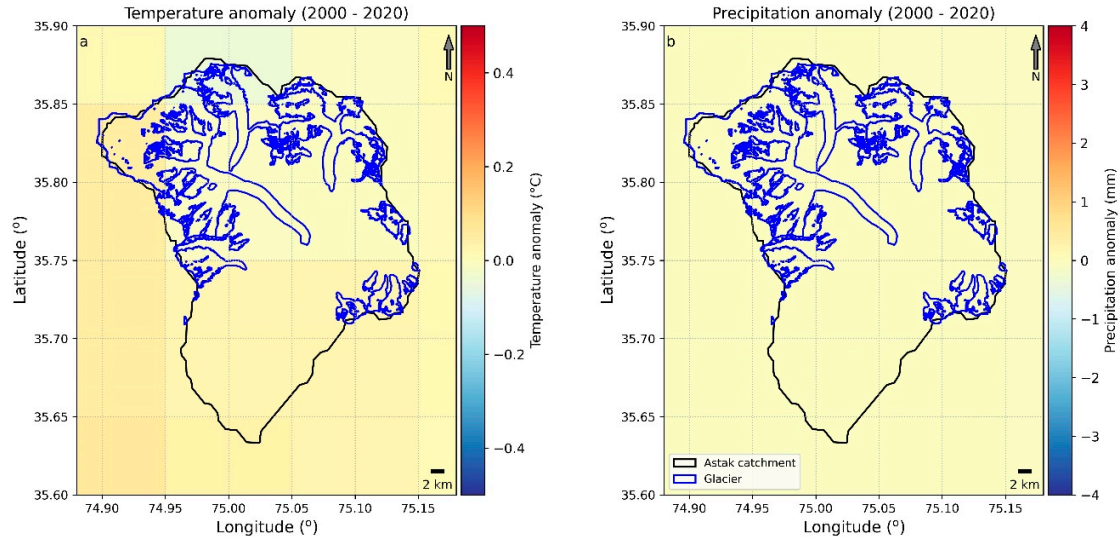


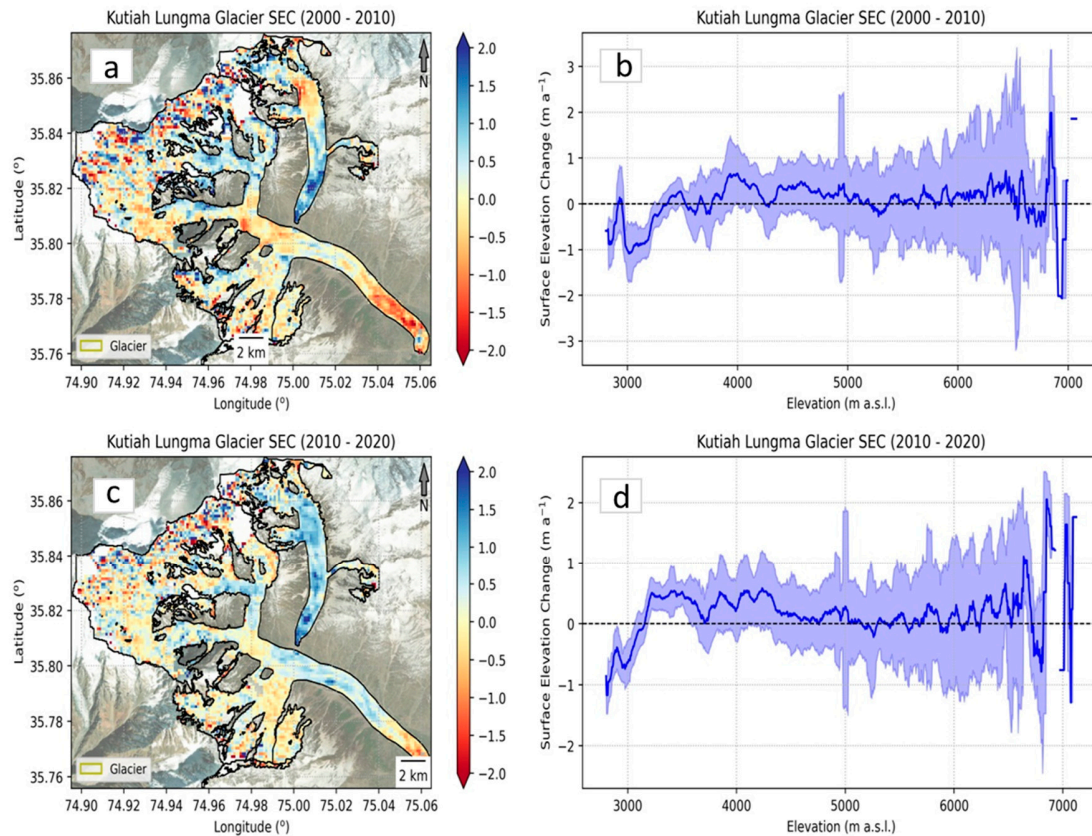
## Supplementary materials

### Two-decadal Glacier Changes in the Astak, a Tributary Catchment of the Upper Indus River in