# Supplement to: Using novel remote sensing methods to better constrain surge dynamics and test generalized glacier slip behavior, example of Shisper glacier, Pakistan

Flavien Beaud[1,2], Saif Aati[1], Ian Delaney[3], Shan Gremion[1], Surendra Adhikari[3], and Jean-Philippe Avouac[1]

[1]Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA, USA
[2]Now at Department of Geography, University of British Columbia, Vancouver, BC, CA
[3]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA

**Correspondence:** Flavien Beaud (flavien.beaud@ubc.ca)

## S1 Methodology

Table S1: Overview of image pairs used in this study.

| **Pre-Ortho** [date/platform] | **Post-ortho** [date/platform] | **Time span** [day] |
|---|---|---|
| 2016-05-21 (S2A) | 2016-07-20 (S2A) | 60 |
| 2016-07-20 (S2A) | 2016-10-28 (S2A) | 100 |
| 2016-10-28 (S2A) | 2017-04-16 (S2A) | 170 |
| 2017-04-16 (S2A) | 2017-05-06 (S2A) | 20 |
| 2017-05-06 (S2A) | 2017-07-25 (S2A) | 80 |
| 2017-07-25 (S2A) | 2017-11-02 (S2A) | 100 |
| 2017-11-02 (S2A) | 2017-11-07 (S2B) | 5 |
| 2017-11-07 (S2B) | 2017-12-07 (S2B) | 30 |
| 2017-12-07 (S2B) | 2018-01-01 (S2A) | 25 |
| 2018-01-01 (S2A) | 2018-01-21 (S2A) | 20 |
| 2018-01-21 (S2A) | 2018-02-05 (S2B) | 15 |
| 2018-02-05 (S2B) | 2018-03-07 (S2B) | 30 |
| 2018-03-07 (S2B) | 2018-03-17 (S2B) | 10 |
| 2018-03-17 (S2B) | 2018-03-22 (S2A) | 5 |
| 2018-03-22 (S2A) | 2018-04-01 (S2A) | 10 |

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**Table S1 – continued from previous page**

| Pre-Ortho | Post-ortho | Time span |
|---|---|---|
| 2018-04-01 (S2A) | 2018-04-06 (S2B) | 5 |
| 2018-04-06 (S2B) | 2018-05-01 (S2A) | 25 |
| 2018-05-01 (S2A) | 2018-05-11 (S2A) | 10 |
| 2018-05-11 (S2A) | 2018-05-21 (S2A) | 10 |
| 2018-05-21 (S2A) | 2018-05-26 (S2B) | 5 |
| 2018-05-26 (S2B) | 2018-06-05 (S2B) | 10 |
| 2018-06-05 (S2B) | 2018-07-10 (S2A) | 35 |
| 2018-07-10 (S2A) | 2018-07-15 (S2B) | 5 |
| 2018-07-15 (S2B) | 2018-07-25 (S2B) | 10 |
| 2018-07-25 (S2B) | 2018-08-04 (S2B) | 10 |
| 2018-08-04 (S2B) | 2018-08-14 (S2B) | 10 |
| 2018-08-14 (S2B) | 2018-08-24 (S2B) | 10 |
| 2018-08-24 (S2B) | 2018-08-29 (S2A) | 5 |
| 2018-08-29 (S2A) | 2018-09-08 (S2A) | 10 |
| 2018-09-08 (S2A) | 2018-09-13 (S2B) | 5 |
| 2018-09-13 (S2B) | 2018-09-18 (S2A) | 5 |
| 2018-09-18 (S2A) | 2018-09-23 (S2B) | 5 |
| 2018-09-23 (S2B) | 2018-10-23 (S2B) | 30 |
| 2018-10-23 (S2B) | 2018-10-28 (S2A) | 5 |
| 2018-10-28 (S2A) | 2018-11-07 (S2A) | 10 |
| 2018-11-07 (S2A) | 2018-11-17 (S2A) | 10 |
| 2018-11-17 (S2A) | 2018-12-02 (S2B) | 15 |
| 2018-12-02 (S2B) | 2018-12-07 (S2A) | 5 |
| 2018-12-07 (S2A) | 2019-03-07 (S2A) | 90 |
| 2019-03-07 (S2A) | 2019-04-01 (S2B) | 25 |
| 2019-04-01 (S2B) | 2019-04-06 (S2A) | 5 |
| 2019-04-06 (S2A) | 2019-04-21 (S2B) | 15 |
| 2019-04-21 (S2B) | 2019-05-01 (S2B) | 10 |
| 2019-05-01 (S2B) | 2019-07-20 (S2B) | 80 |
| 2019-07-20 (S2B) | 2019-07-25 (S2A) | 5 |
| 2019-07-25 (S2A) | 2019-07-30 (S2B) | 5 |
| 2019-07-30 (S2B) | 2019-08-04 (S2A) | 5 |

