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Concentrations and source regions of light-absorbing particles in snow/ice in northern Pakistan and their impact on snow albedo

Chaman Gul et al.

Correspondence to: Shichang Kang (shichang.kang@lzb.ac.cn), Siva Praveen Puppala (sivapraveen.puppala@icimod.org) and Chaman Gul (chaman.gul@icimod.org, chaman@lzb.ac.cn)

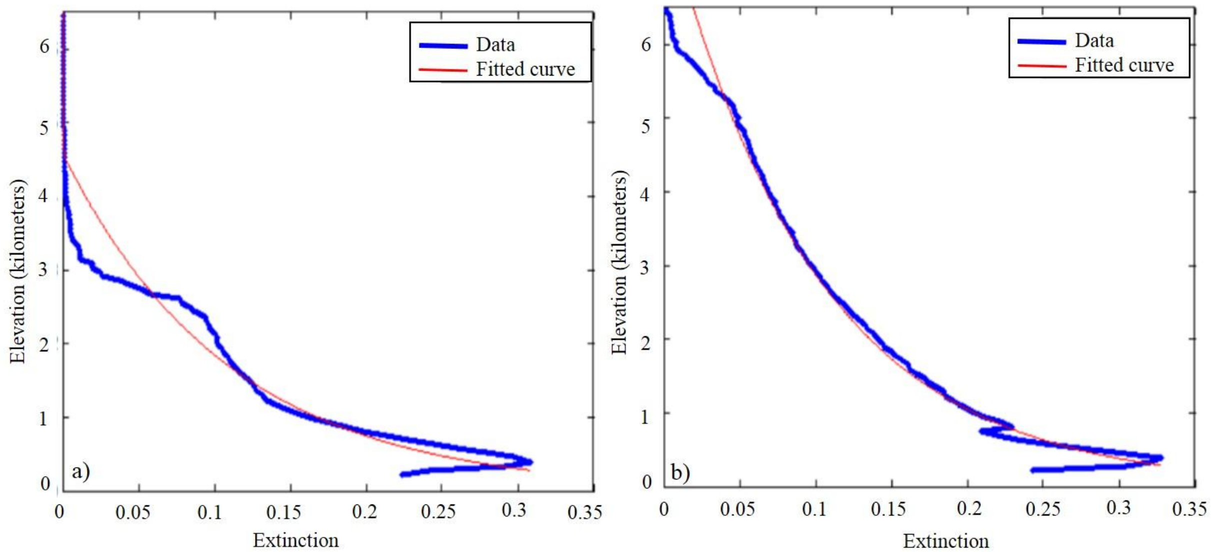

Figure S1. CALPISO extinction profile for a) winter (December, January), and b) summer (May, June)