Northern Pakistan

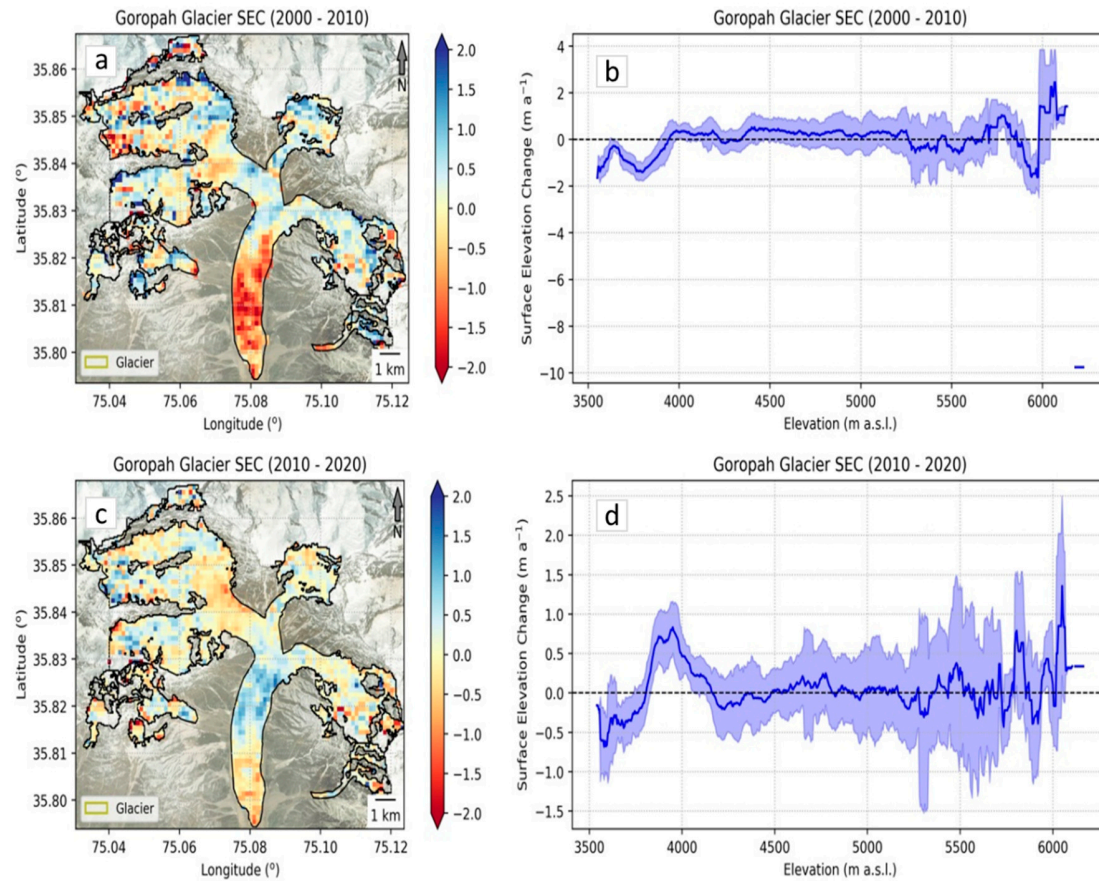
#### Supplementary Figures



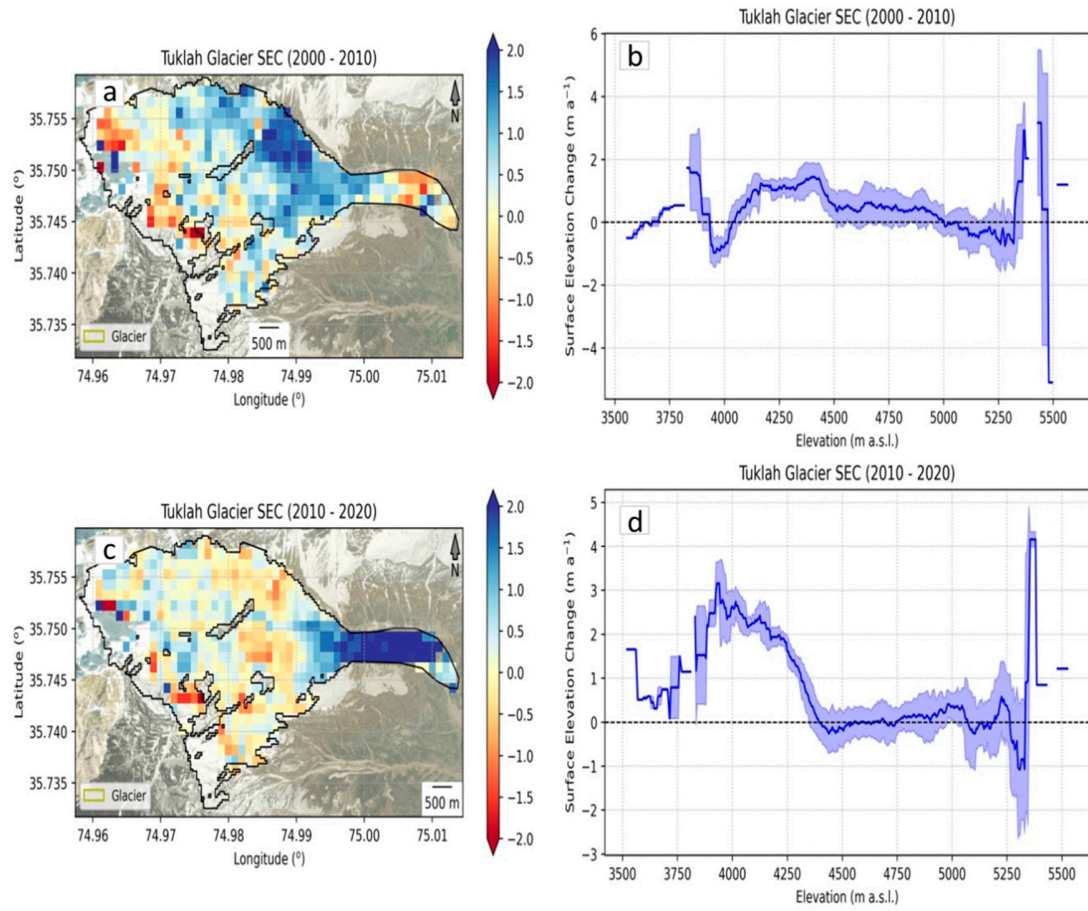
**Figure S1.** Mean annual climate change anomalies for the Astak catchment from 2000 to 2020 compared to the baseline period 1990 to 2000. (a) Temperature anomalies, and (b) precipitation anomalies. Boundary of Astak catchment is shown in black and glacier boundaries are shown in blue.



