Supplement of

Optical images reveal the role of high temperatures in triggering the 2021 Chamoli landslide

Jing Tian[1], Wentao Yang[1, 2], Jian Fang[3], Chong Xu[4]

[1]Three-gorges reservoir area (Jinyun Mountain, Chongqing) Forest Ecosystem National Observation and Research Station, School of Soil and Water Conservation, Beijing Forestry University, Beijing 100083, PR China
[2]Academy of Plateau Science and Sustainability, People's Government of Qinghai Province and Beijing Normal University, Xining 810016, China
[3]College of Urban and Environmental Sciences, Central China Normal University, Wuhan, 430079, China
[4]National Institute of Natural Hazards, Ministry of Emergency Management of China, Beijing, 100085, China

Correspondence to: Wentao Yang (yang_wentao@bjfu.edu.cn)

Supplement 1: List of all remote sensing images that were used in this study.

Clear Landsat 8				Clear Landsat 8 without shadows		Sentinel-2			
ID	Time	ID	Time	ID	Time	ID	Time	ID	Time
1	2013-05-22	37	2017-02-26	1	2013-05-22	1	2016-03-23	37	2020-05-21
2	2013-10-29	38	2017-03-14	2	2013-09-27	2	2016-05-02	38	2020-09-13
3	2013-11-30	39	2017-03-30	3	2014-03-06	3	2016-05-22	39	2020-09-18
4	2013-12-16	40	2017-04-15	4	2014-09-14	4	2016-09-19	40	2020-09-28
5	2014-01-01	41	2017-05-01	5	2014-10-16	5	2016-10-09	41	2020-10-08
6	2014-02-02	42	2017-10-08	6	2015-03-25	6	2017-03-28	42	2020-10-13
7	2014-02-18	43	2017-10-24	7	2015-04-10	7	2017-04-17	43	2020-10-18
8	2014-06-10	44	2017-11-25	8	2015-05-28	8	2017-05-07		
9	2014-10-16	45	2017-12-11	9	2015-09-01	9	2017-09-19		
10	2014-11-17	46	2017-12-27	10	2015-09-17	10	2017-10-09		
11	2014-12-03	47	2018-01-28	11	2015-10-03	11	2017-10-14		
12	2015-01-20	48	2018-03-17	12	2015-10-19	12	2018-03-08		
13	2015-02-05	49	2018-04-02	13	2016-04-12	13	2018-03-18		
14	2015-02-21	50	2018-04-18	14	2016-04-28	14	2018-03-23		
15	2015-03-25	51	2018-05-04	15	2016-05-14	15	2018-04-02		
16	2015-04-10	52	2018-10-27	16	2016-09-19	16	2018-04-22		
17	2015-05-28	53	2018-11-12	17	2017-03-14	17	2018-05-17		
18	2015-09-01	54	2018-12-14	18	2017-03-30	18	2018-05-22		
19	2015-09-17	55	2019-03-04	19	2017-04-15	19	2018-09-19		
20	2015-10-03	56	2019-04-05	20	2017-05-01	20	2018-09-29		
21	2015-10-19	57	2019-04-21	21	2017-10-08	21	2018-10-04		
22	2015-11-20	58	2019-05-07	22	2018-03-17	22	2018-10-14		
23	2015-12-06	59	2019-10-14	23	2018-04-02	23	2018-10-19		
24	2016-01-07	60	2019-12-01	24	2018-04-18	24	2019-03-23		
25	2016-01-23	61	2019-12-17	25	2018-05-04	25	2019-03-28		
26	2016-02-08	62	2020-02-03	26	2018-09-25	26	2019-04-02		
27	2016-02-24	63	2020-04-07	27	2019-03-04	27	2019-04-27		
28	2016-04-12	64	2020-05-09	28	2019-04-05	28	2019-05-07		
29	2016-05-14	65	2020-05-25	29	2019-05-07	29	2019-05-27		
30	2016-09-19	66	2020-09-30	30	2019-10-14	30	2019-09-09		
31	2016-10-21	67	2020-10-16	31	2020-04-07	31	2019-09-14		
32	2016-11-06	68	2020-11-17	32	2020-05-09	32	2019-10-14		
33	2016-11-22	69	2020-12-03	33	2020-05-25	33	2020-03-17		
34	2016-12-08	70	2020-12-19	34	2020-09-30	34	2020-04-06		
35	2017-01-09	71	2021-01-20	35	2020-10-16	35	2020-04-11		
36	2017-02-10					36	2020-05-16		

