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Supplement of

Timing and climatic-driven mechanisms of glacier advances in Bhutanese Himalaya during the Little Ice Age

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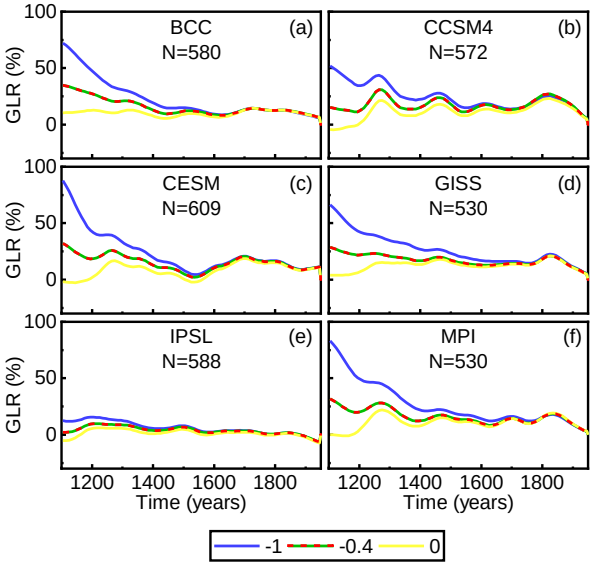

Figure S1. The regional average *GLR* from 1100 to 1950 CE with different β in (a) BCC, (b) CCSM4, (c) CESM, (d) GISS, (e) IPSL, and (d) MPI experiment. The number of available glaciers (N) with β = *-0.4* is also shown in each figure.

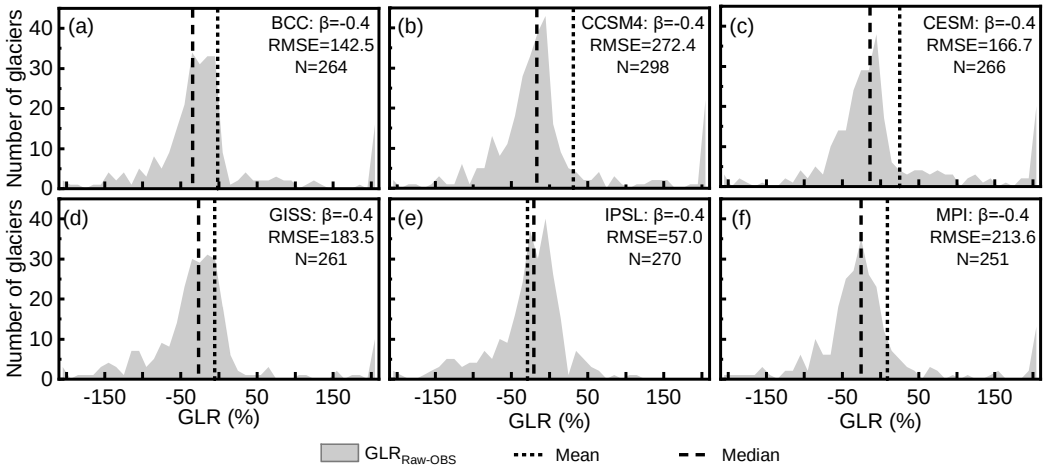

Figure S2. The simulation bias distribution of *maximum peak GLR*. The forcing data, β, RMSE, and the number of glaciers used to observation-simulation comparison (N) are also shown in the top right corner of the figure.