**Figure S2.** (a) Spatially distributed elevation change for Kutiah Glaceir and it tributaries from 2000 to 2010. The changes in color corresponds to the change in glacier surface elevation shown in the color bar. (b) Altitudinal variations in glacier elevation change shown with the blue line at each 50 meter in-terval. Range of error at each point is shown in the blue shaded line. And the glacier elevation changes for the period of 2010 to 2020 is shown in panel c and d.

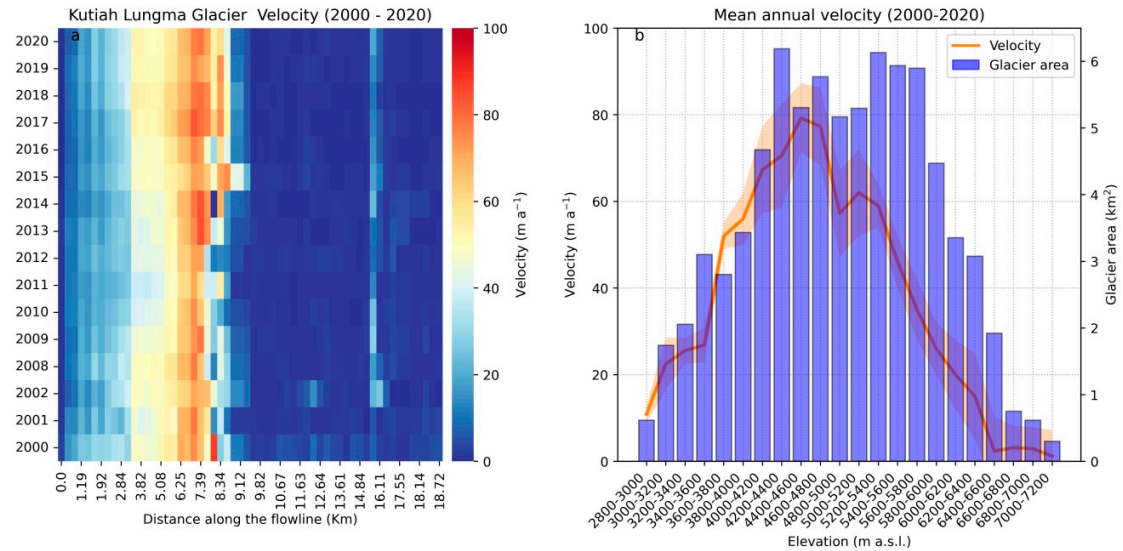


**Figure S3.** (a) Spatially distributed elevation change for Goropah Glaceir and it tributaries from 2000 to 2010. The changes in color corresponds to the change in glacier surface elevation shown in the color bar. (b) Altitudinal variations in glacier elevation change shown with the blue line at each 50 meter in-terval. Range of error at each point is shown in the blue shaded line. And the glacier elevation changes for the period of 2010 to 2020 is shown in panel c and d.