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**Table S1 – continued from previous page**

| Pre-Ortho | Post-ortho | Time span |
|---|---|---|
| 2019-08-04 (S2A) | 2019-08-09 (S2B) | 5 |
| 2013-05-02 (LC) | 2013-05-18 (LC) | 16 |
| 2013-05-18 (LC) | 2013-06-19 (LC) | 32 |
| 2013-06-19 (LC) | 2013-07-05 (LC) | 16 |
| 2013-07-05 (LC) | 2013-07-21 (LC) | 16 |
| 2013-07-21 (LC) | 2013-09-07 (LC) | 48 |
| 2013-09-07 (LC) | 2013-10-09 (LC) | 32 |
| 2013-10-09 (LC) | 2013-10-25 (LC) | 16 |
| 2013-10-25 (LC) | 2013-11-10 (LC) | 16 |
| 2013-11-10 (LC) | 2013-11-26 (LC) | 16 |
| 2013-11-26 (LC) | 2013-12-12 (LC) | 16 |
| 2013-12-12 (LC) | 2014-01-29 (LC) | 48 |
| 2014-01-29 (LC) | 2014-02-14 (LC) | 16 |
| 2014-02-14 (LC) | 2014-06-06 (LC) | 112 |
| 2014-06-06 (LC) | 2014-07-08 (LC) | 32 |
| 2014-07-08 (LC) | 2014-07-24 (LC) | 16 |
| 2014-07-24 (LC) | 2014-08-25 (LC) | 32 |
| 2014-08-25 (LC) | 2014-09-10 (LC) | 16 |
| 2014-09-10 (LC) | 2014-09-26 (LC) | 16 |
| 2014-09-26 (LC) | 2015-01-16 (LC) | 112 |
| 2015-01-16 (LC) | 2015-03-21 (LC) | 64 |
| 2015-03-21 (LC) | 2015-04-06 (LC) | 16 |
| 2015-04-06 (LC) | 2015-04-22 (LC) | 16 |
| 2015-04-22 (LC) | 2015-08-12 (LC) | 112 |
| 2015-08-12 (LC) | 2015-09-13 (LC) | 32 |
| 2015-09-13 (LC) | 2015-10-15 (LC) | 32 |
| 2015-10-15 (LC) | 2015-10-31 (LC) | 16 |
| 2015-10-31 (LC) | 2015-11-16 (LC) | 16 |
| 2015-11-16 (LC) | 2015-12-02 (LC) | 16 |
| 2015-12-02 (LC) | 2015-12-18 (LC) | 16 |
| 2015-12-18 (LC) | 2016-01-19 (LC) | 32 |
| 2016-01-19 (LC) | 2016-04-24 (LC) | 96 |

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**Table S1 – continued from previous page**

| Pre-Ortho | Post-ortho | Time span |
|---|---|---|
| 2016-04-24 (LC) | 2016-05-10 (LC) | 16 |
| 2016-05-10 (LC) | 2016-05-26 (LC) | 16 |
| 2016-05-26 (LC) | 2016-10-01 (LC) | 128 |
| 2016-10-01 (LC) | 2016-10-17 (LC) | 16 |
| 2016-10-17 (LC) | 2016-11-02 (LC) | 16 |
| 2016-11-02 (LC) | 2016-12-20 (LC) | 48 |
| 2016-12-20 (LC) | 2017-03-26 (LC) | 96 |
| 2017-03-26 (LC) | 2017-04-11 (LC) | 16 |
| 2017-04-11 (LC) | 2017-04-27 (LC) | 16 |
| 2017-04-27 (LC) | 2017-05-13 (LC) | 16 |
| 2017-05-13 (LC) | 2017-05-29 (LC) | 16 |
| 2017-05-29 (LC) | 2017-08-17 (LC) | 80 |
| 2017-08-17 (LC) | 2017-09-18 (LC) | 32 |
| 2017-09-18 (LC) | 2017-11-05 (LC) | 48 |
| 2017-11-05 (LC) | 2017-11-21 (LC) | 16 |
| 2017-11-21 (LC) | 2017-12-07 (LC) | 16 |
| 2017-12-07 (LC) | 2018-02-09 (LC) | 64 |
| 2018-02-09 (LC) | 2018-04-14 (LC) | 64 |
| 2018-04-14 (LC) | 2018-04-30 (LC) | 16 |
| 2018-04-30 (LC) | 2018-07-03 (LC) | 64 |
| 2018-07-03 (LC) | 2018-07-19 (LC) | 16 |
| 2018-07-19 (LC) | 2018-08-04 (LC) | 16 |
| 2018-08-04 (LC) | 2018-09-21 (LC) | 48 |
| 2018-09-21 (LC) | 2018-10-23 (LC) | 32 |
| 2018-10-23 (LC) | 2019-01-27 (LC) | 96 |
| 2019-01-27 (LC) | 2019-02-28 (LC) | 32 |
| 2019-02-28 (LC) | 2019-03-16 (LC) | 16 |
| 2019-03-16 (LC) | 2019-04-01 (LC) | 16 |