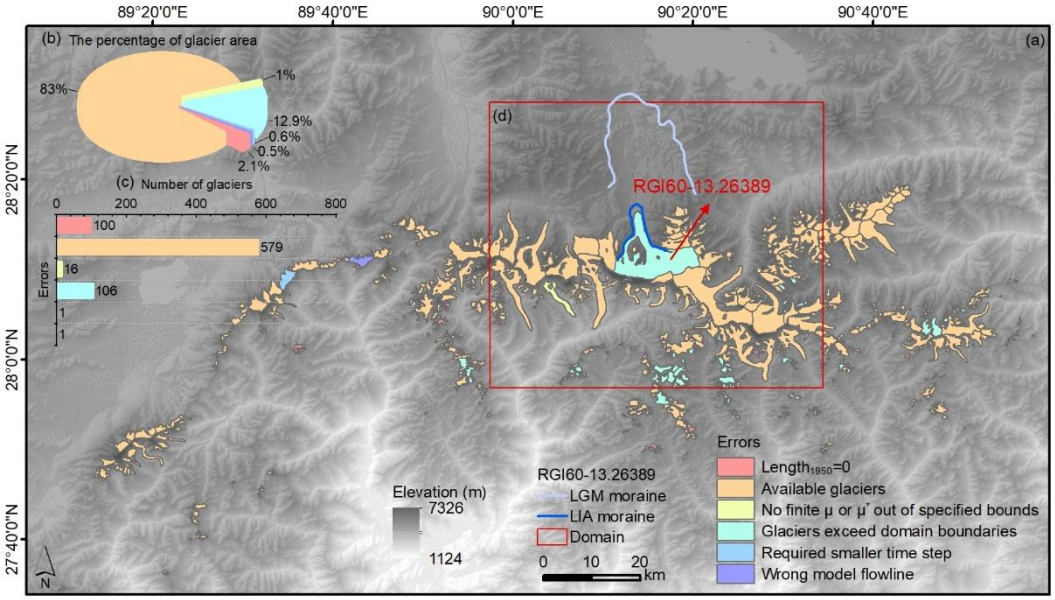

Figure S3 (a) Different simulation errors in the MC experiment with $\beta = -0.4$ and border parameter=160; (b) the percentage of glacier area of each error type; (c) the number of glaciers of each error type; (d) the spatial distribution of LIA and LGM moraine of glacier RGI60-13.26389. The LGM moraine is mapped based on regional glacial chronology and the evidence of sediment-landform assemblages (Peng et al., 2019).

Table S1. Recalculated previously published minimum ^{10}Be surface exposure ages in the monsoon-influenced Hiamlaya using the CRONUS Earth V3 online calculator with the time-dependent scaling scheme "LSDn".

