



Supplement of

Weak precipitation, warm winters and springs impact glaciers of south slopes of Mt. Everest (central Himalaya) in the last 2 decades (1994–2013)

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Supplementary Material 1

Reconstruction methods of the daily temperature and precipitation time series at Pyramid station (5035 m a.s.l.)

In the following, we describe the missing daily data reconstruction performed on daily T (minimum, maximum, and mean) and Prec time series collected at Pyramid (5035 m a.s.l.) for the 1994-2013 period. As already mentioned in the main text, we consider AWS1 as the reference station (REF) for the reconstruction, which has been operating continuously from 2000 to the present. This station replaced AWS0 (1994-2005). These two stations have a recorded percentage of missing daily values of approximately 20% over the last twenty years (Table S1). The other five stations (ABC, AWSKP, AWS2, AWSN and AWS3) taken into account for the reconstruction process will be referred to as secondary stations. Information regarding the sensors used in the reconstruction process are reported in Table S2.

The time series reconstruction process considers four steps:

- 1) Pre-processing of data
- 2) Infilling method
- 3) Multiple imputation technique
- 4) Monthly aggregation of data

Step 1 – Pre-processing of data

Table 1 shows the sampling frequency of stations (ranging from 10 minutes to 2 hours). After an accurate data quality control according to Ikoma et al., 2007, a daily aggregation of the time series (temporal homogenization) is performed. Daily data have been computed only if the 100% of sub-daily data are available; otherwise, it is considered missing. These rules ensure a maximum quality of daily values with a loss of information limited to the first and last day of the failure events.

Step 2 – Infilling method

The selected daily infilling method is based on a quantile mapping regression (e.g. Déqué 2007). This method estimates a rescaling function F between two time series. This function ensures that the daily cumulated density function (cdf) of a secondary station reproduces the daily cdf of the REF over their over their common observation period. Applying the inverse function (F^{-1}) to each secondary station, a new time series is computed for each of them. In the following, these new time series with the systematic bias corrected are indicated as '*' (e.g., AWS0*, ABC*). In our case the bias is mainly due to the altitude gradient, all stations being located along the same valley (Fig. 1b).

A new time series (REF_filled) has been created merging REF and the * time series according to a priority criterion based on the degree of correlation among data (Fig. S1). The specific rules of computing are described below:

- all available data of REF are maintained in the final reconstruction without any further processing;

- the priority criterion for infilling is based on the magnitude of correlation coefficient (r) between REF and each secondary station, for each variable (Table S1); In case the daily data of the secondary station with higher *r* is missing the station with the slight lower r is selected.

We can observe from Table S1 that AWS0, located few tens of meters far from REF, presenting r = 0.99 and r = 0.97 for temperature and precipitation, respectively, has been the first choice. The 82% of missing daily values of temperature and 72% of precipitation are filled using the AWS0*. The second choice is ABC. Together these two stations cover more than the 90% of missing values; the whole infilling procedure allows for filling the 86% and the 91% of the overall missing values of temperature and precipitation, respectively.

Table S1. Correlation coefficients (r) between the reference station (REF) and the other secondary stations for temperature and precipitation. Furthermore the table reports the number of daily data (n) that each station has provided to the reconstruction of the time series.

Stations	Т	emperature	Precipitation	
	r	n	r	n
AWS0	0.99	2,144 (82.2%)	0.97	2,298 (72.2%)
ABC	0.98	254 (9.7%)	0.84	646 (20.3%)
AWSKP	0.96	48 (1.8%)	0.62	13 (0.4%)
AWS2	0.94	95 (3.6%)	0.81	145 (4.6%)
AWSN	0.92	66 (2.5%)	0.56	78 (2.5%)
AWS3	0.87	0 (0.0%)	0.53	3 (0.1%)
Total infilled missing				
values		2,607		3,183

Table S2. List of sensors with measurement height, manufacturer and accuracy. Communicated nonregular intervention as sensors or data logger replacements are reported at the table bottom.