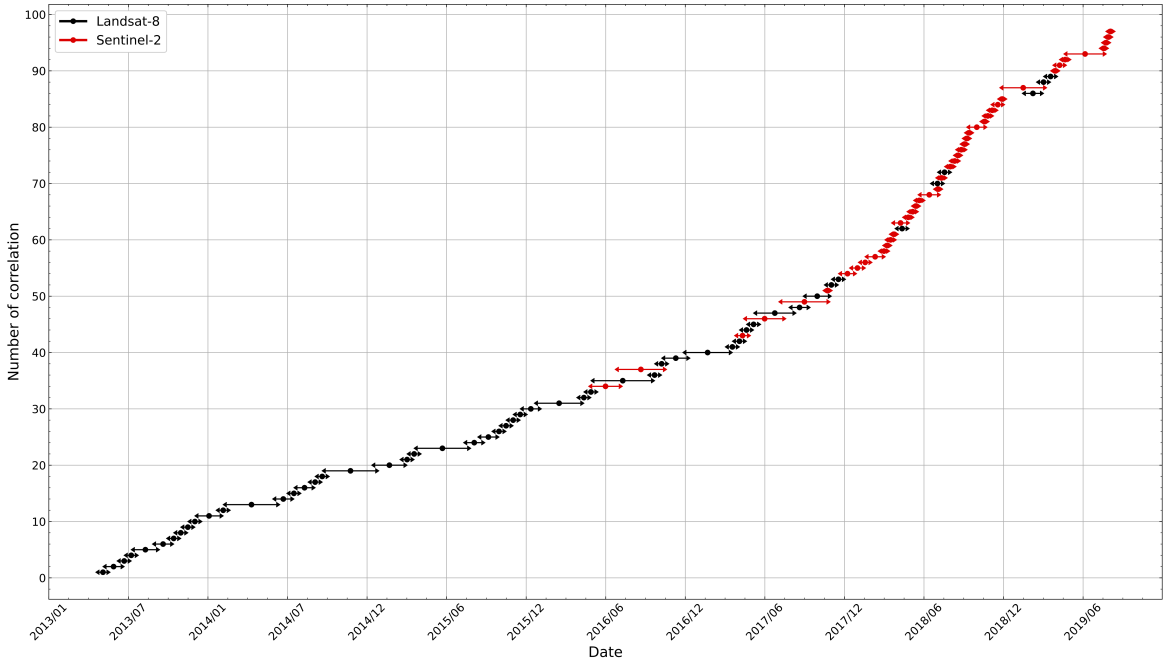


**Figure S1.** Time span distribution covered by image pairs denoted by arrows. Landsat 8 spans are in green and Sentinel 8 images are in red. All the correlations are sorted according to the slave date, and then only the displacement maps, which cover the smallest period are selected. When staggering the velocity maps, each map is considered from the data of its master image until that of the date of the master image of the next velocity map.

### S1.1 Image time span

### S1.2 Determination of glacially dammed lake volume

A glacially dammed lake appears in November of 2018 (Shah et al., 2019) and drains on 28 June, 2019. We determine the lake's area by outlining lake in the RBG imagery from S2. We then evaluated the topography over the lake area to determine the lake's volume.

## S2 Surge history of Mochowar and Shisper

The Google Earth Engine timelapse video can be found at this link. The timelaspse shows that the two glaciers are still connected until 2006, after what the stagnant ice in front of Mochowar becomes apparent. In 2009, the two glaciers are clearly