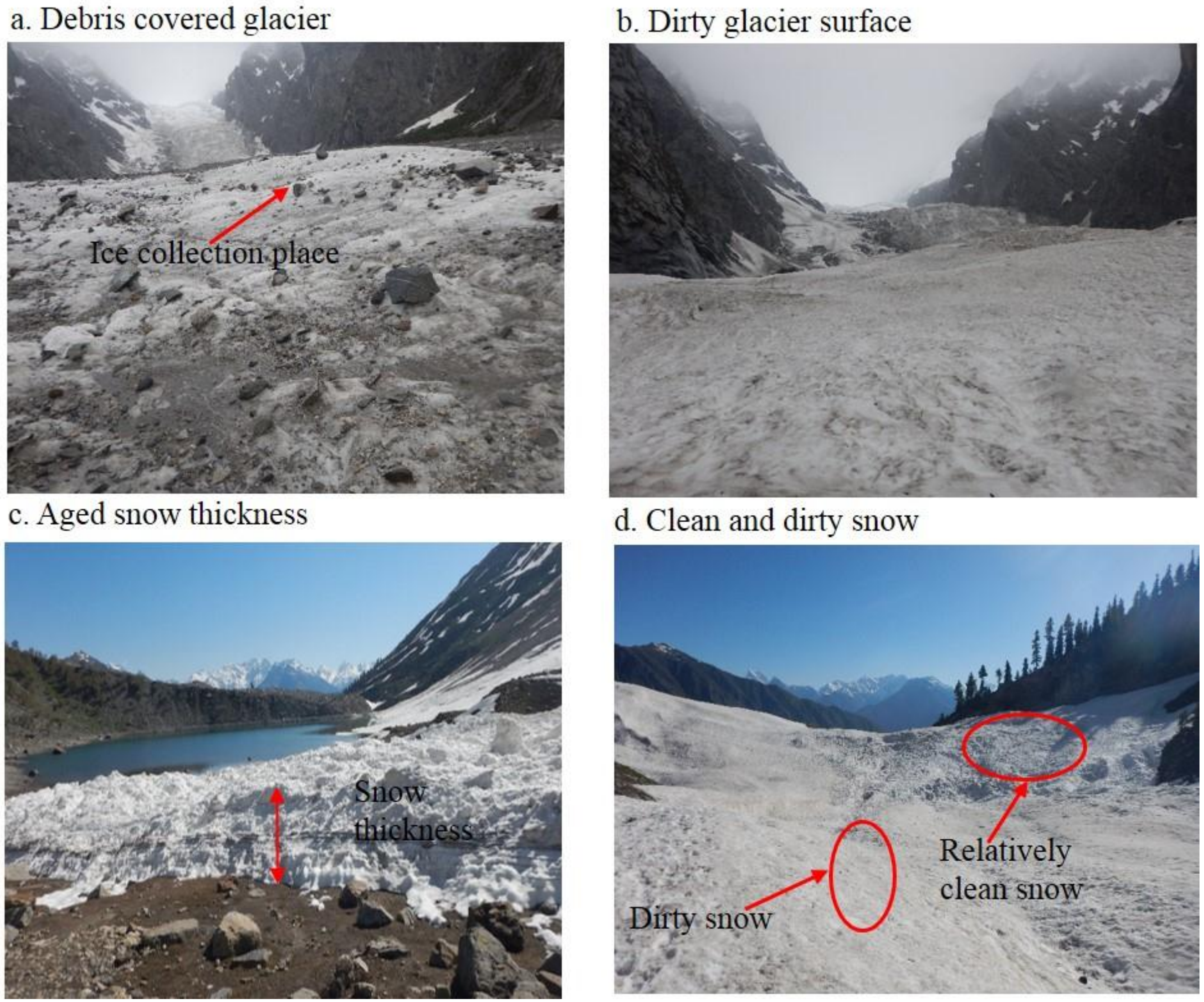

Figure S2. Appearance of different summer snow/ice sampling sites on a) b) Gulkin glacier, c) near Sachin glacier, and d) Sachin glacier

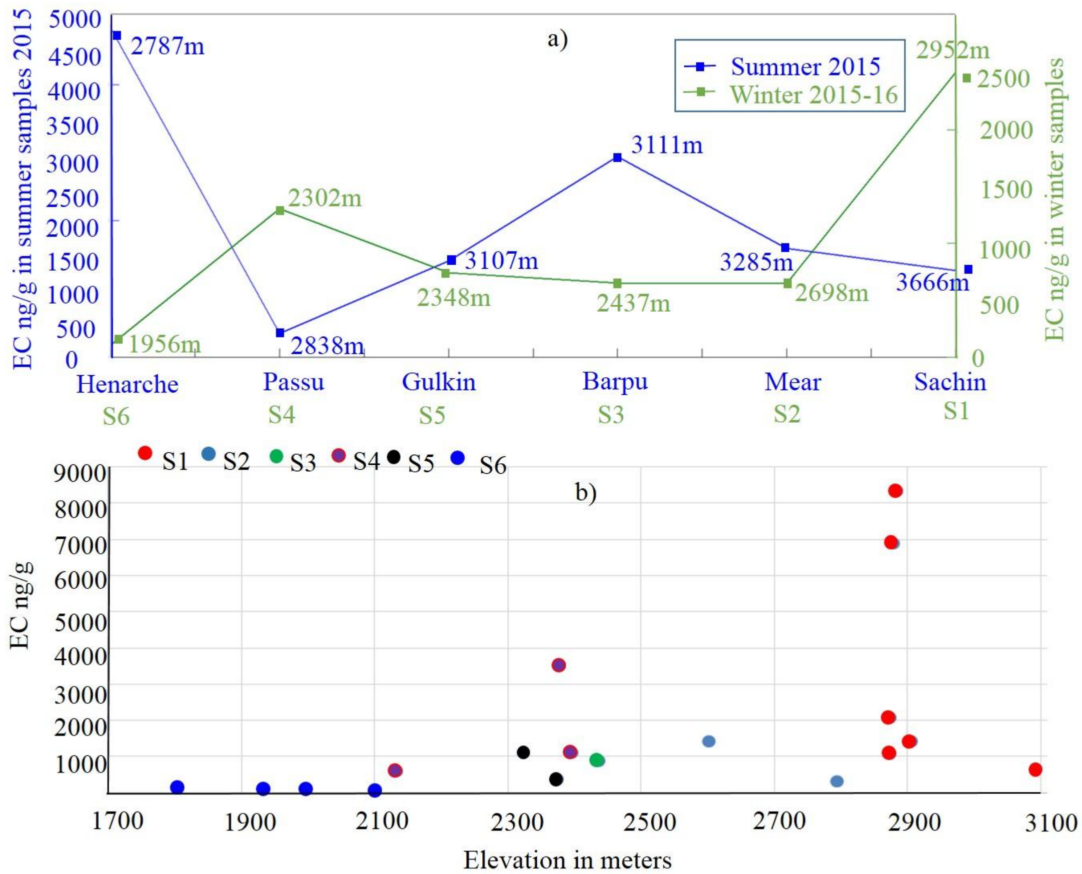

Figure S3. a) Average concentration of black carbon at sites S1 to S6 sampled in winter and glaciers sampled in summer; b) individual sample concentration in winter samples.