Parameter		Sensor	~ o(l)	Manufacturer	Accura	cy	
A * , ,	D · ·	AWS	$\frac{SO^{(1)}}{(1-c)^2}$	N //TN/	0.100		
Air temperature Precipitation	Tipping	Linear Therm Bucket (1.5m)	listor (2m)	MIX	0.1 °C	'n	
Relative humidity	Solid stat	te hvgrometer	(2m)	MTX	3%	.11	
Atmospheric pressure	Aneroid	capsule (2m)	()	MTX	0.5hP	a	
* *		AW	/S1				
Air temperature	Thermore	esistance (2m)		Lsi-Lastem	0.1°C	2	
Precipitation	Tipping l	Bucket (1.5m)		Lsi-Lastem	2%		
Relative humidity	Capacitiv	ve Plate (2m)		Lsi-Lastem	2.5%		
Atmospheric pressure	Slice of S	Silica (2m)		Lsi-Lastem	1hPa	<u>. </u>	
	771	AE	BC	*7 * 1	0.000		
Air temperature	Acoustic	esistance (2m)		Vaisala	0.3°C	2	
Relative humidity	Capacitix	(2111) ve Plate (2m)		Vaisala	3%-50	16	
Atmospheric pressure	Slice of S	Silica (2m)		Vaisala	0.5 hF	'a	
		AWS	SKP				
Air temperature	Thermore	esistance (2m)		Lsi-Lastem	0.1°C	2	
Precipitation	Tipping l	Bucket (1.5m)		Lsi-Lastem	1%		
Relative humidity	Capacitiv	ve Plate (2m)		Lsi-Lastem	1.5%		
Atmospheric pressure	Slice of S	Silica (2m)	(2)	Lsi-Lastem	1hPa	L	
(3)	771	AWS	\$2 ⁽²⁾	.	1 0 100/0		
Air temperature ⁽³⁾	Thermore	esistance (2m)		Lsi-Lastem / Vai	sala $0.1^{\circ}C/0.$	3°C	
Precipitation Pelative humidity ⁽³⁾	Capaciti	Ducket (1.311)		Lsi-Lastem /Vai	2% دماع 1.5%	5%	
Atmospheric pressure ⁽³⁾	Slice of S	Silica $(2m)$		Lsi-Lastem /Vai	sala $1.5\%/2$.	hPa	
	blice of t	AWS	SN ⁽⁴⁾	Lor Lustein / Vu	5ulu 111 u 0.5	iii u	
Air temperature	Thermor	esistance (2m)		Lsi-Lastem	0.1°C		
Precipitation	Tipping l	Bucket (1.5m)		Lsi-Lastem	2%		
Relative humidity	Capacitiv	ve Plate (2m)		Lsi-Lastem	2.50%	ó	
	Slice of S	2:1: (0)		Lsi-Lastem	1hPa		
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Atmospheric pressure Air temperature ⁽⁶⁾ Precipitation Relative humidity ⁽⁶⁾ Atmospheric pressure ⁽⁶⁾ ⁽¹⁾ dissmissed in 2005 ⁽²⁾ data logger replacement ⁽³⁾ sensors change on 05// ⁽⁴⁾ data logger replacement ⁽⁶⁾ sensors change on 05// REF (AWS1) AN REF (AWS1) AN REF (AWS1) AN REF (AWS1) AN REF (AWS1) AN REF (AWS1) AN Atmospheric pressure ⁽⁶⁾ sensors change on 05// ⁽¹⁾ distribution ⁽¹⁾ distribution ⁽⁶⁾ sensors change on 05// ⁽¹⁾ REF (AWS1) AN ⁽¹⁾ distribution ⁽¹⁾ distribution ⁽¹⁾ distribution ⁽¹⁾ distribution ⁽²⁾ distribution ⁽³⁾ sensors change on 05// ⁽⁴⁾ data logger replacement ⁽⁵⁾ data logger replacement ⁽⁶⁾ sensors change on 05// ⁽¹⁾ distribution ⁽¹⁾ distribution ⁽²⁾ distribution ⁽²⁾ distribution ⁽³⁾ distribution ⁽⁴⁾ distribution ⁽⁴⁾ distribution ⁽⁵⁾ distribution ⁽⁶⁾ distrib	Thermore Tipping I Capacitiv Slice of S at on 08/12 2012 to Va at on 08/10 2013 to Va NSO*	AWS esistance (2m) Bucket (1.5m) ve Plate (2m) Silica (2m) 2/2010 nisala sensors D/2010 0/2010 aisala sensors ABC*	AWSKP*	AWS2*	sala 0.1°C/0. 2% sala 1.5%/2. sala 1hPa/0.5	3°C 5% hPa AWS3*	REF_filled
Atmospheric pressure Air temperature ⁽⁶⁾ Precipitation Relative humidity ⁽⁶⁾ Atmospheric pressure ⁽⁶⁾ ⁽¹⁾ dissmissed in 2005 ⁽²⁾ data logger replacement ⁽³⁾ sensors change on 05// ⁽⁴⁾ data logger replacement ⁽⁶⁾ sensors change on 05// REF (AWS1) AN REF (AWS1) AN REF (AWS1) AN REF (AWS1) AN REF (AWS1) AN REF (AWS1) AN REF (AWS1) AN ATMOSPHERIC AND AN ATMOSPHERIC AND	Thermore Tipping I Capacitiv Slice of S at on 08/12 2012 to Va at on 08/10 2013 to Va NSO*	AWS esistance (2m) Bucket (1.5m) ve Plate (2m) Silica (2m) 2/2010 nisala sensors 0/2010 0/2010 aisala sensors ABC*	AWSKP*	AWS2*	sala 0.1°C/0. 2% sala 1.5%/2. sala 1hPa/0.5	3°C 5% hPa AWS3*	REF_filled
Atmospheric pressure Air temperature ⁽⁶⁾ Precipitation Relative humidity ⁽⁶⁾ Atmospheric pressure ⁽⁶⁾ ⁽¹⁾ dissmissed in 2005 ⁽²⁾ data logger replacement ⁽³⁾ sensors change on 05// ⁽⁴⁾ data logger replacement ⁽⁶⁾ sensors change on 05// REF (AWS1) AN REF (AWS1) AN REF (AWS1) AN REF (AWS1) AN REF (AWS1) AN REF (AWS1) AN REF (AWS1) AN ATMOSPHERIC AND AN ATMOSPHERIC AND	Thermore Tipping I Capacitiv Slice of S at on 08/12 2012 to Va at on 08/10 2013 to Va NSO*	AWS esistance (2m) Bucket (1.5m) ve Plate (2m) Silica (2m) 2/2010 nisala sensors D/2010 nisala sensors ABC*	AWSKP*	AWS2*	sala 0.1°C/0. 2% sala 1.5%/2. sala 1hPa/0.5	3°C 5% hPa AWS3*	REF_filled
Atmospheric pressure Air temperature ⁽⁶⁾ Precipitation Relative humidity ⁽⁶⁾ Atmospheric pressure ⁽⁶⁾ ⁽¹⁾ dissmissed in 2005 ⁽²⁾ data logger replacement ⁽³⁾ sensors change on 05// ⁽⁴⁾ data logger replacement ⁽⁶⁾ sensors change on 05// REF (AWS1) AN REF (AWS1) AN Atmospheric pressure ⁽⁶⁾ sensors change on 05// ⁽⁶⁾ sensors change on 05	Thermore Tipping I Capacitiv Slice of S at on 08/12 2012 to Va at on 08/10 2013 to Va NSO*	AWS esistance (2m) Bucket (1.5m) ve Plate (2m) Silica (2m) 2/2010 nisala sensors D/2010 nisala sensors ABC*	AWSKP*	AWS2*	sala 0.1°C/0. 2% sala 1.5%/2. sala 1hPa/0.5	3°C 5% hPa AWS3*	REF_filled