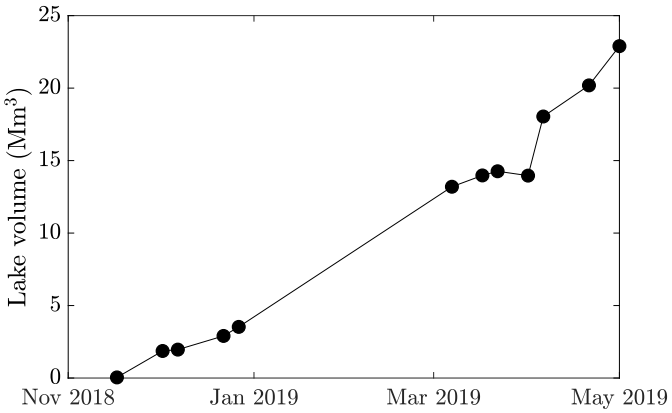


**Figure S2.** Estimated lake volume determined from lake areas and DEM.

disconnected while a significant amount of stagnant ice is left in the valley. That ice has completely disappeared by 2014. In this timelapse, it is also apparent that Shisper surges from 1999 until 2005. While a significant terminus advance is apparent, it merely advances past the stagnant ice in the valley and stops $\sim 700\,\mathrm{m}$ up-valley from the most recent surge.

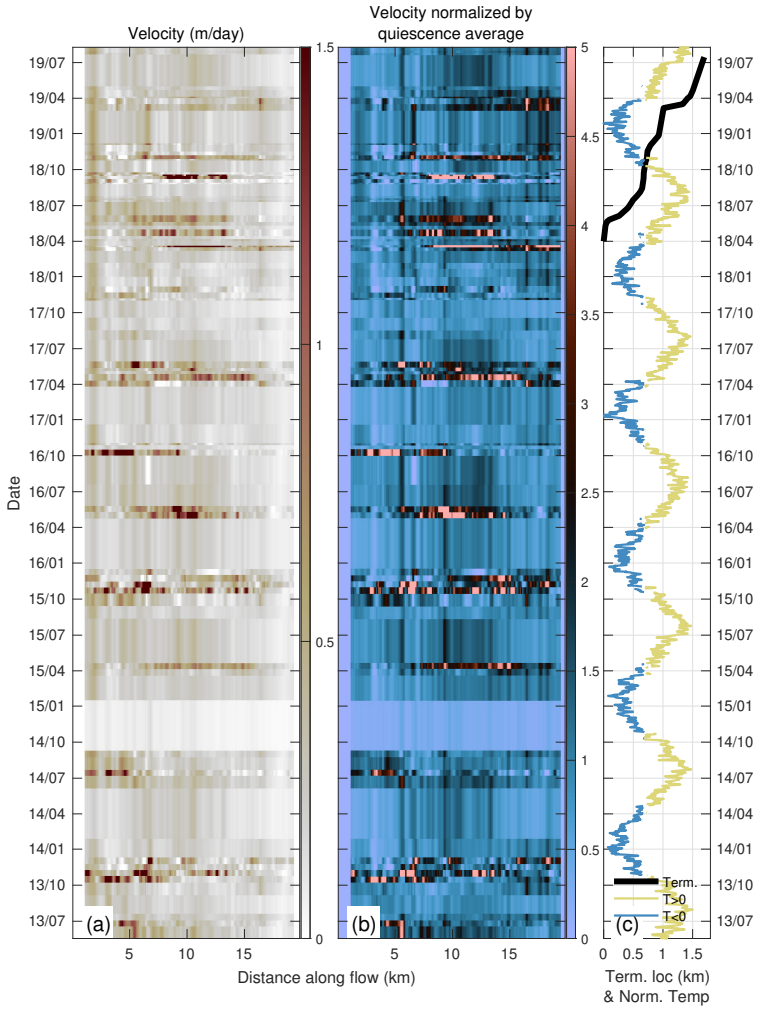


**Figure S3.** Time series of Mochowar glacier (a) surface velocities along the flowline (See Fig. 2 in manuscript) from 2013 to 2019 for Landsat 8 and Sentinel 2 imagery, (b) normalized surface velocities compared to pre-2018 velocity average, (c) MERRA-2 sat reanalysis temperature data and advance of Shisper terminus for reference.

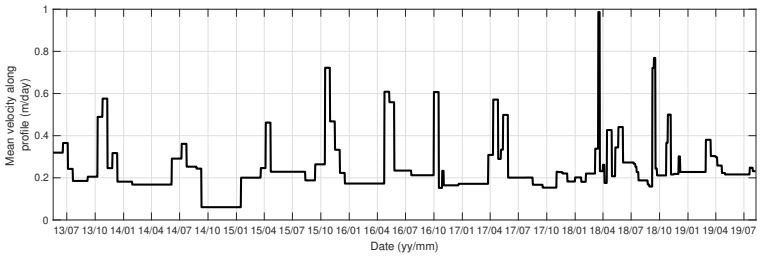


**Figure S4.** Spatial average of surface velocities along the profile of Mochowar glacier as a function of time. Note that the speed-up in fall / winter may be related to snow fall and not ice flow.

