Supplemental Information

S1. Timescale development for Naimona'nyi ice core record

The Naimona'nyi and Dasuopu glaciers receive most precipitation from both the Indian summer monsoon and the continental westerlies. However, because it is located in the western Himalayas and further inland away from the monsoon source, the westerly to monsoon moisture ratio is higher for Naimona'nyi. In addition, in 1997 Dasuopu had a ~50 meter firn layer, while the Naimona'nyi glacier currently lacks firn and is composed of ice to the surface, which has been ablating for an undetermined number of years. Although Dasuopu contains well defined wet summer/dry winter seasonal oscillations in $\delta^{18}O$, the seasonality on Naimona'nyi is more difficult to detect.

Despite these difficulties, the $\delta^{18}O$ profiles between these two Himalayan glaciers can be matched using AnalySeries software (Paillard et al., 1996) (Fig. S1). We know that the lack of a 1962/63 beta radioactivity horizon (from early 1960s Soviet bomb tests in the Arctic) and the lack of a 1950s ^{36}Cl signal from marine nuclear tests in the South Pacific indicate that the top of the Naimona'nyi core is not more recent than the late 1950s (Kehrwald et al., 2008). Since the 1962/63 horizon occurs in the Dasuopu core at 42 meters, we disregarded that part of the Dasuopu core during the AnalySeries match with the Naimona'nyi $\delta^{18}O$ data. With the depth of each Naimona'nyi $\delta^{18}O$ value matched to its corresponding depth in the Dasuopu record, the annual timescale from the latter can be transferred to the former.

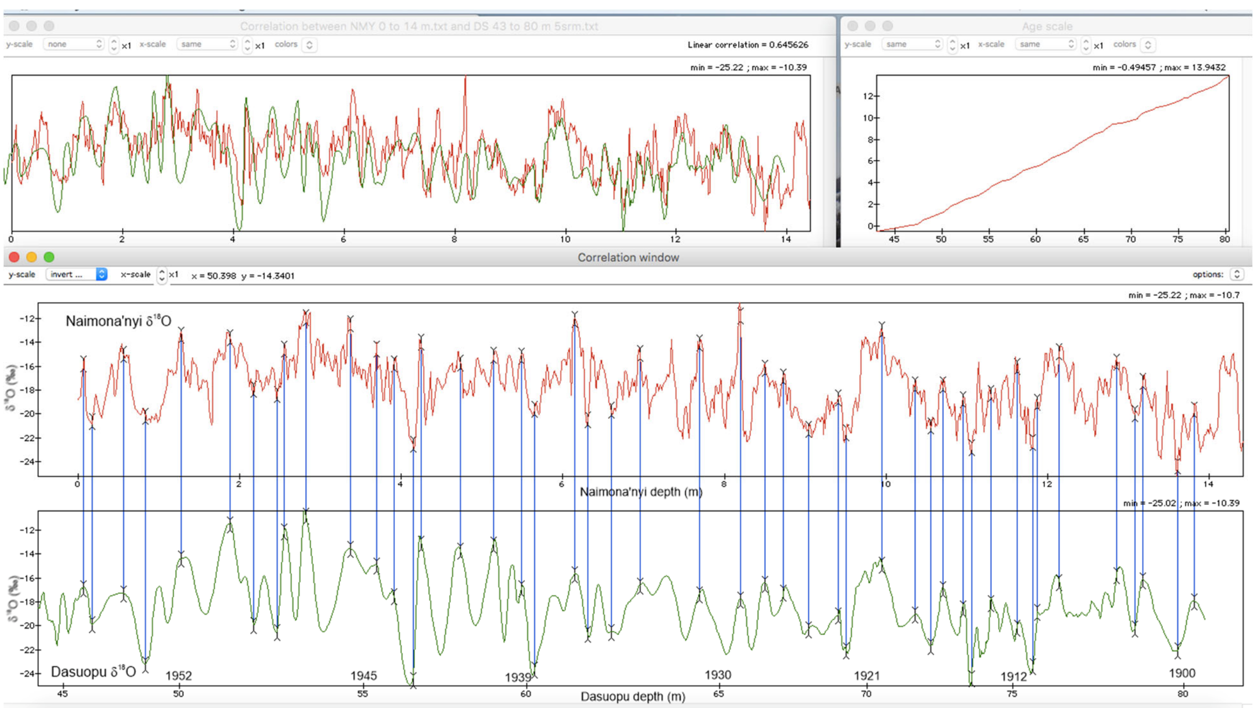

Figure S1. AnalySeries match between $\delta^{18}O$ from the Naimona'nyi ice core (red curve) and smoothed (11-sample running means) Dasuopu ice core $\delta^{18}O$ data. The year (CE) is shown every five meters on the Dasuopu depth scale. The linear correlation between the curves is +0.65 ($p < 0.001$).

S2. Estimation of glacier surface area

S2.1. Imagery Selection

To minimize uncertainty in our area estimates, we chose to analyze only selected images from the entire archive available through the USGS's Global Visualization Viewer (GloVis). Because GloVis allows the analyst to step through every image available for a specific location, several essential advantages are achieved. First, because the viewer's cursor can be placed on a specific geographic reference point, images that are poorly geolocated, especially early in the Landsat time series, can be excluded from the analysis. Second, time periods with few acquisitions or acquisitions not useful for this particular study such as ascending scenes (essentially night acquisitions in the mid-latitudes) can also be identified. Third, by looking at multiple images per year in succession, it becomes fairly clear by inspection which images have the least cloud, snow cover, and the most solar illumination to limit shadows over the area's terrain and ice-covered areas. And lastly, by limiting the Landsat images selected for detailed analysis, it then becomes clearer which periodic images over the Landsat time frame allow ice area changes to be determined for a specific ice-remnant area.