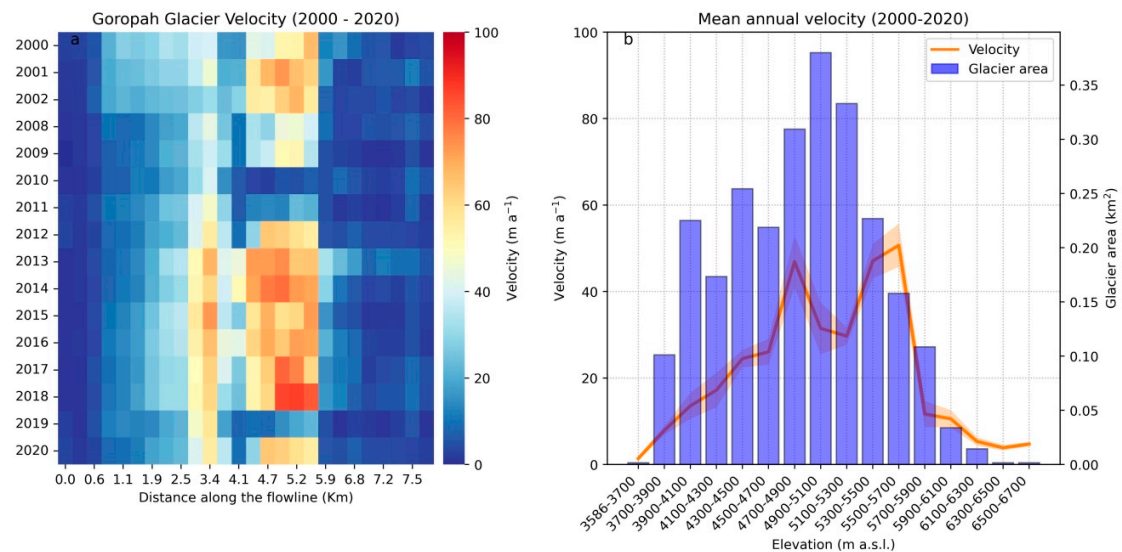


**Figure S4.** (a) Spatially distributed elevation changes for Tuklah Glaceir and it tributaries from 2000 to 2010. The changes in color corresponds to the change in glacier surface elevation shown in the color bar. (b) Altitudinal variations in glacier elevation change shown with the blue line at each 50 meter in-terval. Range of error at each point is shown in the blue shaded line. And the glacier elevation changes for the period of 2010 to 2020 is shown in panel c and d.