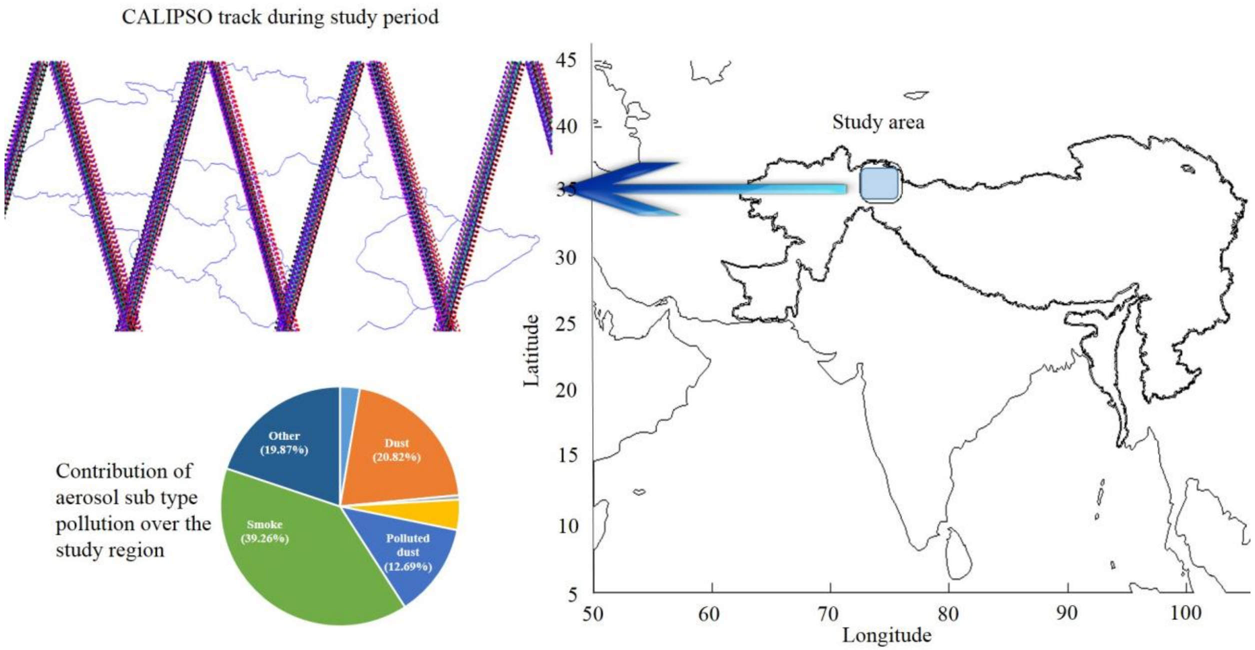

Figure S4. Contribution of subtype aerosols (%) in the atmosphere along the track of CALIPSO during the selected month June in 2006-2014