REF_filled

PYRAMID_daily

PYRAMID_daily

Figure S1. Scheme followed for the infilling process. Upper panel: daily mean temperature. Lower panel: precipitation. On the left, for each station, the daily data availability and the re-computed values, according to the quantile mapping procedure, are shown. On the right, a new time series (REF_filled) is created by merging REF (reference station) and the * time series, according to a priority criterion described in the text. In case all stations recorded some simultaneous gaps, a multiple imputation technique is applied to obtain the PYRAMID_daily time series.

The uncertainty associated with REF_filled (σ_{REF_filled}) time series derives from the quantile mapping procedure and in particular from the miss-correlation and possible non stationarity in the quantile relationship.

In order to estimate the σ_{REF_filled} , the probability distribution of the residues between REF and *time series is considered. In order to take into account the possible seasonal variability of the uncertainty, residues have been analyzed on monthly basis.

The Kolmogorov-Smirnov test (Massey, 1951), applied to distribution of the residues, verifies their normality. As a consequence, the daily uncertainty σ_{REF_filled} is estimated as the standard deviation of the residues. The estimated daily uncertainties are reported in Table S3.

Table S3. Daily uncertainty (expressed as °C and mm for temperature and precipitation, respectively) for each station associated with the daily data infilled through the quantile mapping regression.