Supplement 2

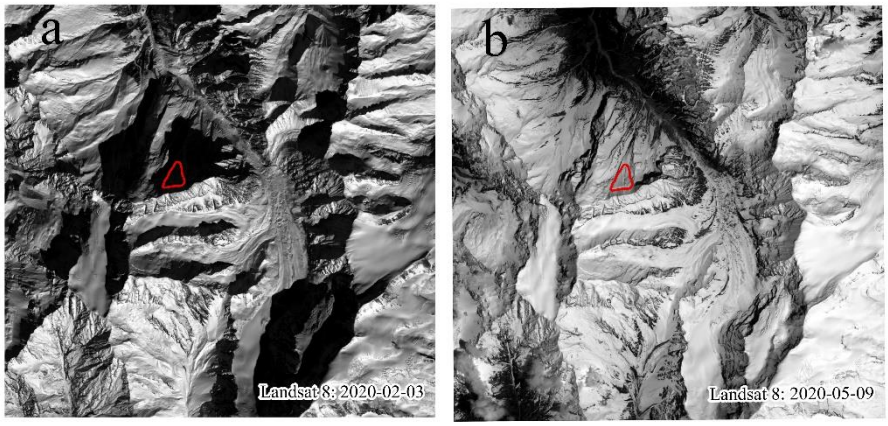

Figure S1: (a) (b) is two Landsat 8 red band images taken. The impact of mountain shadows on the study area at different times

Supplement 3: Comparison of the temperature data between the EAR5 and a meteorological station

As the elevation of the landslide is >5000m, it is very difficult to get in-situ temperature data. The Chamoli landslide is located near the Sino-India border (Fig. S2). The closest meteorological station that has a similar elevation is ~170 km northeast of the landslide (Fig. S2). The location of the station is 31.1˚N 81.3˚E at an elevation of ~5039m. The location of the Chamoli landslide is 30.4˚N, 79.7˚E. The elevation of the landslide ranges from 5000 m to 5500 m.

Daily temperatures between the EAR5 and the station from 2016 to 2021 are consistent with each other, though EAR5 temperatures are ~3℃ higher (Fig. S3). Note the EAR5 temperature data has a spatial resolution of 0.25˚ meaning the pixel of the EAR5 of the Chamoli landslide also covers much of the low elevation area with higher temperatures. So, the temperature of the landslide was probably much lower than the EAR5 temperatures. In addition, the Chamoli landslide faces north, which could further lead to lower temperatures. Therefore, the temporal fluctuations of the EAR5 are valid for the landslide but with much lower values (probably similar to the station mean of ~-3℃).

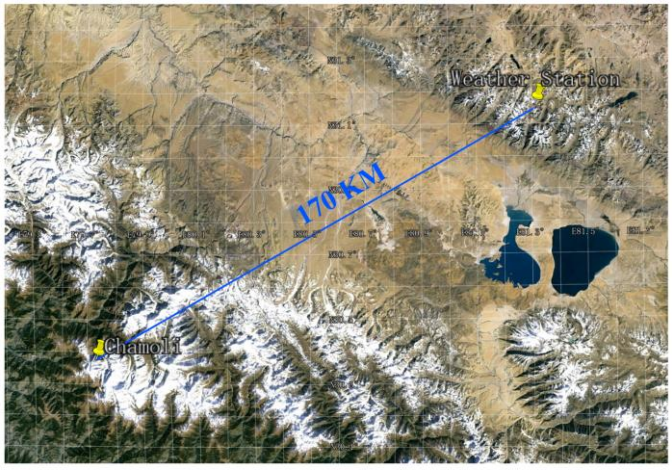

Figure S2: Distance between the Chamoli landslide (30.4˚N, 79.7˚E, 5000~5500 m abs.) and the nearest weather station with an elevation of 5039m above sea level (31.1˚N 81.3˚E).