Location and Source	Moraine	Sample ID	Lat (°)	Lon (°)	Ele (m)	Thickness (cm)	Topographic shielding factor	^{10}Be Concentration (atoms/g)	Recalculated ^{10}Be age (ka)	Date of sample collection	Moraine age (CE)
LIA-4											
Nepal Himalaya; Barnard et al. (2006)	inner moraine, Langtang Khola Valley	KTM4	28.21	85.56	3924	5	0.97	25000 ± 8000	741 ± 241	2003	837 ± 325
		KTM5	28.21	85.56	3922	5	0.97	44000 ± 12000	1166 ± 325	2003	
		KTM6	28.21	85.56	3923	5	0.97	22000 ± 8000	658 ± 242	2003	
	outer moraine, Langtang Khola Valley	KTM7	28.21	85.57	3840	5	0.98	27000 ± 9000	817 ± 277	2003	1038 ± 298*
		KTM8	28.21	85.57	3838	5	0.98	28000 ± 8000	845 ± 246	2003	
		KTM9	28.21	85.57	3839	5	0.98	33000 ± 10000	965 ± 298	2003	
Garhwal Himalaya; Barnard et al. (2004b)	Gangotri glacial stage, Upper Bhagirathi Valley	BH29	30.945	79.061	3973	5	0.97	31241 ± 8369	821 ± 225	2000	935 ± 182*
		BH30	30.945	79.062	3956	5	0.97	15261 ± 6683	427 ± 189	2000	
		BH31	30.945	79.062	3973	5	0.97	11177 ± 6842	319 ± 196	2000	
		BH32	30.945	79.062	3956	5	0.97	43712 ± 7013	1065 ± 182	2000	
Garhwal; Scherler et al. (2010)	Jaundhar Glacier, Tons Valley	DS6-057	31.142	78.454	3636	3	0.95	13695 ± 538	515 ± 37	2009	1012 ± 66*
		DS6-058	31.142	78.453	3623	3	0.94	28171 ± 821	997 ± 66	2009	
Garhwal Himalaya; Barnard et al. (2004a)	m4, Gori Ganga Valley	NDL2	30.45	80.12	3534	5	0.97	14000 ± 5000	492 ± 178	2003	1088 ± 146*
		NDL4	30.45	80.12	3522	5	0.96	27000 ± 4000	915 ± 146	2003	
Lahul Himalaya; Saha et al. (2018)	m_{A2c}, Lato valley	LATO-1409(1)	33.6851	77.59525	5314	3	0.9593	2651000 ± 56400	26351 ± 1664	2016	1188 ± 57*
		LATO-1410(1)	33.6851	77.59531	5321	2.5	0.9593	218600 ± 8700	2862 ± 204	2016	
		LATO-1411(1)	33.6851	77.5952	5315	2	0.9593	296300 ± 17800	3861 ± 325	2016	
		LATO-1412	33.685	77.59566	5315	1	0.9576	27600 ± 1500	424 ± 34	2016	
		LATO-1413	33.6849	77.59573	5317	2	0.9594	57700 ± 2000	828 ± 57	2016	
		LATO-1414	33.6851	77.59538	5314	2	0.9596	37600 ± 1800	560 ± 43	2016	
West Himalaya; Dortch et al. (2013)	Pangong Cirque, Ladakh, Nn India	Pang-24	33.888	78.425	5375	5	1	14824 ± 6621	229 ± 103	2013	1220 ± 270*
		Pang-25	33.888	78.425	5375	5	1	162492 ± 37623	1885 ± 451	2013	
		Pang-26	33.888	78.425	5368	5	1	49909 ± 8581	698 ± 127	2013	
		Pang-27	33.888	78.425	5371	5	1	57723 ± 19329	793 ± 270	2013	
		Pang-28	33.888	78.426	5363	5	1	163049 ± 23407	1902 ± 295	2013	
		Pang-29	33.888	78.426	5360	4	1	35547 ± 9858	509 ± 144	2013	
Lahul Himalaya; Saha et al. (2018)	m_{M1}, Karzok valley	KO-7	32.933	78.214	5524	6	1	20400 ± 1400	306 ± 28	2016	1230 ± 56*
		KO-8	32.933	78.214	5516	2.5	1	59200 ± 5500	782 ± 86	2016	
		KO-9	32.934	78.215	5503	1	1	60000 ± 2400	786 ± 56	2016	
		KO10	32.934	78.215	5503	1	1	47300 ± 6700	630 ± 97	2016	
Annapurna Range; Heimsath & McGlynn (2008)	W moraine crest, Milarepa's Glacier	NP212	28.641	84.044	3844	2	1	26460 ± 1620	763 ± 65	2006	1243 ± 65*
		NP213	28.641	84.044	3797	2	0.935	7042 ± 1780	234 ± 61	2006	
		NP214	28.641	84.044	3669	2	1	19810 ± 1400	634 ± 58	2006	
	E moraine crest, Milarepa's Glacier	NP222	28.635	84.042	4000	2	0.91	43480 ± 6510	1141 ± 184	2006	1263 ± 125
		NP223	28.635	84.042	3813	2	0.912	23060 ± 3620	743 ± 125	2006	
		NP233	28.635	84.042	4275	2	0.907	15090 ± 3380	401 ± 93	2006	