Minimum	Minimum Temperature (minT)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
AWS0	0.95	0.98	0.72	0.65	0.49	0.48	0.29	0.35	0.49	0.77	1.09	0.86
ABC	0.82	0.79	1.6	1.29	0.9	0.58	0.66	0.45	0.56	1	0.87	0.89
AWSKP	1.41	1.3	2.25	1.62	1.54	0.84	0.84	0.71	0.65	1.29	1.18	1.61
AWS2	2.06	2.09	2.11	1.85	1.49	1.11	0.88	0.78	0.99	1.99	2.15	1.87
AWSN	2.8	2.44	1.98	1.3	1.14	0.81	0.62	0.72	0.79	1.89	2.95	2.96
AWS3	3.18	2.48	2.35	1.33	1.31	1.25	0.82	0.8	0.88	2.02	3.39	3.23
	_		_									
Maximum Temperature (maxT)												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
AWS0	0.81	0.9	0.71	1.05	0.65	0.75	0.63	0.61	0.71	1.02	0.74	1.43
ABC	0.61	0.92	1.68	1.2	1.53	1	1.07	0.65	0.75	0.77	0.65	0.62
AWSKP	1.4	1.91	2	1.58	2.12	1.31	1.02	1.07	0.8	1.21	1.49	1.35
AWS2	2.2	2.05	2.07	1.71	1.62	1.13	1.06	0.99	1.12	1.47	1.91	1.9
AWSN	3.41	3.04	2.89	2.25	2.06	1.84	1.42	1.3	1.39	2.14	3.31	3.26
AWS3	4.08	4.11	3.99	2.68	2.6	2.55	2.2	2.23	2.62	3.11	4.15	3.91
Mean Tei	mnerature	(meanT)										
mean rei	mperature	(incuir)										
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
AWS0	Jan 0.56	Feb	Mar 0.57	Apr 0.24	May 0.28	Jun 0.29	Jul 0.24	Aug	Sep 0.27	Oct	Nov	Dec
AWS0 ABC	Jan 0.56 0.34	Feb 0.7 0.32	Mar 0.57 1.46	Apr 0.24 1.02	May 0.28 0.96	Jun 0.29 0.54	Jul 0.24 0.72	Aug 0.24 0.41	Sep 0.27 0.36	Oct 0.46 0.59	Nov 0.45 0.46	Dec 0.5 0.4
AWS0 ABC AWSKP	Jan 0.56 0.34 0.91	Feb 0.7 0.32 0.74	Mar 0.57 1.46 2.08	Apr 0.24 1.02 1.3	May 0.28 0.96 1.29	Jun 0.29 0.54 0.82	Jul 0.24 0.72 0.58	Aug 0.24 0.41 0.52	Sep 0.27 0.36 0.47	Oct 0.46 0.59 0.94	Nov 0.45 0.46 1.07	Dec 0.5 0.4 1.4
AWS0 ABC AWSKP AWS2	Jan 0.56 0.34 0.91 1.8	Feb 0.7 0.32 0.74 1.88	Mar 0.57 1.46 2.08 1.71	Apr 0.24 1.02 1.3 1.38	May 0.28 0.96 1.29 1.1	Jun 0.29 0.54 0.82 0.66	Jul 0.24 0.72 0.58 0.5	Aug 0.24 0.41 0.52 0.43	Sep 0.27 0.36 0.47 0.57	Oct 0.46 0.59 0.94 1.56	Nov 0.45 0.46 1.07 1.88	Dec 0.5 0.4 1.4 1.53
AWS0 ABC AWSKP AWS2 AWSN	Jan 0.56 0.34 0.91 1.8 2.78	Feb 0.7 0.32 0.74 1.88 2.43	Mar 0.57 1.46 2.08 1.71 1.85	Apr 0.24 1.02 1.3 1.38 1.17	May 0.28 0.96 1.29 1.1 1.03	Jun 0.29 0.54 0.82 0.66 0.69	Jul 0.24 0.72 0.58 0.5 0.56	Aug 0.24 0.41 0.52 0.43 0.54	Sep 0.27 0.36 0.47 0.57 0.64	Oct 0.46 0.59 0.94 1.56 1.78	Nov 0.45 0.46 1.07 1.88 2.79	Dec 0.5 0.4 1.4 1.53 2.83
AWS0 ABC AWSKP AWS2 AWSN AWS3	Jan 0.56 0.34 0.91 1.8 2.78 3.09	Feb 0.7 0.32 0.74 1.88 2.43 2.44	Mar 0.57 1.46 2.08 1.71 1.85 2.43	Apr 0.24 1.02 1.3 1.38 1.17 1.41	May 0.28 0.96 1.29 1.1 1.03 1.25	Jun 0.29 0.54 0.82 0.66 0.69 1.15	Jul 0.24 0.72 0.58 0.5 0.56 0.75	Aug 0.24 0.41 0.52 0.43 0.54 0.79	Sep 0.27 0.36 0.47 0.57 0.64 1.03	Oct 0.46 0.59 0.94 1.56 1.78 1.91	Nov 0.45 0.46 1.07 1.88 2.79 3.16	Dec 0.5 0.4 1.4 1.53 2.83 3.06