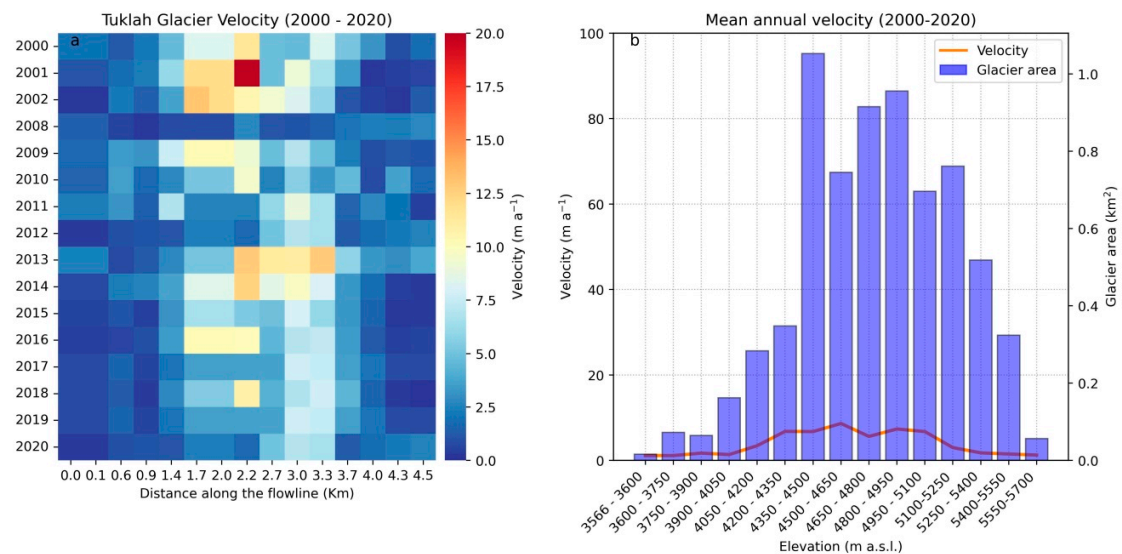




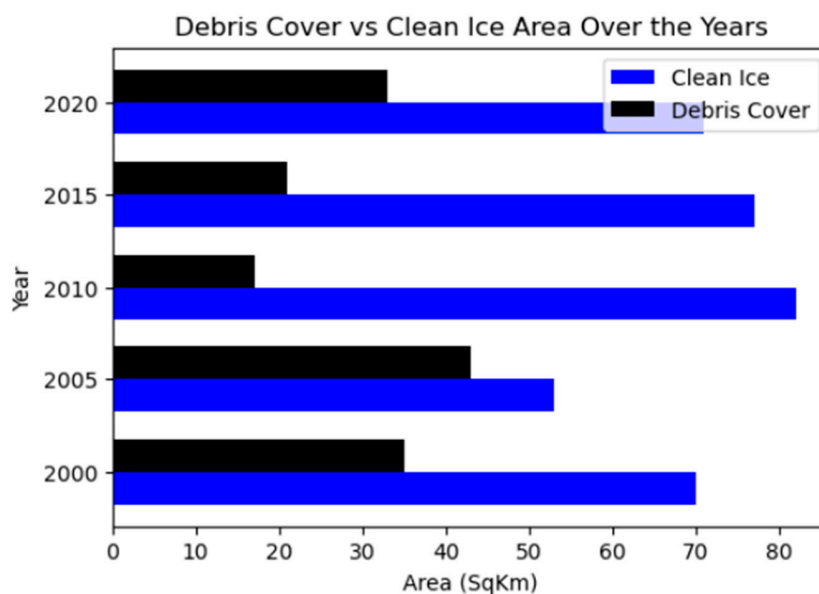
**Figure S5.** (a) Variation in Kutiah Lungma Glacier velocity from 2000 to 2020. Distance away from the glacier terminus is presented along x-axis and the mean annual velocity is shown in y-axis. (b) Altitudinal variation in glacier velocity is shown with the brown line corresponds to the primary y-axis and the glacier area at each 200 m elevation bin is shown with the blue bar corresponds to the secondary y-axis.



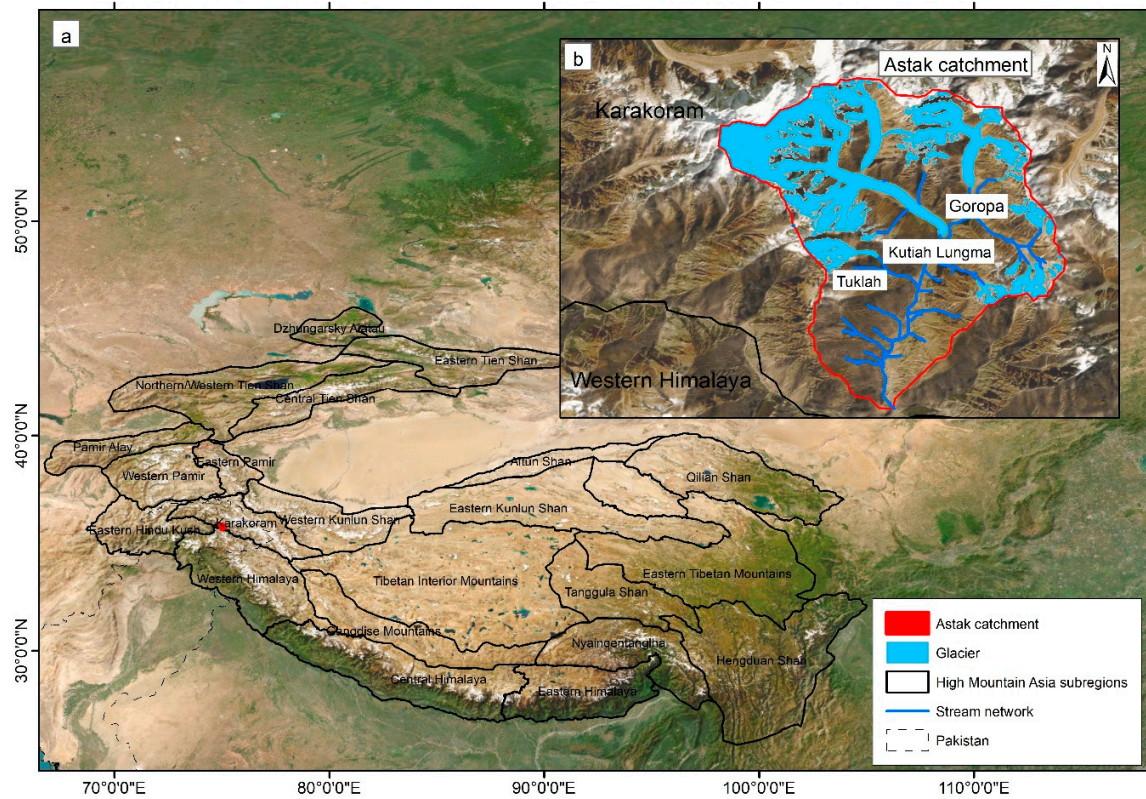
**Figure S6.** (a) Variation in Goropah Glacier velocity from 2000 to 2020. Distance away from the glacier terminus is presented along x-axis and the mean annual velocity is shown in y-axis. (b) Altitudinal variation in glacier velocity is shown with the brown line corresponds to the primary y-axis and the glacier area at each 200 m elevation bin is shown with the blue bar corresponds to the secondary y-axis.