## S3 Results

### S3.1 Mochowar results

## S4 Discussion points

### S4.1 Combining Landat 8 and Sentinel 2 datasets

In the manuscript we only display the velocity timeseries from the composite of L8 and S2. To clearly highlight their respective importance, we show the two timeseries independently in Fig. S5.

### S4.2 Effect of DEM on sliding relationship

The uncertainty surrounding the bed topography and ice surface elevation are the main source of uncertainty for constraining the generalized sliding relationship. In order to asses the effect of the surface DEM on the sliding relationship, we plot Fig. 8 from the main manuscript using either the SRTM DEM only (Fig. S6) and the 2019 Worldview DEM only (Fig. S7). We find some small differences, but generally the set of parameters use are still adequate to encompass the sliding behavior observed at Shisper glacier.

### S4.3 Axis scale rendering of sliding relationship

*Code availability.* TEXT

*Data availability.* TEXT

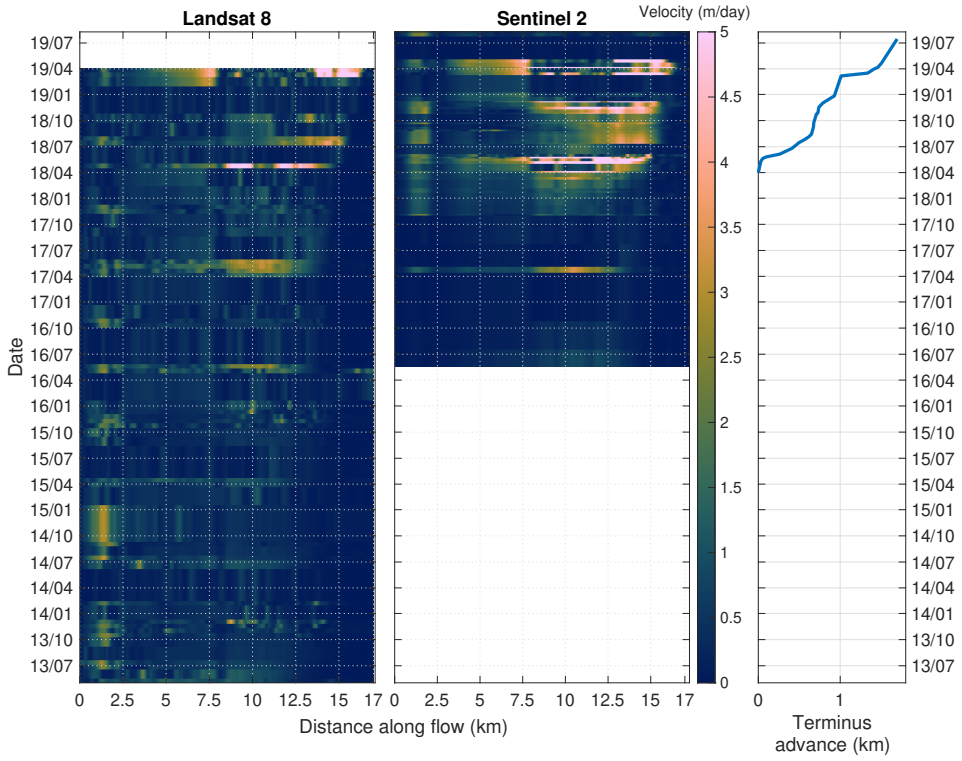


**Figure S5.** Comparison between velocity maps for Shisper glacier obtained with L8 and S2 data, with the terminus advance for reference. The data from L8 is useful to understand the surface velocities before the surge, in particular the presence of seasonal speed-ups and increase in amplitude of the spring speed-up leading up to the surge. The S2 data is limited temporally due to launch date, but it shines light on the surface velocity changes during the surge. The slow onset of the surges and the different phases and their link with terminus advance can only be made with S2 data.

