shows the sample size (n) for each site (*colored lines*) and for the entire nested reconstruction (*black line*)

Afghanistan, and western Xinjiang, China (Fig. 6, left). The striking inverse pattern between temperatures in the Karakorum with those in peninsular India is very similar to the temperature pattern across Asia as a result of the summer circum-global wavetrain (Ding and Wang 2005). We also compared our reconstruction with the (Cook et al. 2013a) Central and High Asia hemispheric-scale temperature reconstruction and observed an out-of-phase relationship in low frequency variability (20–40 years) between the two (Fig. 2, bottom panel). For example, the pronounced 1800s cold period in High Asia related to the Little Ice Age, is absent in our reconstruction. We note that our seven Karakorum records were also used in the Cook et al. (2013a) reconstruction, but their High Asia record is heavily biased towards tree rings from the Himalayas and Central Asia (a total of 585 tree ring records were used).

Our reconstruction correlates inversely with the (Cook et al. 2010) tree-ring based Palmer Drought Severity Index (PDSI) reconstruction, while the same opposite sign pattern between the Himalaya and peninsular India is also clearly depicted (Fig. 6, right). Since PDSI is a proxy for soil moisture conditions and is a metric used to measure drought (Palmer 1965), positive values are reflective of increasing soil moisture while negative values reflect dry conditions. Soil moisture increases with increased precipitation and decreases with increasing temperature, though other factors like wind coefficients and saturation vapor pressure deficits are also important (Allen et al. 1998). The MADA is a reconstruction of June–August (JJA) PDSI for Monsoon

Asia from 1300 to 2005 (Cook et al. 2010) and thus is directly comparable to our summer temperature reconstruction. It is therefore reassuring that our Gilgit–Astore summer temperature reconstruction is *inversely* related to PDSI over the region around Gilgit–Astore (Fig. 6, right), such that an increase in summer temperature leads to greater soil moisture deficit, reduced photosynthetic potential and a corresponding decrease in radial growth (*sensu* Fritts 1976).

As mentioned earlier only one-third of the annual precipitation in the region falls in the summer monsoon season, whereas the majority is from westerly cyclonic storm systems (Benn and Owen 1998; Bookhagen and Burbank 2010; Dimri 2006; Gardelle et al. 2012; Hewitt et al. 1988; Hewitt 2005; Kapnick et al. 2014). During spring and summer the trees have access to additional moisture in the form of snowmelt. The trees in four of the seven sites are growing on north facing slopes, and one each on northwest, east, and east-south facing slopes (Table 1). This serves to insulate them from the higher evaporative stress common to south and west facing slopes. In this particular region, moist-temperate trees like spruce (*Picea*), and pines (*Pinus*) tend to be found on moist north facing slopes, and only junipers (*Juniperus*) can grow on south facing slopes (Esper 2000). Given the lack of a strict seasonality in precipitation, access to snowmelt, and slope aspect, the absence of a significant relationship between tree-growth and precipitation is not surprising. Consequently, given the robust relationship between summer temperature and growth, we targeted JJA mean temperature for reconstruction.

Fig. 6 *Left* spatial correlation field between the Gilgit–Astore JJA temperature reconstruction and gridded CRU Ts 3.21 temperature between 1901–2004 (only $p < 0.1$ shown); *Right* correlation between Gilgit JJA temperature reconstruction and Cook et al. 2010 JJA PDSI

(1737–2004). The location of boundary lines are as per shape files downloaded from <http://www.diva-gis.org/gdata> and these boundary designations may differ from the official maps of the Governments of Pakistan, India, and Tajikistan

Table 1 Details of site locations and tree-ring indices

Sr. no	Species	Site	Year		No. of cores	AR(1)	Lat	Lon	Elev (m)	Slope	Aspect
			First	Last							
Gilgit valley sites											
1	<i>Picea smithiana</i>	Kargah	1475	2008	21	0.4735	35°53	74°11	2989	34°	NW
2	<i>P. smithiana</i>	Jutial	1523	2008	36	0.4281	35°50	74°20	3250	40°	N
3	<i>P. smithiana</i>	Harmosh	1467	2009	20	0.4678	35°53	74°53	3296	53°	E/S
4	<i>P. smithiana</i>	Bagrot	1480	2009	20	0.5150	36°01	74°36	3130	45°	E
5	<i>P. smithiana</i>	Chera	1394	2005	18	0.5046	36°90	74°11	2900	36°	N
Hunza valley sites											
1	<i>P. smithiana</i>	Chaprot	1520	2008	16	0.7249	36°14	74°16	3000	35°	N
2	<i>Pinus gerardiana</i>	Chaprot	1737	2008	22	0.5291	36°14	74°16	2850	26°	N