**Figure S7.** (a) Variation in Tuklah Glacier velocity from 2000 to 2020. Distance away from the glacier terminus is presented along x-axis and the mean annual velocity is shown in y-axis. (b) Altitudinal variation in glacier velocity is shown with the brown line corresponds to the primary y-axis and the glacier area at each 200 m elevation bin is shown with the blue bar corresponds to the secondary y-axis.



**Figure S7.** Temporal variations in debris covered and clean-ice glacier in the Astak catchment. Debris cover glacier area for the corresponding year is shown in black bar and blue bar represents the clean-ice glacier area.



**Figure S8.** (a) The geographical extent of High Mountain Asia (HMA) with all subregions highlighted by black boundaries. The location of the Astak catchment within HMA is indicated by the red polygon. (b) The boundary of the Astak catchment is outlined in red, with glaciers highlighted by gray boundaries.

## Supplementary tables

**Table S1.** Details of the optical satellite images from Landsat images used for the estimation of glacier area change in Astak catchment.

| Acquisition Date | Product ID                               | Path/Row | Resolution(m) | Cloud Cover % |
|------------------|--|----------|---------------|---------------|
| 11/9/2000        | LE07_L1TP_149035_20000911_20200918_02_T1 | 149/35   | 30            | 2.61          |
| 24/8/2005        | LE07_L1TP_149035_20050824_20200914_02_T1 | 149/35   | 30            | 5.35          |
| 22/08/2010       | LE07_L1TP_149035_20100822_20200911_02_T1 | 149/35   | 30            | 3.18          |
| 20/8/2015        | LE07_L1TP_149035_20150820_20200903_02_T1 | 149/35   | 30            | 2.94          |
| 17/08/2020       | LE07_L1TP_149035_20200817_20200917_02_T1 | 149/35   | 30            | 3.45          |

**Table S2.** Details of the ASTER DEMs used for the estimation of glacier surface elevation change from 2000 to 2020 for the Astak catchment.