		NP234	28.635	84.042	4216	2	1	24830 ± 1990	601 ± 60	2006	
		NP235	28.635	84.042	4157	2	0.91	43480 ± 6510	210 ± 22	2006	
Northwestern India; Lee et al. (2014)	TG3, Nun-Kun massif	NK29	34.06	75.92	3679	2.5	0.96	15631 ± 513.7	513 ± 35	2012	1295 ± 70*
		NK-30	34.05	75.92	3720	4	0.96	22600 ± 1764.7	717 ± 70	2012	
Lahul massif; Saha et al. (2019)	M_{k2}, Kulti valley	S9	32.4233	77.3067	3676	2	0.917	12700 ± 4600	468 ± 172	2016	1317 ± 80*
		S10	32.4233	77.3067	3678	2	0.913	19500 ± 1900	699 ± 80	2016	
LIA-3											
Bhutanese Himalaya; Peng et al. (2019)	M1, Cogarbu valley	YDT14-1	28.2386	89.8913	4955	5	0.9735	58500 ± 2300	1098 ± 78	2014	1484 ± 44*
		YDT14-2	28.2383	89.8915	4946	5	0.9743	12300 ± 1100	270 ± 29	2014	
		YDT14-3	28.239	89.8911	4947	5	0.9735	24200 ± 1400	520 ± 43	2014	
		YDT14-4	28.2397	89.8906	4945	4	0.9657	36300 ± 1600	758 ± 56	2014	
		YDT14-5	28.2401	89.8904	4942	5	0.9657	24500 ± 1400	530 ± 44	2014	
Bhutanese Himalaya; Peng et al. (2020)	M1, Shimo valley	YDT15-1	28.2851	89.99504	5064	3	0.99	7387 ± 607	147 ± 15	2014	1514 ± 69*
		YDT15-4	28.2852	89.9949	5072	3	0.99	144194 ± 3240	2614 ± 165	2014	
		YDT15-6	28.2838	89.9938	5103	4	0.92	22257 ± 1646	470 ± 44	2014	
		YDT15-7	28.2837	89.99367	5104	5	0.92	47302 ± 11166	937 ± 228	2014	
		YDT15-8	28.2837	89.99375	5103	5	0.92	22466 ± 5240	478 ± 115	2014	
		YDT15-9	28.2837	89.99385	5100	5	0.97	24796 ± 3072	500 ± 69	2014	
		YDT15-10	28.2833	89.99351	5107	4	0.98	8768 ± 1443	175 ± 31	2014	
Garhwal Himalaya; Barnard et al. (2004a)	M3, Gori Ganga Valley	NDL9	30.45	80.13	3505	5	0.97	7000 ± 5000	261 ± 187	2003	1542 ± 76
		NDL10	30.45	80.13	3510	5	0.98	13000 ± 2000	461 ± 76	2003	
central Gangdise Mountains; Zhang et al. (2018)	M4, Lopu Kangri Area	13GDS6-1	29.8185	84.69688	5497	2.2	0.9992	17083 ± 5786	276 ± 95	2013	1549 ± 154*
		13GDS6-2	29.8185	84.69686	5495	2.3	0.9992	29569 ± 9646	464 ± 154	2013	
		13GDS6-3	29.8185	84.69686	5495	2	0.9992	83279 ± 11788	1109 ± 170	2013	
		13GDS6-4	29.8186	84.6968	5495	2	0.9992	24311 ± 7756	386 ± 125	2013	
Lahul Himalaya; Saha et al. (2018)	$m_{H1a,}$ Hamtah valley	HAMTAH-1405	32.2725	77.35738	4014	2	0.9429	8900 ± 1900	281 ± 62	2016	1553± 125*
		HAMTAH-1406	32.2722	77.3575	4023	1	0.9444	15600 ± 4100	463 ± 125	2016	
		HAMTAH-1408	32.2686	77.35847	4111	2.5	0.9540	90600 ± 5500	2209 ± 187	2016	
		HAMTAH-1410	32.2678	77.35892	4125	2.5	0.9476	6000 ± 1000	179 ± 32	2016	
		HAMTAH-1502	32.2954	77.36555	3861.182	2	0.9233	25700 ± 2500	816 ± 93	2016	
		HAMTAH-1405	32.2725	77.35738	4014	2	0.9429	8900 ± 1900	281 ± 62	2016	
Garhwal; Murari et al. (2014)	m_{bd2}, Bhillangana and Dudhganga valleys	KAL1	30.7778	78.9515	3641	1.5	0.937	9900 ± 800	386 ± 39	2013	1568 ± 54*
		KAL2	30.7777	78.9512	3650	2	0.923	11400 ± 1200	445 ± 54	2013	
		KAL3[(1)]	30.7782	78.9506	3646	1.5	0.935	2500 ± 300	98 ± 13	2013	
		KAL4[(1)]	30.7782	78.9504	3657	1.5	0.923	500 ± 200	19 ± 8	2013	
		KAL5[(1)]	30.7782	78.9533	3644	5	0.929	2300 ± 300	94 ± 13	2013	
LIA-2											
	M1B, Karola Pass	TB-14-39	28.9493	90.1338	5017	6	0.944	14270 ± 870	312 ± 27	2014	1598 ± 101*