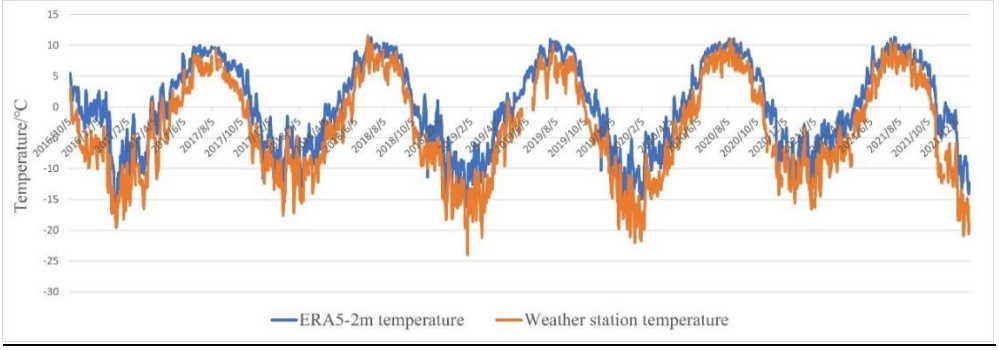

Figure S3: Temporal variations of the temperature during the study period (2016-2021) measured by the ERA5 and the weather station.

Supplement 4:

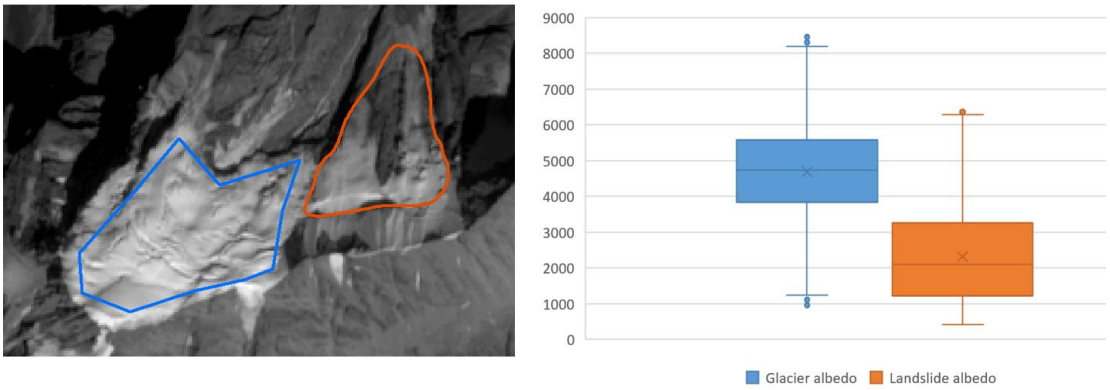

Figure S4: Albedo of the landslide surface and its neighbouring glacier.

Supplement 5: High temperatures before the final collapse in 2021

Fig. S5 displays EAR5 daily temperatures from January 20 to February 10 for 2013-2023, which are 17 days before and 3 days after the landslide (occurred on 7 February 2021). The figure shows that the mean temperature in 2021 was ~3°C higher than that of 2019 and 2020. Fig. S6 shows the temperature dropped and rise again six days before the landslide. The temperature on the 7 February was > 5°C than previous days. This increase of temperature may have an effect on triggering the landslide by decreasing the bonding strength of the ice in rock joints.