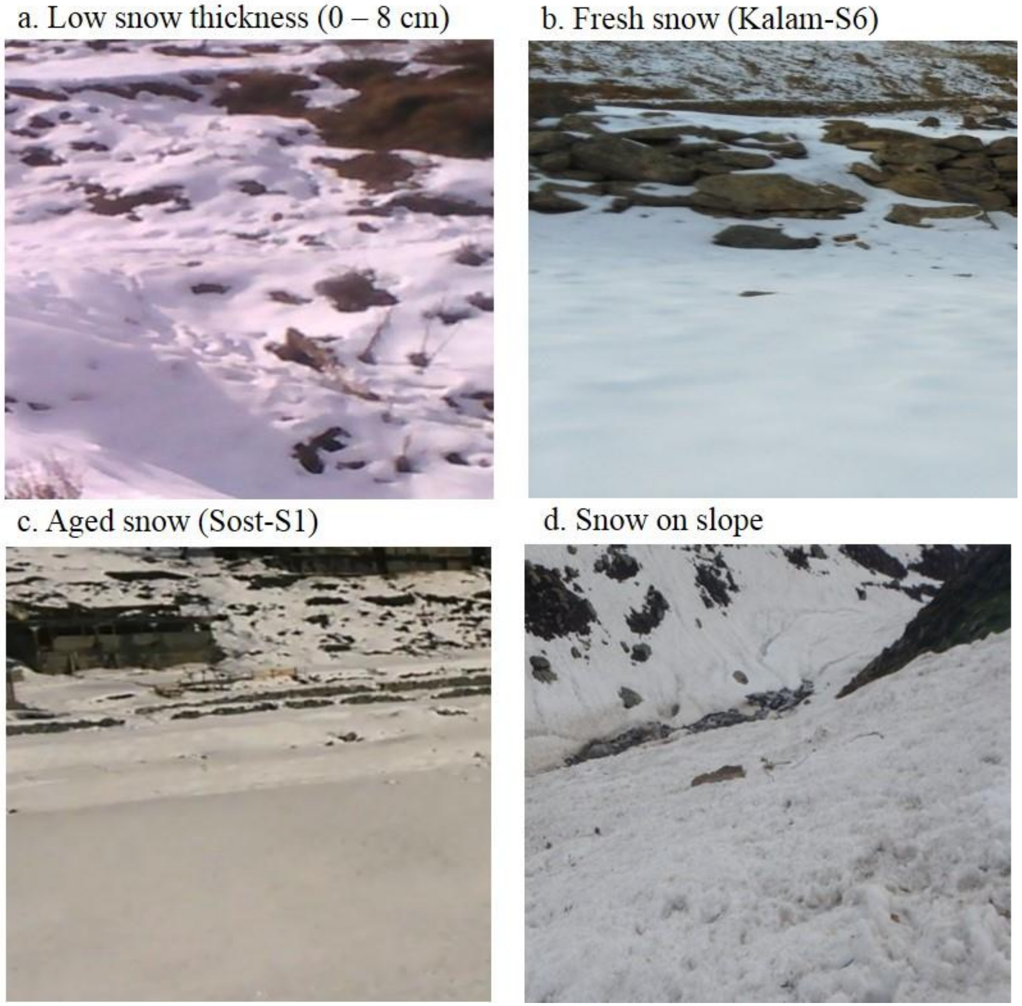

Figure S5. Appearance of different snow areas sampled in winter

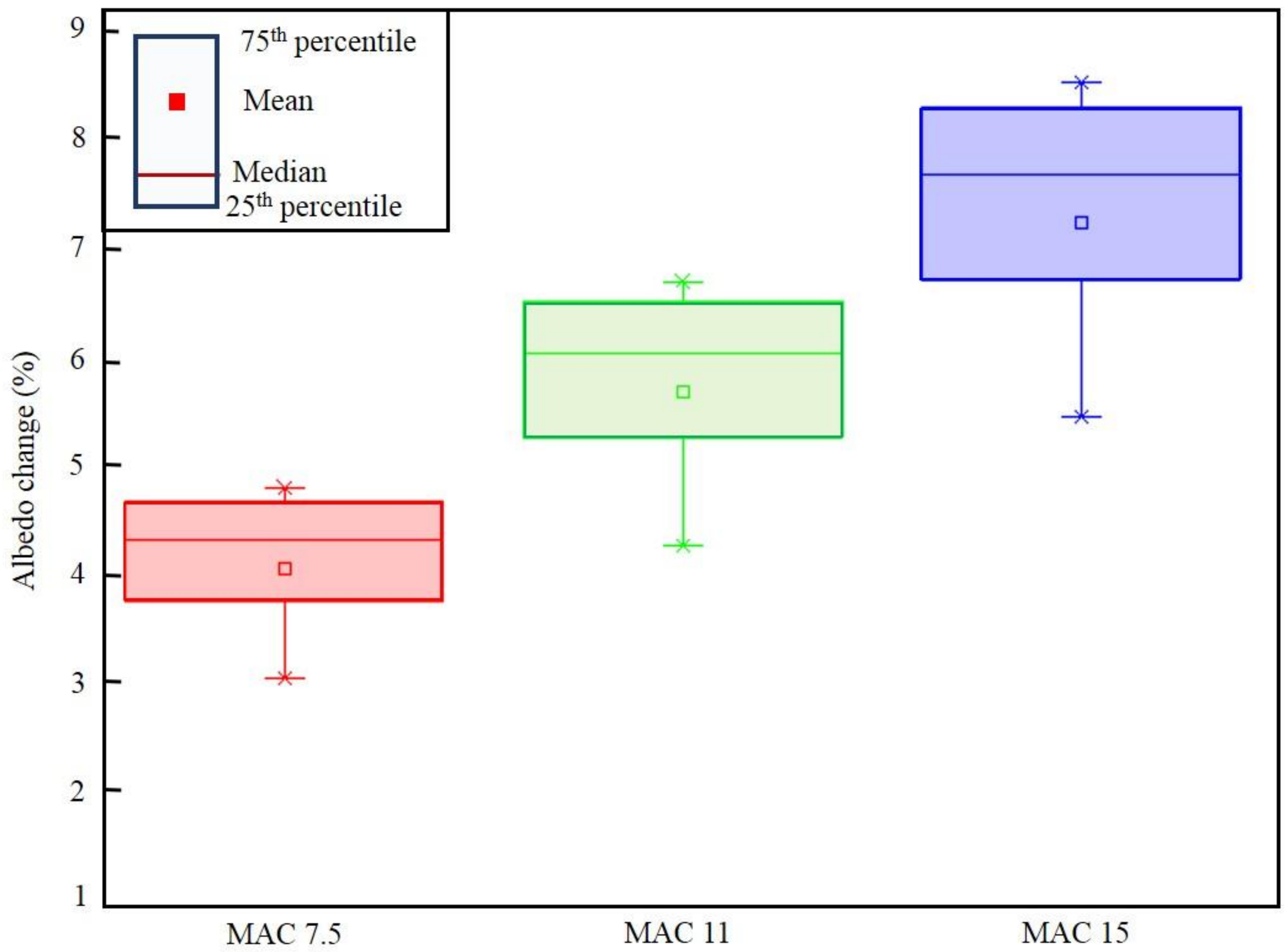
75th percentile
Mean
Median
25th percentile
Albedo change (%)
1
2
3
4
5
6
7
8
9
MAC 7.5
MAC 11
MAC 15