*Code and data availability.* TEXT

*Sample availability.* TEXT

*Video supplement.* TEXT

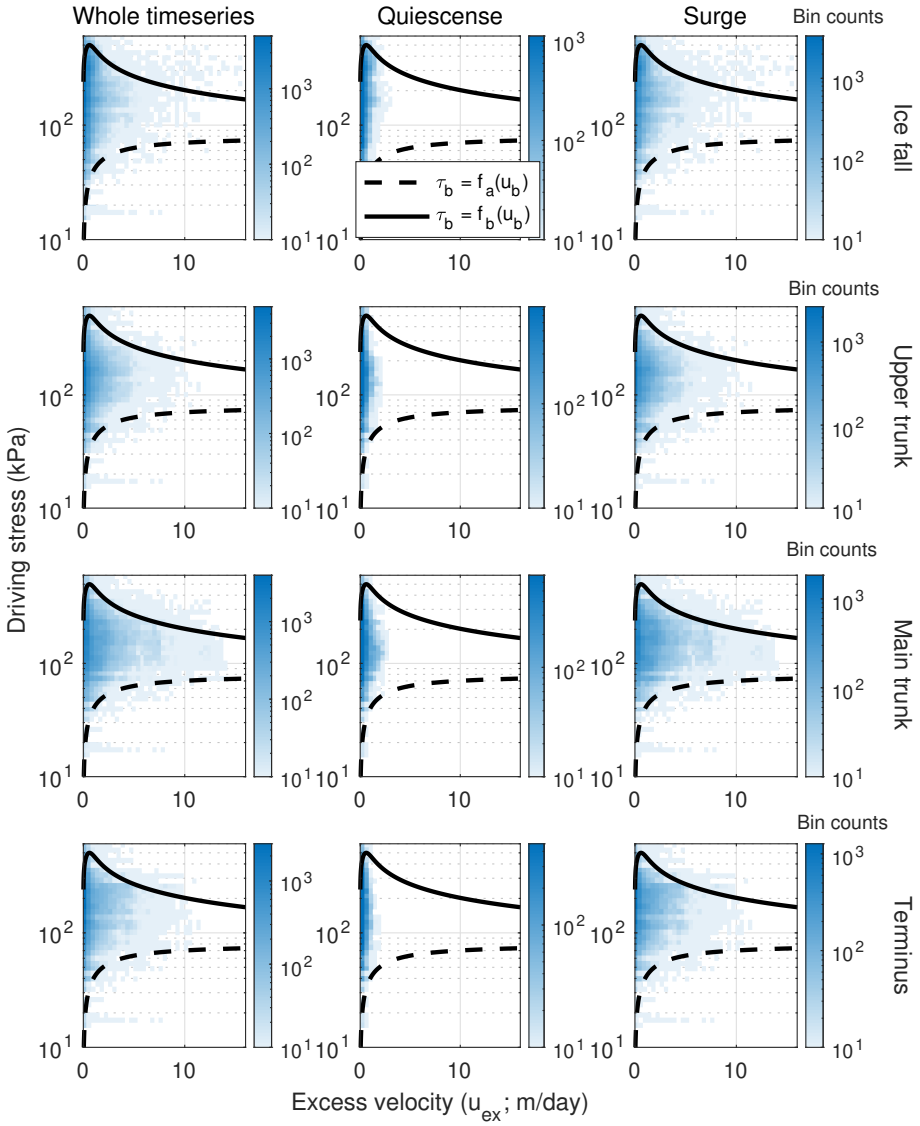


**Figure S6.** Driving stress calculated with SRTM DEM only plotted against excess velocity.

## Appendix A: Algorythms

*Author contributions.* TEXT

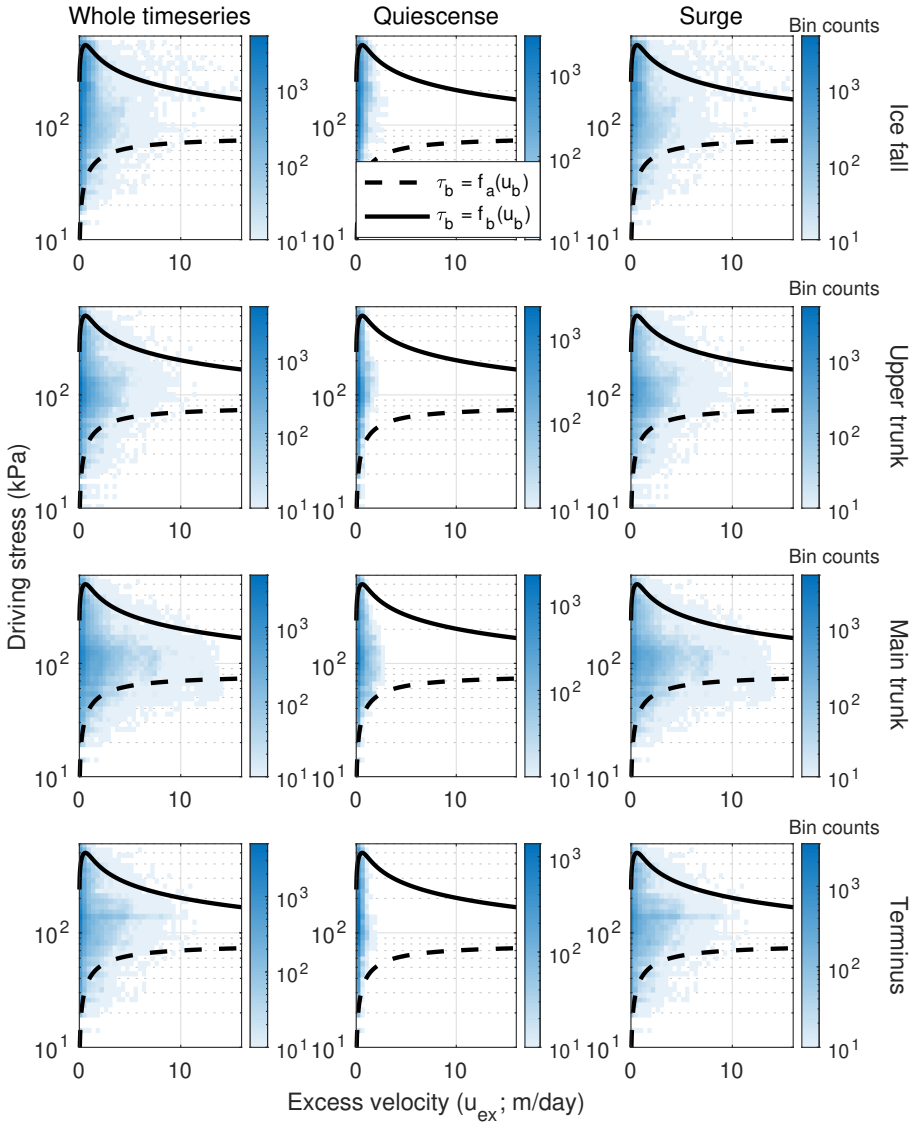