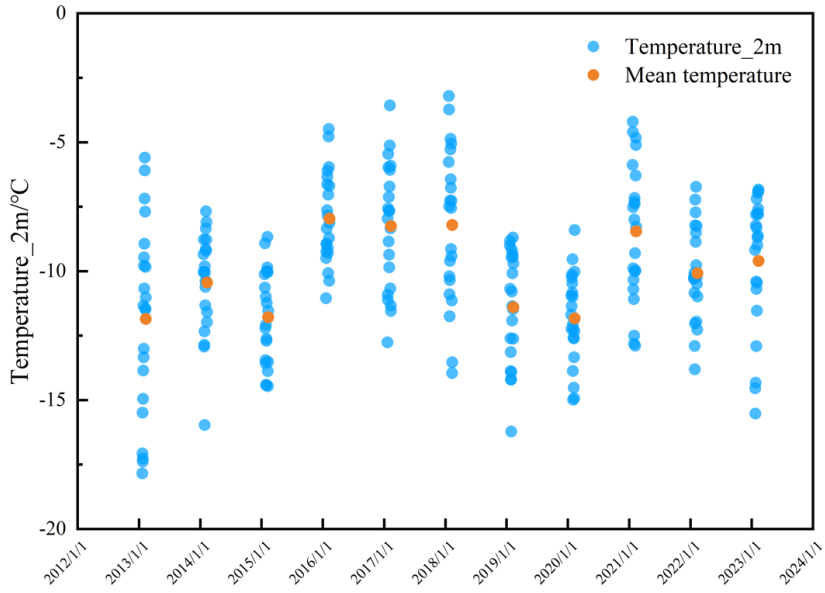

Figure S5: Daily mean EAR5 temperatures from January 20 to February 10 for 2013-2023.

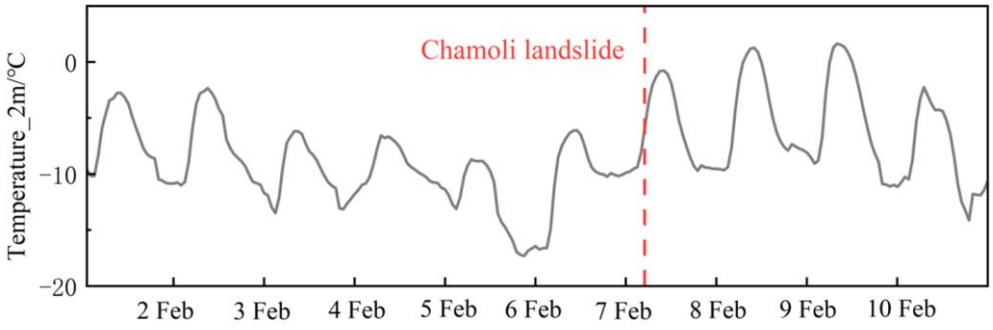

Figure S6: Hourly EAR5 temperatures from 1st to the 10th of February in 2021.

Supplement 6: Manually interpreted crack width in optical images

We selected a few Sentinel-2 true colour images of good quality with low clouds before and after the occurrence of the landslide (Fig. S7). In the Sentinel-2 image of November 28, 2016 (Fig. S7a), the crack in the upper part of the landslide is hard to discern. The length and width of the upper crack develops gradually with time. The crack is already noticeable in the image taken on November 28, 2017 (Fig. S7b), and the crack expands further on November 23, 2018 (Fig. S7c). Between 2019 and 2020, the crack continues to be covered by snow and ice, and the image shows what appears to be no significant change in the crack, which is not expanding as fast as it did in 2016-2018. In the optical image from February 5, 2021 (two days prior to the event, Fig. S7f), it is clearly shown that the open fissures to the top, left, and right sides formed a triangular landslide block. The width of the cracks was measured to be >80 m. Three days after the incident, on February 10, 2021, the triangle-shaped block had vanished, exposing the bedrock.