Lhagoi Kangri Range; Liu et al. (2017)		TB-14-41	28.9508	90.134	4980	3	0.952	10900 ± 800	234 ± 22	2014	
		TB-14-42	28.9506	90.134	4980	6	0.958	19250 ± 4540	416 ± 101	2014	
Puga valley, Sanskrit in the Transhimalaya; Hedrick et al. (2011)	PM-3	India-45	33.226	78.166	5266	3	1	44500 ± 3000	658 ± 59	2010	1611 ± 58*
		India-46	33.226	78.167	5263	3	1	18200 ± 2100	295 ± 38	2010	
		India-47	33.226	78.167	5257	3	1	117400 ± 4700	1440 ± 103	2010	
		India-48	33.226	78.167	5267	2	1	102200 ± 4800	1245 ± 94	2010	
		India-49	33.226	78.167	5260	4	1	24000 ± 3100	382 ± 54	2010	
		India-50	33.226	78.167	5265	3	1	25500 ± 3400	399 ± 58	2010	
Central Gangdise Mountains; Zhang et al. (2018)	M3, Lopu Kangri Area	14GDS1-1	29.8199	84.69476	5487	2.7	0.9991	24815 ± 1263	396 ± 31	2014	1618 ± 31
		14GDS1-2	29.8197	84.69494	5487	1.8	0.9991	24372 ± 1496	387 ± 33	2014	
		14GDS1-3	29.8197	84.69493	5490	2.1	0.9991	22040 ± 1462	353 ± 31	2014	
		14GDS1-4	29.8197	84.69496	5489	2.3	0.9991	23087 ± 1329	369 ± 30	2014	
	M5, Lopu Kangri Area	13GDS7-1	29.8191	84.69875	5507	1.9	0.9995	24986 ± 6518	393 ± 105	2013	1620 ± 105
		13GDS7-2	29.8195	84.69881	5504	2.1	0.9996	15735 ± 7287	253 ± 118	2013	
		13GDS7-3	29.8195	84.69893	5507	1.6	0.9996	18660 ± 7520	298 ± 121	2013	
		13GDS7-4	29.8195	84.69896	5508	2	0.9996	22186 ± 5085	352 ± 83	2013	
		13GDS7-5	29.8196	84.69889	5508	2	0.9996	44702 ± 9611	677 ± 151	2013	
	M2, Lopu Kangri Area	13GDS5-1	29.8182	84.6951	5499	2.3	0.9987	16841 ± 5336	272 ± 88	2013	1737 ± 38
		13GDS5-2	29.8183	84.69497	5502	2.3	0.9987	15443 ± 1656	249 ± 30	2013	
		13GDS5-3	29.8184	84.69493	5499	1.6	0.9987	15852 ± 1738	254 ± 32	2013	
		13GDS5-4	29.8184	84.69494	5499	2.3	0.9987	16802 ± 2471	271 ± 43	2013	
		13GDS5-5	29.8184	84.69492	5499	2.1	0.9987	17103 ± 2123	276 ± 38	2013	