Figure S6. Albedo reduction (%) range between sulfate coated and uncoated black carbon calculated for different Mass Absorption Cross section (MAS) and the low concentration site S6.

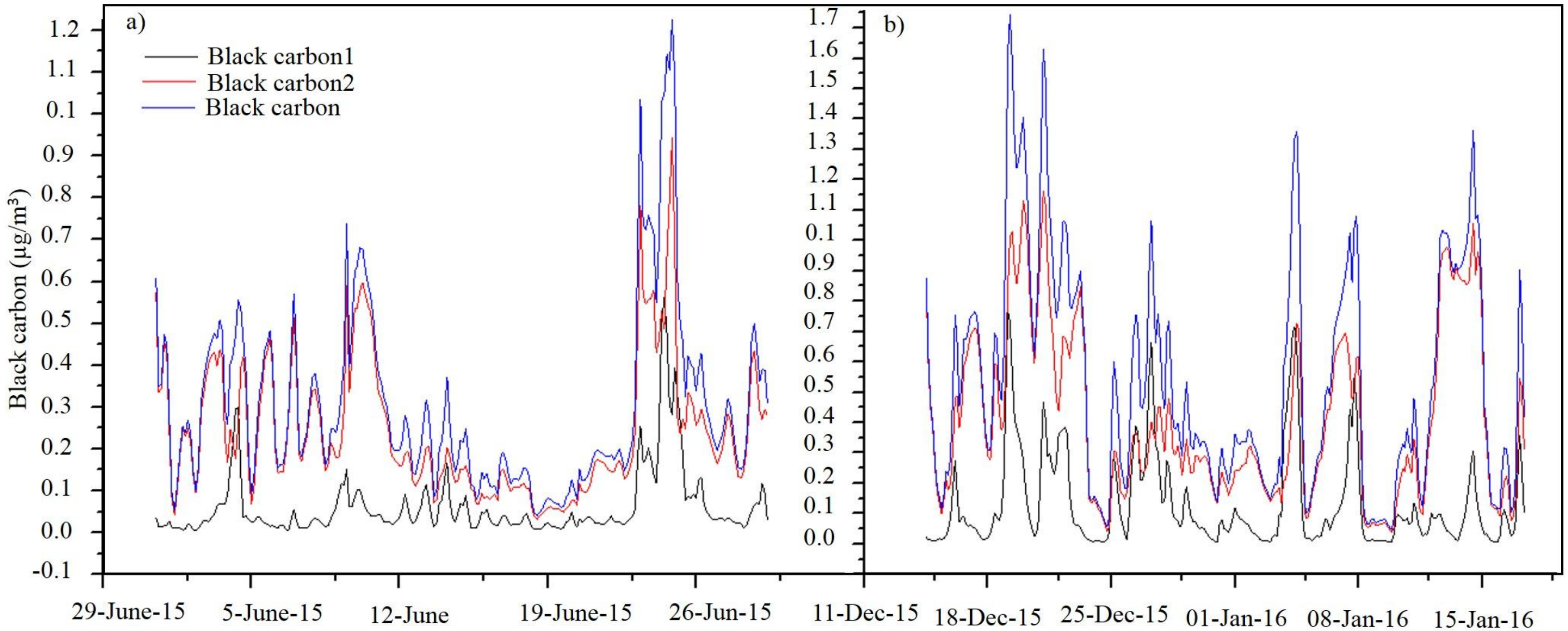

Figure S7. Concentration of black carbon1, black carbon2 and black carbon on the Sachin glacier calculated using the WRF-STEM model: a) summer, b) winter.

Tables

Table S1 Parameters used for sensitivity analysis with SNICAR model for winter snow samples under the input parameters of direct incident radiation and mid-latitude winter, clear-sky conditions.