| Acquisition Date | Sensor     | Resolution | Cloud Cover % |
|------------------|------------|------------|---------------|
| 9/7/2000         | ASTER V003 | 30         | 11            |
| 30/9/2001        | ASTER V003 | 30         | 5             |
| 22/8/2002        | ASTER V003 | 30         | 34            |
| 29/10/2003       | ASTER V003 | 30         | 11            |
| 13/09/2004       | ASTER V003 | 30         | 01            |
| 15/10/2004       | ASTER V003 | 30         | 13            |
| 5/11/2005        | ASTER V003 | 30         | 26            |
| 28/11/2005       | ASTER V003 | 30         | 46            |
| 12/09/2006       | ASTER V003 | 30         | 16            |
| 1/5/2007         | ASTER V003 | 30         | 37            |
| 27/11/2008       | ASTER V003 | 30         | 20            |
| 03/10/2008       | ASTER V003 | 30         | 03            |
| 14/11/2009       | ASTER V003 | 30         | 20            |
| 14/11/2009       | ASTER V003 | 30         | 29            |
| 17/11/2010       | ASTER V003 | 30         | 16            |
| 17/11/2010       | ASTER V003 | 30         | 28            |
| 12/10/2011       | ASTER V003 | 30         | 06            |
| 30/10/2012       | ASTER V003 | 30         | 12            |
| 6/09/2013        | ASTER V003 | 30         | 03            |
| 6/09/2013        | ASTER V003 | 30         | 06            |
| 18/09/2014       | ASTER V003 | 30         | 04            |
| 27/8/2015        | ASTER V003 | 30         | 19            |
| 27/8/2015        | ASTER V003 | 30         | 34            |
| 23/9/2016        | ASTER V003 | 30         | 04            |
| 12/10/2017       | ASTER V003 | 30         | 21            |

|            |            |    |    |
|------------|------------|----|----|
| 5/8/2018   | ASTER V003 | 30 | 04 |
| 10/11/2019 | ASTER V003 | 30 | 21 |
| 10/11/2019 | ASTER V003 | 30 | 19 |
| 17/08/2020 | ASTER V003 | 30 | 01 |

**Table S3.** Details of satellite images used for the extraction of glacier surface velocity in the Astak catchment from 2000 to 2020.

| Acquisition Date | Product ID                               | Path/Row | Resolution(m) | Cloud Cover % |
|------------------|--|----------|---------------|---------------|
| 29/10/2000       | LE07_L1TP_149035_20001029_20200918_02_T1 | 149/35   | 30            | 02            |
| 30/09/2001       | LE07_L1TP_149035_20010930_20200917_02_T1 | 149/35   | 30            | 1.0           |
| 3/10/2002        | LE07_L1TP_149035_20021003_20200916_02_T1 | 149/35   | 30            | 2.0           |
| 31/7/2008        | LE07_L1TP_149035_20080731_20200912_02_T1 | 149/35   | 30            | 1.0           |
| 20/09/2009       | LE07_L1TP_149035_20090920_20200911_02_T1 | 149/35   | 30            | 1.0           |
| 22/08/2010       | LE07_L1TP_149035_20100822_20200911_02_T1 | 149/35   | 30            | 4.0           |
| 12/10/2011       | LE07_L1TP_149035_20111012_20200909_02_T1 | 149/35   | 30            | 2.0           |
| 30/10/2012       | LE07_L1TP_149035_20121030_20200908_02_T1 | 149/35   | 30            | 2.0           |
| 7/9/2013         | LC08_L1TP_149035_20130907_20200912_02_T1 | 149/35   | 30            | 2.14          |
| 26/09/2014       | LC08_L1TP_149035_20140926_20200910_02_T1 | 149/35   | 30            | 5.19          |
| 31/10/2015       | LC08_L1TP_149035_20151031_20200908_02_T1 | 149/35   | 30            | 3.94          |
| 14/08/2016       | LC08_L1TP_149035_20160814_20200906_02_T1 | 149/35   | 30            | 45.52         |
| 1/8/2017         | LC08_L1TP_149035_20170801_20200903_02_T1 | 149/35   | 30            | 3.60          |
| 4/8/2018         | LC08_L1TP_149035_20180804_20200831_02_T1 | 149/35   | 30            | 2.57          |
| 24/09/2019       | LC08_L1TP_149035_20190924_20200826_02_T1 | 149/35   | 30            | 1.11          |
| 15/07/2020       | LC08_L1TP_149035_20200825_20200905_02_T1 | 149/35   | 30            | 5.50          |