Himalaya; Owen et al. (2009)	T7, Mount Everest	Ron-51	28.13	86.853	5216	4	0.97	11000 ± 8000	214 ± 156	2008	1627 ± 44*
		Ron-53	28.129	86.854	5213	2	0.97	20000 ± 2000	381 ± 44	2008	
		Ron-55	28.13	86.856	5225	2	0.97	39000 ± 3000	716 ± 69	2008	
Garhwal; Scherler et al. (2010)	Bandarpunch Glacier	DS6-032	31.072	78.499	4071	3	0.95	12086 ± 551	374 ± 28	2009	1635 ± 28
		DS6-033	31.072	78.498	4046	2	0.97	7688 ± 873	239 ± 31	2009	
Garhwal; Murari et al. (2014)	m_{bd1}, Bhillangana and Dudhganga valleys	KAL18	30.7565	78.9629	4132	2	0.949	8600 ± 1200	263 ± 40	2013	1691 ± 31
		KAL19	30.7585	78.9627	4182	2	0.937	10700 ± 800	322 ± 31	2013	
		KAL20[(1)]	30.7567	78.9628	4115	2	0.94	36400 ± 3000	999 ± 101	2013	
		KAL21	30.7567	78.9653	4108	2	0.939	8700 ± 1200	272 ± 41	2013	
Lahul Himalaya; Saha et al. (2018)	m_{A1}, Lato valley	LATO-1415[(1)]	33.6822	77.59202	5366	3	0.9501	133100 ± 3100	1603 ± 102	2016	1726 ± 28
		LATO-1416	33.6822	77.5921	5358	4	0.9501	16600 ± 1800	270 ± 33	2016	
		LATO-1417	33.6826	77.59203	5348	2	0.9508	27400 ± 1000	421 ± 29	2016	
		LATO-1418	33.6826	77.59207	5351	3	0.9459	17900 ± 1400	290 ± 28	2016	
		LATO-1419[(1)]	33.6827	77.592	5339	3	0.9517	246600 ± 18500	3162 ± 302	2016	
Garhwal; Murari et al. (2014)	m_{bd4}, Bhillangana and Dudhganga valleys	KAL7	30.7898	78.9522	3635	3	0.911	6800 ± 1200	282 ± 53	2013	1731 ± 53
		KAL9	30.7897	78.9523	3637	3	0.911	1700 ± 300	69 ± 13	2013	
	m_{bd3}, Bhillangana and Dudhganga valleys	KAL10	30.7839	78.9511	3579	3	0.937	6200 ± 1200	258 ± 52	2013	1722 ± 41
		KAL11	30.7838	78.9509	3576	2.5	0.937	7000 ± 900	291 ± 41	2013	
		KAL12[(1)]	30.7836	78.9507	3568	2	0.937	47300 ± 2500	1596 ± 126	2013	
		KAL13[(1)]	30.7834	78.9504	3571	3	0.943	69300 ± 3200	2510 ± 188	2013	