1 = solar zenith angle

2 = snow grain effective radius (µm)

3 = snowpack thickness (m)

4 = snowpack density (kg m^{-3})

5 = albedo of underlying ground (a. visible, 0.3-0.7µm, b. near-infrared, 0.7-5.0µm)

6 = Mass Absorption Cross section scaling factor (experimental) for black carbon

7= BC concentration (ppb, uncoated)

8 = dust concentration (ppm, 5.0–10.0 µm diameter)

9 = volcanic ash concentration (ppm)

10 = experimental particle 1 concentration (ppb)

Site	1	2	3	4	5a	5b	6	7	8	9	10
Kalam-S6	80.34	150	0.08	200	0.2	0.4	7.5/11/15	100	5.5	0	0
Kalam-S6	71.25	150	0.08	200	0.2	0.4	7.5/11/15	100	5.5	0	0
Kalam-S6	63.96	150	0.08	200	0.2	0.4	7.5/11/15	100	5.5	0	0
Kalam-S6	59.21	150	0.08	200	0.2	0.4	7.5/11/15	100	5.5	0	0
Kalam-S6	57.66	150	0.08	200	0.2	0.4	7.5/11/15	100	5.5	0	0
Kalam-S6	59.54	150	0.08	200	0.2	0.4	7.5/11/15	100	5.5	0	0
Kalam-S6	64.57	150	0.08	200	0.2	0.4	7.5/11/15	100	5.5	0	0

Kalam-S6	72.07	150	0.08	200	0.2	0.4	7.5/11/15	100	5.5	0	0
Kalam-S6	81.31	150	0.08	200	0.2	0.4	7.5/11/15	100	5.5	0	0
Kalam-S6	88.95	150	0.08	200	0.2	0.4	7.5/11/15	100	5.5	0	0
Sost-S1	82.61	350	0.04	320	0.19	0.35	7.5/11/15	1000	57	0	0
Sost-S1	73.66	350	0.04	320	0.19	0.35	7.5/11/15	1000	57	0	0
Sost-S1	66.45	350	0.04	320	0.19	0.35	7.5/11/15	1000	57	0	0
Sost-S1	61.64	350	0.04	320	0.19	0.35	7.5/11/15	1000	57	0	0
Sost-S1	59.66	350	0.04	320	0.19	0.35	7.5/11/15	1000	57	0	0
Sost-S1	61.36	350	0.04	320	0.19	0.35	7.5/11/15	1000	57	0	0
Sost-S1	65.93	350	0.04	320	0.19	0.35	7.5/11/15	1000	57	0	0
Sost-S1	72.98	350	0.04	320	0.19	0.35	7.5/11/15	1000	57	0	0
Sost-S1	81.80	350	0.04	320	0.19	0.35	7.5/11/15	1000	57	0	0
Sost-S1	88.95	350	0.04	320	0.19	0.35	7.5/11/15	1000	57	0	0

Table S2. EC concentrations in glacier ice and snow and plains snow in north Pakistan, and other regions

Location	Lat/long	Elevation (masl)	Min. EC (ngg^{-1})	Max. EC (ngg^{-1})	Time period (years)	Sample type/snow age	Reference
Mera Glacier, Nepal	27.72°N 86.8°E	6376	3	13	1999–2010	Ice core (rBC)	Ginot et al., 2014
Numanani, China	30.45°N 81.27°E	5900	4	14	Annual mean 2004	Ss (EC)	Xu et al., 2006
Greenland	72.6°N, 38.5°W	3209	4.2	30.1	1994 – 1996		Slater et al., 2002
NCO-P, Nepal	27.95°N, 86.82°E	5079	26	68.2	March – May 2006		Yasunari et al., 2010
Kangwure, China	28.47°N 85.82°E	6000	22	122	Annual mean 2001	Ss (EC)	Xu et al., 2007
Qiangyong, China	28.83°N 90.25°E	5400	43	143	Annual mean 2001	Ss (EC)	Xu et al., 2008
Zhadang, China	30.47°N 90.50°E	5802	334	473	2001–2010		Qu et al., 2014
Muji glacier, China	39.19°N 73.74° E	5062	25	731	2012		Yang et al., 2015
Zhadang, China	30.47°N 90.5°E	5802	114	1114	2005–2006		Ming et al., 2009
Tien Shan, China	43.1°N 86.82°E	4050		3000	2011	bottom firn-pack	Xu et al., 2012
Mera glacier, Nepal	27.72°N 86.8°E	5400		3535	2009		Kaspari et al., 2014
Northern China			60	4020	Jan-14		Wang et al., 2016
Urumqi glacier, China	43.10°N 86.80°E	4040	16	4093	2013		Ming et al., 2016
LHG glacier, China	39.17°N 96.17°E	5480		28,636	summer 2013-14	superimposed ice	Li et al., 2016
Present study							
Passu glacier	36.45°N 74.85°E	2838	87	734	May-June 2015	DCI (EC)	This study
Sachin glacier	35.32°N 74.76°E	3666	492	1789	May-June 2015	DCI & snow (EC)	This study
Sachin glacier	35.32°N 74.76°E	3666	543	3478	Oct-16	DCI & snow	This study
Gulkin glacier	36.42°N 74.77°E	3066	266	3574	Oct-16	DCI	This study
Mear glacier	36.15°N 74.82°E	3281	222	3656	May-June 2015	DCI (EC)	This study