The column AR(1) shows the first order autocorrelation of the standardized tree ring indices; *Lat* latitude, *Lon* longitude, *Elev* elevation

Table 2 Calibration and verification statistics of the Gilgit JJA temperature reconstruction

	Calibration 1955–1985	Verification 1987–2004	Calibration 1975–2004	Verification 1955–1973	Reconstruction 1955–2004
Durbin–Watson	1.885		1.7866		1.6969
Variance explained	54.04 %		30.91 %		41.00 %
RE	0.593	0.255	0.350	0.511	
CE	0.593	0.255	0.350	0.511	
PR	0.804	0.530	0.601	0.790	0.6403

The RE and CE measure the shared variance between the actual and reconstructed temperatures, and non-negative values indicate that the regression model has skill (Cook and Kairiukstis 1990)

RE reduction of error, CE coefficient of efficiency, PR Pearson's correlation coefficient

As mentioned above the dominant mode of common variability between six of the seven tree ring indices correlated most to prior year summer JJA temperatures. It is possible that this lagged, inverse response is due to the relatively short growing season. At high elevations conifer needles typically reach peak photosynthetic potential only in the next growing season, and thus climate of the previous year has a greater influence on current-year growth than it does on current year climate (Fritts 1976). We did not observe high sensitivity to precipitation, possibly due to the lack of seasonality of precipitation in this region, which is influenced both by summer monsoon moisture and winter westerly cyclonic systems causing precipitation to not be limiting to tree growth (Fig. S3). It is also possible that the poor quality and relative dearth of instrumented precipitation limits our ability to elucidate a clear response. However, we feel that the location of all of our tree sites at the upper elevational limits of their ecological amplitude, combined with their locations on slopes other than southerly, all point to the validity of our interpretation that temperature is the dominant limiting factor for all of our sites (Tables 2 and 3).

Hewitt (2005) proposed that an increase in summertime cloudiness from monsoonal moisture was one of the factors responsible for the cooling in the Karakorum, as clouds decrease incident solar insolation and hence temperature. We too find that there is a significant inverse relationship ($r = -0.60$, $p < 0.01$, two-sided t test, 1955–2013) between percentage low-level cloudiness and summer temperature, and an increasing trend in cloudiness since the 1960s that tracks the dramatic rise in the Cook et al. (2013a) High Asia temperature reconstruction (see Fig. 7, left). Interestingly, while temperatures in the High Asia reconstruction increase dramatically after the 1960s, our reconstruction shows a slight decrease.

Phillips et al. (2000) developed an ice core chronology from the Nanga Parbat glacier, approximately 80 km south of Gilgit (Fig. 1). Their study shows that Karakorum ice volumes expanded during warm and wet climatic optima, when monsoon activity was enhanced, and decreased during historical periods of glacial maxima when monsoons were weak. This behavior is typical of high-elevation arid glaciers that are precipitation limited (Rupper and Roe 2008) and is reflective of the relationship between Eurasian snow cover and the strength of the Indian Monsoon as noted by Chang et al. (2001) and Dash et al. (2005). In other words, increased Eurasian snow cover is correlated with a weaker land–sea thermal contrast, and hence the inland extent of monsoonal moisture in this region is reduced. The Karakorum lies outside of the influence of all but the strongest of monsoonal incursions, at the northernmost reach of a typical monsoon. Hence even a slight reduction in monsoon vigor may reduce summer

Table 3 The five coldest and warmest single year (top) and 10-year periods (bottom) as determined from our tree-ring reconstruction of Karakorum temperature

Year	Temperature (°C)	Year	Temperature (°C)
<i>Coldest 1 year</i>		<i>Warmest 1 year</i>	
1	1574 12.19	1571	19.48
2	1688 12.40	1601	19.32
3	1660 13.32	1916	18.72
4	1588 13.47	1662	18.56
5	1579 13.51	1625	18.56
<i>Coldest 10 year</i>		<i>Warmest 10 year</i>	
1	1683–1692 14.70	1911–1920	16.75
2	1584–1593 14.77	1599–1608	16.59
3	1950–1949 15.01	1698–1707	16.56
4	1552–1563 15.01	1860–1869	16.49
5	1901–1910 15.03	1642–1651	16.46

precipitation and cloudiness, serving to increase temperature in valleys like Gilgit and Hunza.