AWS0 ABC AWSKP AWS2 AWSN AWS3	Jan 0.56 0.34 0.91 1.8 2.78 3.09	Feb 0.7 0.32 0.74 1.88 2.43 2.44	Mar 0.57 1.46 2.08 1.71 1.85 2.43	Apr 0.24 1.02 1.3 1.38 1.17 1.41	May 0.28 0.96 1.29 1.1 1.03 1.25	Jun 0.29 0.54 0.82 0.66 0.69 1.15	Jul 0.24 0.72 0.58 0.5 0.56 0.75	Aug 0.24 0.41 0.52 0.43 0.54 0.79	Sep 0.27 0.36 0.47 0.57 0.64 1.03	Oct 0.46 0.59 0.94 1.56 1.78 1.91	Nov 0.45 0.46 1.07 1.88 2.79 3.16	Dec 0.5 0.4 1.4 1.53 2.83 3.06
AWS0 ABC AWSKP AWS2 AWSN AWS3 Precipitat	Jan 0.56 0.34 0.91 1.8 2.78 3.09 ion (P)	Feb 0.7 0.32 0.74 1.88 2.43 2.44	Mar 0.57 1.46 2.08 1.71 1.85 2.43	Apr 0.24 1.02 1.3 1.38 1.17 1.41	May 0.28 0.96 1.29 1.1 1.03 1.25	Jun 0.29 0.54 0.82 0.66 0.69 1.15	Jul 0.24 0.72 0.58 0.5 0.56 0.75	Aug 0.24 0.41 0.52 0.43 0.54 0.79	Sep 0.27 0.36 0.47 0.57 0.64 1.03	Oct 0.46 0.59 0.94 1.56 1.78 1.91	Nov 0.45 0.46 1.07 1.88 2.79 3.16	Dec 0.5 0.4 1.4 1.53 2.83 3.06
AWS0 ABC AWSKP AWS2 AWSN AWS3 Precipitat	Jan 0.56 0.34 0.91 1.8 2.78 3.09 ion (P) Jan	Feb 0.7 0.32 0.74 1.88 2.43 2.44 Feb	Mar 0.57 1.46 2.08 1.71 1.85 2.43 Mar	Apr 0.24 1.02 1.3 1.38 1.17 1.41 Apr	May 0.28 0.96 1.29 1.1 1.03 1.25 May	Jun 0.29 0.54 0.82 0.66 0.69 1.15 Jun	Jul 0.24 0.72 0.58 0.5 0.56 0.75 Jul	Aug 0.24 0.41 0.52 0.43 0.54 0.79 Aug	Sep 0.27 0.36 0.47 0.57 0.64 1.03	Oct 0.46 0.59 0.94 1.56 1.78 1.91 Oct	Nov 0.45 0.46 1.07 1.88 2.79 3.16 Nov	Dec 0.5 0.4 1.4 1.53 2.83 3.06 Dec
AWS0 ABC AWSKP AWS2 AWSN AWS3 Precipitat AWS0	Jan 0.56 0.34 0.91 1.8 2.78 3.09 ion (P) Jan 0.68	Feb 0.7 0.32 0.74 1.88 2.43 2.44 Feb 0.22	Mar 0.57 1.46 2.08 1.71 1.85 2.43 Mar 0.43	Apr 0.24 1.02 1.3 1.38 1.17 1.41 Apr 0.99	May 0.28 0.96 1.29 1.1 1.03 1.25 May 0.61	Jun 0.29 0.54 0.82 0.66 0.69 1.15 Jun 0.72	Jul 0.24 0.72 0.58 0.5 0.56 0.75 Jul 1.34	Aug 0.24 0.41 0.52 0.43 0.54 0.79 Aug 0.93	Sep 0.27 0.36 0.47 0.57 0.64 1.03 Sep 0.61	Oct 0.46 0.59 0.94 1.56 1.78 1.91 Oct 0.29	Nov 0.45 0.46 1.07 1.88 2.79 3.16 Nov 0.38	Dec 0.5 0.4 1.4 1.53 2.83 3.06 Dec 0.04
AWS0 ABC AWSKP AWS2 AWSN AWS3 Precipitat AWS0 ABC	Jan 0.56 0.34 0.91 1.8 2.78 3.09 ion (P) Jan 0.68 0.02	Feb 0.7 0.32 0.74 1.88 2.43 2.44 Feb 0.22 0.03	Mar 0.57 1.46 2.08 1.71 1.85 2.43 Mar 0.43 0.07	Apr 0.24 1.02 1.3 1.38 1.17 1.41 Apr 0.99 0.28	May 0.28 0.96 1.29 1.1 1.03 1.25 May 0.61 0.52	Jun 0.29 0.54 0.82 0.66 0.69 1.15 Jun 0.72 1.17	Jul 0.24 0.72 0.58 0.5 0.56 0.75 Jul 1.34 1.91	Aug 0.24 0.41 0.52 0.43 0.54 0.79 Aug 0.93 3.42	Sep 0.27 0.36 0.47 0.57 0.64 1.03 Sep 0.61 1.49	Oct 0.46 0.59 0.94 1.56 1.78 1.91 Oct 0.29 0.1	Nov 0.45 0.46 1.07 1.88 2.79 3.16 Nov 0.38 0.19	Dec 0.5 0.4 1.4 1.53 2.83 3.06 Dec 0.04 0.04