Gulkin glacier	36.42°N 74.77°E	3066	81	5676	May-June 2015	DCI (EC)	This study
Barpu glacier	36.18°N 74.08°E	3055	877	5994	May-June 2015	DCI (EC)	This study
Henarche glacier	36.05°N 74.57°E	2941	778	10,502	May-June 2015	Surface ice (EC)	This study
S6-Kalam	35.43°N 72.6°E	1958	79	123	8-Jan-16	1–2 days	This study
S3-Tawas	36.39°N 73.36°E	2437		650	2-Jan-16	8–17 days	This study
S2- Hopar	36.22°N 74.75°E	2698	229	1064	1-Jan-16	1–15 days	This study
S5-Shangla	34.83°N 74.82°E	2348	367	1111	6–7 Jan 2016	8–9 days	This study
S4-Astore	35.37°N 74.80°E	2302	450	2640	3–4 Jan 2016	4–7 days	This study
S1- Sost	36.78°N 74.93°E	2951	482	5957	30–31 Dec 2015	2–17 days	This study

Table S3. Broadband albedo values for selected solar zenith angles, and daily mean albedo reduction (%)

Pollutant	**Site S6 (low BC and dust)**				**Site S1 (high BC and dust)**			
	SZA	**MAC 7.5**	**MAC 11**	**MAC 15**	**SZA**	**MAC 7.5**	**MAC 11**	**MAC 15**
	80.34	0.79	0.78	0.77	82.61	0.59	0.56	0.52
	71.25	0.77	0.75	0.74	73.66	0.54	0.50	0.46
	63.96	0.75	0.74	0.72	66.45	0.50	0.46	0.42
	59.21	0.74	0.72	0.71	61.64	0.48	0.43	0.40
	57.66	0.74	0.72	0.71	59.66	0.47	0.43	0.39
BC only	59.54	0.74	0.72	0.71	61.36	0.48	0.43	0.39
	64.57	0.75	0.74	0.72	65.93	0.50	0.46	0.42
	72.07	0.77	0.76	0.74	72.98	0.54	0.49	0.46
	81.31	0.80	0.78	0.77	81.80	0.59	0.55	0.51
	88.95	0.82	0.81	0.80	88.95	0.64	0.60	0.57
	Daily mean reduction (%)	1.77	2.35	2.87		8.70	10.49	12.03
	80.34	0.83	0.83	0.83	82.61	0.76	0.76	0.76
	71.25	0.81	0.81	0.81	73.66	0.73	0.73	0.73
	63.96	0.80	0.80	0.80	66.45	0.71	0.71	0.71
Dust only	59.21	0.79	0.79	0.79	61.64	0.70	0.70	0.70
	57.66	0.79	0.79	0.79	59.66	0.70	0.70	0.70
	59.54	0.79	0.79	0.79	61.36	0.70	0.70	0.70
	64.57	0.80	0.80	0.80	65.93	0.71	0.71	0.71
	72.07	0.81	0.81	0.81	72.98	0.73	0.73	0.73

	81.31	0.83	0.83	0.83	81.80	0.76	0.76	0.76
	88.95	0.85	0.85	0.85	88.95	0.78	0.78	0.78
	Daily mean reduction (%)	0.07	0.07	0.07		0.05	0.05	0.05
	80.34	0.79	0.78	0.77	82.61	0.59	0.55	0.52
	71.25	0.77	0.75	0.74	73.66	0.54	0.50	0.46
	63.96	0.75	0.73	0.72	66.45	0.50	0.46	0.42
	59.21	0.74	0.72	0.71	61.64	0.48	0.43	0.40
	57.66	0.74	0.72	0.70	59.66	0.47	0.42	0.39
BC and dust	59.54	0.74	0.72	0.71	61.36	0.48	0.43	0.39
	64.57	0.75	0.74	0.72	65.93	0.50	0.45	0.42
	72.07	0.77	0.76	0.74	72.98	0.54	0.49	0.46
	81.31	0.79	0.78	0.77	81.80	0.59	0.55	0.51
	88.95	0.82	0.81	0.80	88.95	0.64	0.60	0.57
	Daily mean reduction (%)	1.80	2.36	2.90		8.75	10.51	12.03
	80.34	0.83	0.83	0.83	82.61	0.77	0.77	0.77
	71.25	0.81	0.81	0.81	73.66	0.75	0.75	0.75
	63.96	0.80	0.80	0.80	66.45	0.73	0.73	0.73
	59.21	0.79	0.79	0.79	61.64	0.72	0.72	0.72
	57.66	0.79	0.79	0.79	59.66	0.71	0.71	0.71
No BC/ no dust	59.54	0.79	0.79	0.79	61.36	0.72	0.72	0.72
	64.57	0.79	0.80	0.80	65.93	0.73	0.73	0.73
	72.07	0.81	0.81	0.81	72.98	0.75	0.75	0.75
	81.31	0.83	0.83	0.83	81.80	0.77	0.77	0.77