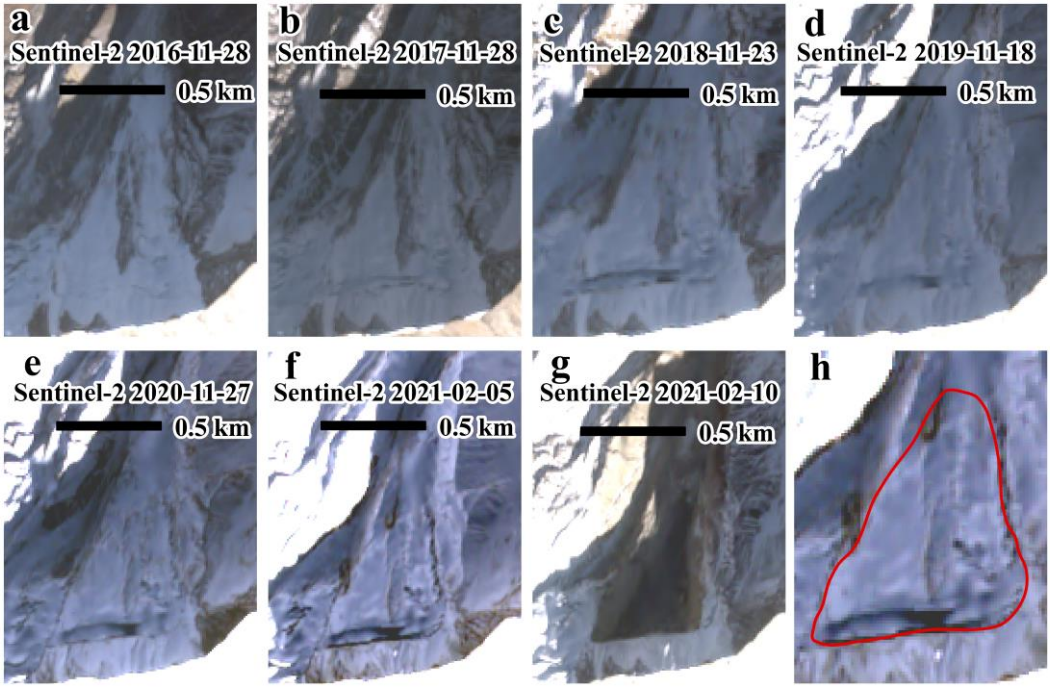

Figure S7: Manually interpreted crack width changes in Sentinel-2 images.

Supplement 7: Rising temperatures

We used the ERA5 dataset to construct the trend since 1979 for the maximum, mean, and minimum annual temperatures (shown in Fig. S8). We found that there is a gradual warming trend in the Chamoli landslide area. The maximum, mean, and minimum annual temperatures rise by 1.3, 1.1 and 1.7°C during this period, respectively.

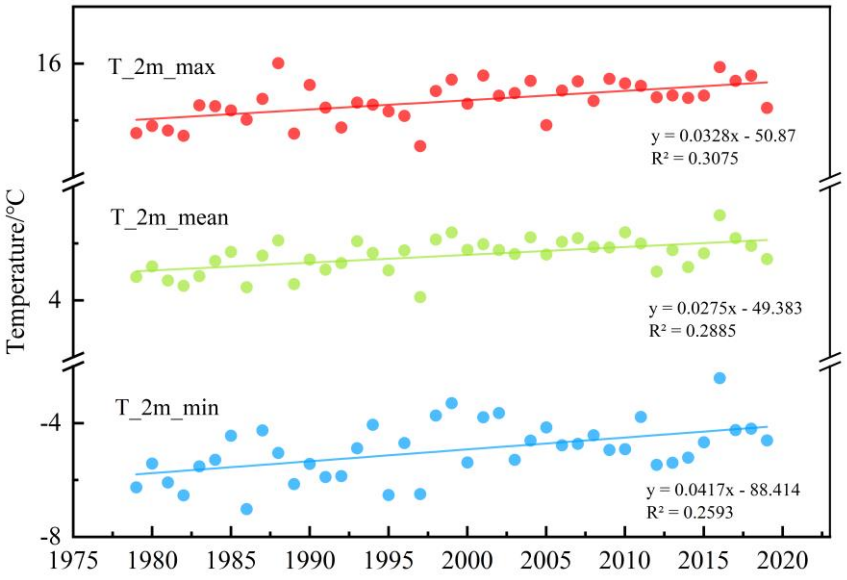

Figure S8: The maximum, mean, and minimum annual EAR5 temperatures for 1979-2020 for the landslide.