AWS0 ABC AWSKP AWS2 AWSN AWS3 Precipitat AWS0 ABC AWSKP	Jan 0.56 0.34 0.91 1.8 2.78 3.09 ion (P) Jan 0.68 0.02 0.27	Feb 0.7 0.32 0.74 1.88 2.43 2.44 Feb 0.22 0.03 0.42	Mar 0.57 1.46 2.08 1.71 1.85 2.43 Mar 0.43 0.07 0.46	Apr 0.24 1.02 1.3 1.38 1.17 1.41 Apr 0.99 0.28 1.04	May 0.28 0.96 1.29 1.1 1.03 1.25 May 0.61 0.52 0.79	Jun 0.29 0.54 0.82 0.66 0.69 1.15 Jun 0.72 1.17 1.62	Jul 0.24 0.72 0.58 0.5 0.56 0.75 Jul 1.34 1.91 2.79	Aug 0.24 0.41 0.52 0.43 0.54 0.79 Aug 0.93 3.42 2.8	Sep 0.27 0.36 0.47 0.57 0.64 1.03 Sep 0.61 1.49 1.97	Oct 0.46 0.59 0.94 1.56 1.78 1.91 Oct 0.29 0.1 2.09	Nov 0.45 0.46 1.07 1.88 2.79 3.16 Nov 0.38 0.19 0.09	Dec 0.5 0.4 1.4 1.53 2.83 3.06 Dec 0.04 0.04 0.19
AWS0 ABC AWSKP AWS2 AWSN AWS3 Precipitat AWS0 ABC AWSKP AWS2	Jan 0.56 0.34 0.91 1.8 2.78 3.09 ion (P) Jan 0.68 0.02 0.27 0.31	Feb 0.7 0.32 0.74 1.88 2.43 2.44 Feb 0.22 0.03 0.42 0.15	Mar 0.57 1.46 2.08 1.71 1.85 2.43 Mar 0.43 0.07 0.46 0.22	Apr 0.24 1.02 1.3 1.38 1.17 1.41 Apr 0.99 0.28 1.04 0.42	May 0.28 0.96 1.29 1.1 1.03 1.25 May 0.61 0.52 0.79 0.7	Jun 0.29 0.54 0.82 0.66 0.69 1.15 Jun 0.72 1.17 1.62 2.36	Jul 0.24 0.72 0.58 0.5 0.56 0.75 Jul 1.34 1.91 2.79 4.71	Aug 0.24 0.41 0.52 0.43 0.54 0.79 Aug 0.93 3.42 2.8 3.68	Sep 0.27 0.36 0.47 0.57 0.64 1.03 Sep 0.61 1.49 1.97 2.04	Oct 0.46 0.59 0.94 1.56 1.78 1.91 Oct 0.29 0.1 2.09 1.93	Nov 0.45 0.46 1.07 1.88 2.79 3.16 Nov 0.38 0.19 0.09 0.6	Dec 0.5 0.4 1.4 1.53 2.83 3.06 Dec 0.04 0.04 0.19 0
AWS0 ABC AWSKP AWS2 AWSN AWS3 Precipitat AWS0 ABC AWSKP AWS2 AWSN	Jan 0.56 0.34 0.91 1.8 2.78 3.09 ion (P) Jan 0.68 0.02 0.27 0.31 0.42	Feb 0.7 0.32 0.74 1.88 2.43 2.44 Feb 0.22 0.03 0.42 0.15 0.66	Mar 0.57 1.46 2.08 1.71 1.85 2.43 Mar 0.43 0.07 0.46 0.22 0.69	Apr 0.24 1.02 1.3 1.38 1.17 1.41 Apr 0.99 0.28 1.04 0.42 1.1	May 0.28 0.96 1.29 1.1 1.03 1.25 May 0.61 0.52 0.79 0.7 1.19	Jun 0.29 0.54 0.82 0.66 0.69 1.15 Jun 0.72 1.17 1.62 2.36 2.2	Jul 0.24 0.72 0.58 0.5 0.56 0.75 Jul 1.34 1.91 2.79 4.71 5.41	Aug 0.24 0.41 0.52 0.43 0.54 0.79 Aug 0.93 3.42 2.8 3.68 5.13	Sep 0.27 0.36 0.47 0.57 0.64 1.03 Sep 0.61 1.49 1.97 2.04 3.07	Oct 0.46 0.59 0.94 1.56 1.78 1.91 Oct 0.29 0.1 2.09 1.93 1.41	Nov 0.45 0.46 1.07 1.88 2.79 3.16 Nov 0.38 0.19 0.09 0.6 0.27	Dec 0.5 0.4 1.4 1.53 2.83 3.06 Dec 0.04 0.04 0.19 0 0.8