**Figure S7.** Driving stress calculated with 2019 Worldview DEM only plotted against excess velocity.

*Competing interests.* TEXT

35 *Disclaimer.* TEXT

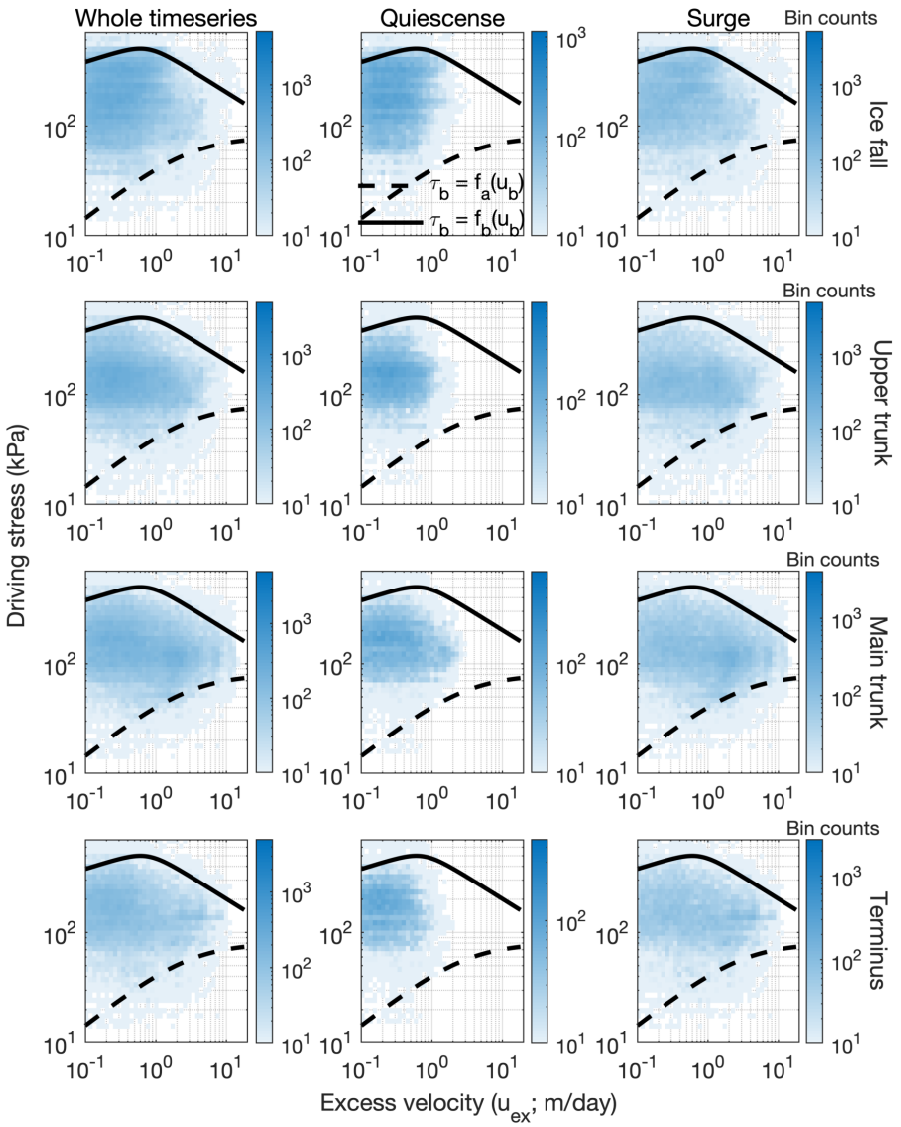


**Figure S8.** Relationship between driving stress and surface velocities departure from mean quiescence velocities with possible bounds by a unified glacier slip relationship (Eq. 6). Note that the Y and X-axes are logarithmic.