		KAL14	30.7831	78.9501	3571	2.5	0.938	10000 ± 100	406 ± 24	2013	
	m_{k2}, Kedarnath	KAL35	30.7448	79.6503	3841	4	0.953	18100 ± 4100	614 ± 144	2013	1724 ± 37*
		KAL36	30.7454	79.0652	3853	5	0.95	8000 ± 900	289 ± 37	2013	
		KAL37	30.7462	79.0655	3884	3	0.959	722000 ± 222000	17750 ± 5582	2013	
		KAL38	30.7473	79.0661	3909	5	0.959	8000 ± 800	278 ± 32	2013	
		KAL39(1)	30.7478	79.0662	3915	2.5	0.096	12200 ± 2200	3286 ± 624	2013	
Gurla Mandhata; Owen et al. (2010)	M10, Muguru Valley	Na48	30.463	81.217	5508	2	0.946	29000 ± 4100	465 ± 71	2009	1757 ± 252*
		Na49(1)	30.463	81.217	5506	1	0.946	229900 ± 6500	3178 ± 208	2009	
		Na50	30.463	81.217	5509	2	0.946	7500 ± 2700	124 ± 45	2009	
		Na52(1)	30.464	81.217	5514	2	0.952	280900 ± 6900	3932 ± 252	2009	
		Na53	30.464	81.216	5509	2	0.955	17800 ± 1200	294 ± 26	2009	
Nun Kun massif; Saha et al. (2019)	M_{P1}, Parkachik valley	PAR1601	34.0835	75.9998	3700	2	0.968	5600 ± 600	192 ± 23	2016	1759 ± 44*
		PAR1602	34.0844	76.0001	3687	3	0.973	3300 ± 800	114 ± 28	2016	
		PAR1603	34.0846	76.0002	3678	3.5	0.974	7100 ± 500	247 ± 23	2016	
		PAR1606	34.085	76.0004	3667	2	0.969	7400 ± 1200	257 ± 44	2016	
LIA-1											
Mount Everest, Khumbu Himal; Finkel et al. (2003)	Lobuche glacial stage and historical	E32	27.9	86.87	4773	5	0.988	53000 ± 7000	978 ± 142	2003	1836 ± 64*
		E36	27.91	86.87	4525	5	0.982	5000 ± 3000	114 ± 68	2003	
		E37	27.9	86.87	4691	5	0.982	76000 ± 21000	1360 ± 384	2003	
		E38	27.9	86.87	4718	5	0.982	8000 ± 3000	167 ± 64	2003	
		E82	27.92	86.81	4270	5	0.979	87000 ± 10000	1948 ± 252	2003	
Annapurna; Zech et al. (2009)	Dudh Khola Valley	DK11	28.627	84.467	3650	2	0.942	3950 ± 3910	162 ± 161	2008	1846 ± 161*
Lhagoi Kangri Range; Liu et al. (2017)	M1A, Karola Pass	TB-14-33	28.9502	90.1346	4988	3	0.937	6960 ± 3350	150 ± 73	2014	1864 ± 73
		TB-14-34	28.9498	90.1344	4996	5	0.94	6760 ± 810	147 ± 20	2014	
		TB-14-36	28.9492	90.1342	5012	3	0.936	12390 ± 680	267 ± 22	2014	

Notes: (1) mean the potential outlier removed according to original published. * mean the time when glacier reached the LIA maximum extent. We grouped the moraine ages based on their temporal distances to each glacial substage simulated in MC experiment.

Table S2. Climate model simulations used to drive OGGM.

Name	Institution	Resolution (lat × lon)	Reference	Time (CE)
CCSM4	National Center for Atmospheric Research	192 × 288	Gent et al. (2011)	850-2006
CESM1	National Center for Atmospheric Research	96 × 144	Otto-Bliesner et al. (2016)	850-2005
GISS-E2-R	NASA Goddard Institute for Space Studies	90 × 144	Schmidt et al. (2014)	850-2005
IPSL-CM5A-LR	Institut Pierre-Simon- Laplace	96 × 96	Dufresne et al. (2013)	850-2006
MPI-ESM-P	Max Planck Institute for Meteorology	96 × 192	Stevens et al. (2013)	850-2005
BCC-CSM1-1	Beijing Climate Center, China Meteorological Administration	64 × 128	Wu et al. (2014)	850-2000
CRU TS4.01	Climatic Research Unit gridded Time Series	360 × 720	Harris et al. (2020)	1901-2018

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