Step 3 – Multiple imputation technique

Unfortunately, all stations recorded some simultaneous gaps for a given variable: 5.7% and 4.3% for temperature and precipitation, respectively. For these cases, we applied a multiple imputation technique (the Regularized Expectation Maximization algorithm, RegEM; Schneider, 2001) to obtain the final PYRAMID_daily time series (Fig. S1).

This algorithm considers more available meteorological variables. In our case, we feed the procedure with the minimum, maximum and mean temperatures, precipitation, atmospheric pressure and relative humidity. The additional two variables (atmospheric pressure and relative humidity) allowed for a reduction of the estimated uncertainty associated with the computing of these missing data (σ_{RegEM}).

RegEM has been applied to the daily missing data on a monthly basis, considering the possible seasonal effect on the uncertainty. Table S3 reports the number of days imputed to the complete PYRAMID_daily time series for each month and for each variable. The daily standard error σ_{RegEM} estimated by the RegEM algorithm (Table S5) has been associated with each imputed data filled into the complete and final time series reconstructions for daily minimum, maximum, and mean temperatures and precipitation.

Table S4. Number of days imputed through RegEM

Variable	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
minT	0	1	1	35	87	48	68	71	60	33	10	0
maxT	0	1	1	35	87	48	68	71	60	33	10	0
meanT	0	1	1	35	87	48	68	71	60	33	10	0
Prec	13	31	14	52	99	48	31	9	1	9	4	0

Table S5. Uncertainty (°*C* and mm for temperature and precipitation, respectively) associated to the daily imputed thought RegEM

Variable	Jan	Feb	Mar	Apr	May	Jun	Jul	Ago	Sep	Oct	Nov	Dic
minT	-	3.25	2.89	2.34	2.21	1.95	0.83	0.96	1.37	2.54	2.46	-
maxT	-	3.64	3.22	2.82	2.47	1.87	1.34	1.31	1.44	2.30	2.55	-
meanT	-	3.20	2.82	2.34	2.07	1.58	0.72	0.84	1.16	2.17	2.29	-
р	0.18	0.35	0.65	0.86	0.93	2.73	4.54	4.51	2.73	1.59	0.69	-

Step 4- Monthly aggregation

Finally, the PYRAMID_daily time series, for each variable, have been aggregated on the monthly scale (hereinafter referred to as PYRAMID). The uncertainty associated with each value of the PYRAMID (named σ_m) is estimated considering the propagation of the daily uncertainty to the monthly one through the computation of the mean (for temperature) or of the sum (for precipitation).

The propagation of the uncertainty from the daily data d_i to the monthly one is different if we consider the monthly average M_m (as for temperature) or the monthly accumulation M_c (as for precipitation):

$$\sigma_m = \sqrt{\sum_{j=1}^N \left(\frac{\partial M_m}{\partial d_j} \cdot \sigma_{d_j}\right)^2} = \sqrt{\sum_{j=1}^N \left(\frac{\partial \left(\frac{1}{N} \sum_{i=1}^N d_i\right)}{\partial d_j} \cdot \sigma_{d_j}\right)^2} = \sqrt{\frac{1}{N} \sum_{j=1}^N \sigma_{d_j}^2} \quad (1)$$

where $M_m = \frac{1}{N} \sum_{i=1}^N d_i$

and

$$\sigma_m = \sqrt{\sum_{j=1}^N \left(\frac{\partial Mc}{\partial d_j} \cdot \sigma_{d_j}\right)^2} = \sqrt{\sum_{j=1}^N \left(\frac{\partial \sum_{i=1}^N d_i}{\partial d_j} \cdot \sigma_{d_j}\right)^2} = \sqrt{\sum_{j=1}^N \sigma_{d_j}^2} \quad (2)$$

where $M_c = \sum_{i=1}^N d_i$

N is the number of days of a given month and σ_{d_i} the daily uncertainty as :

($\sigma_{d_j} = 0$	if the data belongs to the REF
ł	$\sigma_{d_j} = \sigma_{REF_filled}$	if the data is imputed through infilling step
	$\sigma_{d_j} = \sigma_{RegEM}$	if the data is imputed through RegEM

Finally, we estimated the uncertainty associated with the annual Sen's slopes (1994-2013) of each time series through a Monte Carlo uncertainty analysis (e.g., James and Oldenburg 1997):

- For each month value, a random realization of the normal distribution with zero-mean and σ_m standard deviation is computed.
- This uncertainty is added to each monthly estimate coming from eq. (1) or (2), obtaining a time series perturbed by the uncertainty.
- The Sen's slope and associated p-value is computed.
- The process is repeated until the convergence of the mean value of the Sen's slope and the associated standard deviation. In these regards, we observed that approximately 5000 runs are enough to ensure the convergence with a threshold of 10^{-5} °C a⁻¹ and 10^{-3} mm a⁻¹ for temperature and precipitation, respectively.

Table S6 reports the Sen's slopes for the 1994-2013 period calculated for each reconstructed monthly time series (PYRAMID), associated intervals of confidence (95%), median p-value and the associated [5% and 95%] quantiles.

Table S6. Sen's slopes for the 1994-2013 period calculated for each reconstructed monthly time series (*PYRAMID*), associated intervals of confidence (95%), median p-value and the associated [5% and 95%] quantiles.

Time series	Sen's slope	Interval of confidence (95%)	p-value	quantiles [5% and 95%]
PYRAMID minT	$0.072 \ ^{\circ}C \ a^{-1}$	+/- 0.011	0.0021	[0.0001-0.0212]
PYRAMID maxT	$0.009 \ ^{\circ}C \ a^{-1}$	+/- 0.012	0.7212	[0.2843-0.9741]
PYRAMID meanT	0.044 °C a ⁻¹	+/- 0.008	0.035	[0.0053-0.1443]
PYRAMID Prec	-13.66 mm a ⁻¹	+/- 2.36	0.0021	[0.0002-0.0252]

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Supplementary Material 2

Further analysis on the non-stationarity of the reconstructed daily precipitation time series at Pyramid station

The analysis described in the following aims at assessing whether the decreasing trend of precipitation observed for the daily time series reconstructed at Pyramid (1994-2013) is due to a reduction of duration or to a reduction of intensity.

To this goal we considered two different periods p, say p1 = 1994-1998 and p2 = 2009-2013, which correspond to the first and last five years of the whole analysis period p0 = 1994-2013. For a given week w, the mean weekly-cumulated precipitation RR_w^p is defined as $RR_w^p = (\sum_{y=1}^N RR_{w,y})/N$, where N is the number of years during the period p.