*Acknowledgements.* TEXT

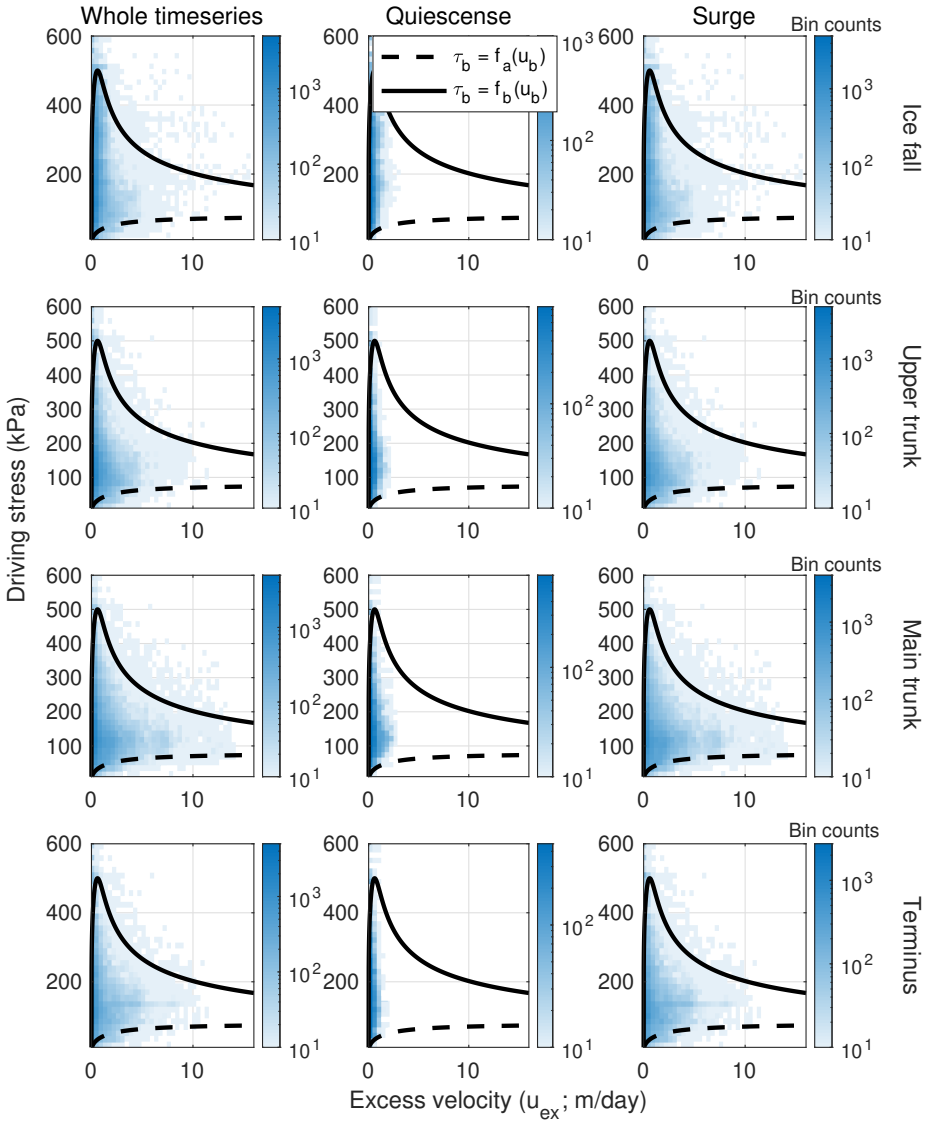


**Figure S9.** Relationship between driving stress and surface velocities departure from mean quiescence velocities with possible bounds by a unified glacier slip relationship (Eq. 6). Note that the Y and X-axes are linear.

## References

Shah, A., Ali, K., Nizami, S., Jan, I., Hussain, I., and Begum, F.: Risk assessment of Shishper Glacier, Hassanabad Hunza, North Pakistan, Journal of Himalayan Earth Sciences Volume, 52, 1–11, 2019.