	88.95	0.85	0.85	0.85	88.95	0.79	0.79	0.79

MAC = Mass Absorption Cross section, SZA = Solar Zenith Angle

Table S4. Radiative forcing for selected solar zenith angles (Wm^{-2}) and daily mean (%)

Pollutant	Site S6 (low EC and dust)				Site S1 (high EC and dust)			
	SZA	MAC 7.5	MAC 11	MAC 15	SZA	MAC 7.5	MAC 11	MAC 15
BC only	80.34	4.90	6.47	8.00	82.61	23.87	29.10	33.71
	71.25	5.86	7.72	9.53	73.66	27.50	33.25	38.21
	63.96	6.57	8.65	10.65	66.45	29.96	36.01	41.16
	59.21	7.00	9.70	11.33	61.64	31.39	37.58	42.82
	57.66	7.14	9.38	11.54	59.66	31.93	38.18	43.44
	59.54	6.97	9.16	11.29	61.36	31.47	37.67	42.91
	64.57	6.51	8.58	10.56	65.93	30.13	36.19	41.35
	72.07	5.78	7.61	9.40	72.98	27.75	33.53	38.52
	81.31	4.79	6.33	7.83	81.80	24.23	29.51	34.16
	88.95	3.93	5.20	6.44	88.95	20.88	25.62	29.86
	Daily mean	2.40	3.18	3.90	-	10.74	12.95	14.85
Dust only	80.34	0.20	0.20	0.20	82.61	1.43	1.43	1.43
	71.25	0.24	0.24	0.24	73.66	1.71	1.71	1.71
	63.96	0.27	0.27	0.27	66.45	1.91	1.91	1.91
	59.21	0.29	0.29	0.29	61.64	2.03	2.03	2.03
	57.66	0.30	0.30	0.30	59.66	2.08	2.08	2.08
	59.54	0.29	0.29	0.29	61.36	2.04	2.04	2.04
	64.57	0.27	0.27	0.27	65.93	1.93	1.93	1.93
	72.07	0.24	0.24	0.24	72.98	1.73	1.73	1.73

	81.31	0.20	0.20	0.20	81.80	1.38	1.38	1.38
	88.95	0.16	0.16	0.16	88.95	1.21	1.21	1.21
	Daily mean	0.10	0.10	0.10	-	0.67	0.67	0.67
BC and dust	80.34	5.00	6.55	8.07	82.61	24.03	29.16	33.71
	71.25	5.98	7.82	9.61	73.66	27.70	33.33	38.22
	63.96	6.70	8.75	10.75	66.45	30.17	36.09	41.17
	59.21	7.14	9.32	11.43	61.64	31.61	37.68	42.83
	57.66	7.28	9.49	11.64	59.66	32.15	38.27	43.45
	59.54	7.11	9.28	11.38	61.36	31.69	37.76	42.92
	64.57	6.65	8.68	10.66	65.93	30.34	36.27	41.36
	72.07	5.89	7.71	9.48	72.98	27.95	33.61	38.52
	81.31	4.89	6.41	7.90	81.80	24.39	29.58	34.16
	88.95	4.01	5.26	6.49	88.95	21.01	25.67	29.85
	Daily mean	2.45	3.20	3.93	-	10.81	12.98	14.86

MAC = Mass Absorption Cross section, SZA = Solar Zenith Angle

Table S5. Potential source countries for pollutants: a) identified using wind vector analysis; b) identified using trajectory analysis; and c) identified using the WRF-STEM model

Method	Region	Countries
a) Wind vector	East Asia	South west China.
	Central Asia	Tajikistan, Kyrgyzstan, Uzbekistan, Azerbaijan, Turkmenistan
	South Asia	India, Pakistan, Afghanistan
	Middle East	Syria, Iraq, Lebanon, Armenia.
	West Asia	Iran, Turkey
	Europe	Western parts of Russia.
b) Trajectory analysis	Central Asia	Uzbekistan, Western part Turkmenistan, Kazakhstan, Azerbaijan
	South Asia	Pakistan
	Middle East	Iraq, Armenia, Syria, United Arab Emirates, Jordan
	West Asia	Iran, Georgia, Turkey, Cyprus
	Russian Federation	Western Russia.
	Europe	Ukraine
	Africa	Egypt, Libya, Tunisia
c) WRF-STEM	East Asia	Indonesia, Singapore, Malaysia, Thailand, Myanmar, Sri Lanka
	Central Asia	Mongolia, Tajikistan, Kyrgyzstan, Kazakhstan, Uzbekistan, Turkmenistan
	South Asia	Bangladesh, India, Bhutan, Nepal
	Middle East	Oman, United Arab Emirates, Qatar, Bahrain, Kuwait, Iraq, Syria, Lebanon, Palestinian Territory, Israel, Jordan, Saudi Arabia, Yemen

Russian Federation	Russia
West Asia	Azerbaijan, Armenia, Georgia, Turkey and Cyprus
Europe	Europe
Africa	Kenia, Somalia, Egypt, Congo
Other	China, Pakistan, Afghanistan, Iran