The difference between the mean weekly-cumulated precipitation RR_w^{p1} and RR_w^{p2} may be attributed to a change in the corresponding duration and/or intensity. To separate the relative contributions, we defined two descriptors:

1-The duration of precipitation for a given week *w* of the year *y* is described by the number of wet days $W_{w,y}$, where a "wet day" is defined by the threshold RR>1 mm. Then, the mean W_w^p over a given period *p* of *N* years is computed as:

$$W_{w}^{p} = \frac{1}{N} \sum_{y=1}^{N} W_{w,y}$$
(1)

2- The daily intensity of precipitation for a given week *w* of the year *y* is computed as the cumulative precipitation $RR_{w,y}$ divided by the number of wet days $W_{w,y}$. Then, a mean intensity index $SDII_w^p$ over a given period *p* of *N* years is computed as:

$$SDII_w^p = \frac{1}{N} \sum_{y=1}^N \frac{RR_{w,y}}{W_{w,y}}$$
(2)

An attempt to quantify the contribution to the variation in precipitation arising from variation in duration and/or intensity is to consider one of the two terms stationary over the whole period. This is a rough approximation as the non-stationarity may not be linear. However, an estimation of the relative contribution arising from the change in duration can be expressed considering the intensity of precipitation as stationary over the whole period p0 $(SDII_w^{p0})$ and computing the variation of precipitation due only to a variation in duration, i.e. $(W_w^{p2} - W_w^{p1}) * SDII_w^{p0}$. The relative contribution RLD to the total change $(RR_w^{p2} - RR_w^{p1})$ can be estimated as:

$$RLD = \frac{(W_w^{p_2} - W_w^{p_1}) * SDII_w^{p_0}}{(RR_w^{p_2} - RR_w^{p_1})} * 100$$
(3)

The indexes proposed above are shown in figure S6 in dark blue area for the 1994-1998 period and light blue area for the 2009-2013 period for the W_w^p , $SDII_w^p$ and RR_w^p (panel a, b and c respectively). For each index, we defined as residues the difference between the two periods (red bar plot).

The *RLD* (shown in red on the right axis of the panel c) indicates that the early and late monsoon are more affected by the reduction in duration than intensity, while it is the opposite during the monsoon.



Figure S6. Panel a: Mean number of wet day per week W_w^p . Panel b: Mean daily precipitation intensity $SDII_w^p$ (mm). Panel c: Mean weekly-cumulated precipitation RR_w^p and relative contribution of the change in duration RLD in % (red line)

Supplementary Material 3

Evaluation of the possible underestimation of solid precipitation at Pyramid

The Chaurikhark station (ID 1202) (Fig. 1b, Table 2) is located at 2619 m a.s.l., along the same valley of PYRAMID (Dud Koshi). This station records only daily precipitation with a tipping bucket. Not having the availability of air temperature data, we estimated for this location the mean daily values for the 1994-2013 period through of the lapse rate and the mean daily air temperature series reconstructed in this study at PYRAMID.

The precipitation phase has been taken into account assuming that the probability of snowfall and rainfall depends on the mean daily air temperature (as well as we did for PYRAMID, see the text). In Figure S7 we observe that 86% of precipitation is concentrated during June-September. The probability of snowfall is very low (0.6%) and it is completely concentrated in December, January, and February (the mean temperature of these months is about 5 °C).

We realized the scatter-plot of Figure S8 between their monthly precipitation (averaged on 1994-2013 period) in order to compare the two stations. Data were previously log transformed assuring their normal distribution. First of all, we observe the strong relationship due to the fact that they belong to the same valley, although there are 2400 m of altitudinal range. Secondly, we note the variability between the two stations is higher for those months which record less precipitation (spring and winter). Probably, during these months, PYRAMID underestimates the solid precipitation which fall in liquid form at lower elevation (Chaurikhark). In this regard we realized the graph of Figure S8 for showing the precipitation ratio between PYRAMID and Chaurikhark. We observe that during the monsoon (June-September), period of the year when the probability of snowfall at PYRAMID is very low (4%) (see the text), the precipitation ratio is $21\pm3\%$ (standard deviation) that means at 5050 m a.s.l. it rains a fifth respect to 2600 m a.s.l. (see Fig. 5). Outside the monsoon months this ratio decreases to $15\pm6\%$. Assuming that this lower ratio if completely attributable to the solid precipitation not captured at high elevations, we calculated an underestimation of 15 ± 5 mm y⁻¹, corresponding to $3\pm1\%$ of the total annual cumulated precipitation at PYRAMID (446 mm y⁻¹).



Figure S7. Mean monthly cumulated precipitation subdivided into snowfall and rainfall and mean temperature at Chaurikhark station (ID 1202) (reference period 1994-2013). The bars represent the standard deviation.



Figure S8. Scatter-plot between the monthly precipitation of PYRAMID and Chaurikhark (averaged on 1994-2013 period).



Figure S9. Ratio between the PYRAMID and Chaurikhark total precipitation for each month (averaged on 1994-2013 period).