4 Conclusions

In this paper we present a reconstruction of summer temperature that reveals that the northern Karakorum has been continuously out of phase with hemispheric-scale temperature for at least the past five centuries, as compared to the ‘High Asia’ temperature reconstruction of Cook et al. (2013a), and the PAGES 2k Consortium (2013) (Fig. 2). We believe, therefore, that our temperature reconstruction validates the localized cooling trend in the Karakorum and Gilgit valleys since the 1960s that is swamped by the overall warming signal at the hemispheric scale. Fowler and Archer (2006) and Shekhar et al. (2010) analyzed Karakorum instrumental data, including Gilgit, and confirmed that summertime temperature has cooled since the 1960s while the hemisphere at large warmed.

All seven of our tree ring indices correlate inversely with both temperature and PDSI, and do not show significant relationships with precipitation, suggesting that temperature and not precipitation is the primary limiting factor for tree growth in this region. In essence, due to annual snow-pack and proximity to river drainage, trees in the Gilgit and Hunza valleys are not easily stressed by low soil moisture, and photosynthesis is most likely to be controlled by the range in temperature. Our reconstruction shows that summer temperatures in the Karakorum have decreased, and one of the factors contributing to this decrease is increased summer cloudiness (Fowler and Archer 2006; Hewitt 2005). We believe that this temperature decrease, coupled with increased cloudiness, has contributed to the

Fig. 7 The plot on the left shows the z-scores of the Gilgit–Astore JJA instrumental temperature (red line) against percentage JJA low-level cloudiness from NCEP–NCAR (Kalnay et al. 1996) (black

line). Note the increasing trend in percentage cloudiness from 1960 to 2005. The scatter plot on the right shows the inverse relationship between the two ($r = -0.6$, $p < 0.001$, two-sided t test, 1955–2013)

‘Karakorum Anomaly’ of glacial stability and in some cases expansion during a period of otherwise widespread glacial retreat. The other contributing factor to the anomaly, as mentioned in other previous studies is the recent increase in winter snowfall (Farhan et al. 2015; Kapnick et al. 2014; Ridley et al. 2013; Tahir et al. 2011). In a recent paper Kumar et al. (2015) used a regional climate model (RCM), with dynamically evolving glaciers to simulate the annual glacial mass balance for the period 1989–2008 over the Himalayas and the Karakorum (see Fig. 3 of Kumar et al. 2015). Their simulations also indicate an increasing glacial mass balance over some regions of the Karakorum. However, they too show that the increasing mass balance is the exception and not the norm, and is limited to a small region of the Karakorum where all of our sites are located. Importantly, we demonstrate with our reconstruction that this out-of-phase temperature relationship between the Karakorum and the hemisphere at large has persisted for at least the past five centuries.

Acknowledgments We express gratitude towards the people of Gilgit and Hunza valleys who assisted with the fieldwork for this project. We thank Dr. Joerg Schaefer (Lamont-Doherty Earth Observatory) for insightful comments that improved the manuscript. We also thank Dr. Paolo Cherubini (Swiss Federal Research Institute) for comments on an earlier version of this manuscript. We are grateful to the Pakistan Meteorological Department for providing climate data. We also express thanks to Dr. Andrew Bell (New York University), Dr. Sonali McDermid (New York University), and Dr. Muhammad Ashfaq for sharing climate data and thank two anonymous reviewers for their comments and suggestions that substantially improved this manuscript. The authors acknowledge funding 20 - 1806/R AND D/10. 5149.IT from the Higher Education Commission, Government of Pakistan. Funding for B.M. Buckley and M.P. Rao came from the support of the US National Science Foundation (AGS 13-03976 and AGS 12-03818). Lamont Contribution No. 7904.

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