Some ancillary considerations include: 1) minimizing scan-line errors that can negatively impact the classification scheme, most common in the limited number of Landsat 1-3 MSS scenes; 2) using Landsat-7 Scan Line Corrector off (SLC-off) imagery only when necessary but considering them especially when the target area is in the complete center swath; 3) accepting that not all snow can be assessed and excluded visually from even the 'best images' available; and 4) in contrast, accepting that the spectral resolution of Landsat sensors means that ice areas in full shadow cannot be assessed by the classification scheme. In essence, the last two factors 'add to' and 'subtract from' the resulting ice estimates. Similar impacts on area estimates result, respectively, from the presence of pro-glacial lakes, sometimes frozen, and debris-covered glacial outlets from some of the larger ice caps and cordillera.

S2.2 Analysis Approach

After all the 'likely' images are ordered from the United States Geological Survey (USGS), they are then downloaded and imported into PCI Geomatica Focus (https://www.pcigeomatics.com). The images are then stacked chronologically and a more detailed check for snow cover and cloud patches is conducted. Small geolocation errors may also be noted and, if insignificant, tolerated for the ice area analyses. Due to the reduced availability of imagery in the 1970s and 1980s, lower quality Multi Spectral Scanner (MSS) and Thematic Mapper (TM) images may be used to establish 'overall ice extent' even though they are more likely to include snow cover on and near actual glacial ice areas. By examining each possible image relative to those before and after, imagery with excessive snow cover can be excluded from further analysis.

Once the imagery series is selected, a region that encompasses the ice areas is subset or clipped from each full image and analyzed using an unsupervised classification algorithm in Focus using the short-wave infrared, near infrared, red, and green data channels. There are multiple analysis options within Focus but our process always used the 'IsoData' option with '16 Clusters'. Once the algorithm has been run, the classification result is saved. The subsequent Post Classification Analysis then requires the analyst to select the classes within the 16 outputs for aggregation as 'ice' and 'non-ice' portions of the image subset. By flickering the classification output relative to the underlying imagery, it is usually quite clear which classes belong in each category. This becomes more difficult if there are clouds or snow in any portion of the area as they tend to classify independently of the actual ice area. For more complex terrain such as Naimona'nyi, multiple subsets are necessary to derive the full ice area estimate. In particular, debris-covered outlet glaciers such as a large north-flowing one at this location cannot be assessed by this technique. For simpler terrain such as Puncak Jaya where all the remaining ice is exposed along a high ridge line, a single image subset is sufficient.

S2.3. Uncertainty Estimate

As summarized by Paul et al. (2015), there is inherent uncertainty within the results of the process outlined above and there are essentially no independent measurements that can be made to fully constrain area estimate uncertainties. Because our goal was to show ice area trends for each location through time, we elected to use a 10% uncertainty for any MSS-based estimate and 5% uncertainty for any TM, Enhanced Thematic Mapper Plus (ETM+), or Operational Land Imager (OLI) based ice area estimate. Although obviously expedient, this conservative area error value, scaling with the resulting ice area estimate, enables consistent comparisons over the full range of Landsat imagery available for each location. For areas with more imagery, the trends are unambiguous but further imagery through time will be required to better constrain the trends for areas with fewer high-quality images available for analysis.

Table S1. Landsat surface area measurements of tropical glaciers

Site	Date	Landsat	Sensor/ Resolution	Path Row	Area Estimate (km^2)	Error Estimate (km^2)
Kibo Crater Kilimanjaro	Aug 17, 1986	5	TM/30	168 062	5.56	0.28
	Aug 21, 2002	7	ETM+/30	168 062	3.09	0.15
	July 15, 2009	5	TM/30	168 062	1.88	0.09
	Sept 7, 2017	8	OLI/30	168 062	1.63	0.08
Naimona'nyi	Dec 6, 1976	2	MSS/60	155 039	87.0[#]	8.70
	Oct 13, 1998	5	TM/30	144 039	82.2	4.11
	Oct 13, 2001	7	ETM+/30	144 039	80.0	4.00
	Sept 9, 2014	8	OLI/30	144 039	79.50	3.98
Quelccaya	Oct 28, 1975	2	MSS 60	003 070	77.25[&]	7.72
	Aug 26, 1985	5	MSS 60	003 070	65.11	6.51
	Aug 2, 1988	5	TM 30	003 070	58.09	2.90
	July 26, 1991	5	TM 30	003 070	57.43	1.15
	Oct 9, 1995	5	TM 30	003 070	55.63	2.78
	Nov 21, 1999	5	TM 30	003 070	51.99	1.04
	Aug 17, 2005	5	TM 30	003 070	47.07	0.94
	Sept 16, 2010	5	TM 30	003 070	44.63	0.89
	Aug 7, 2013	8	OLI 30	003 070	45.80	0.92
	Oct 5, 2017	8	OLI 30	003 070	42.34	0.85
	Oct 11, 2019	8	OLI 30	003 070	41.41	0.83
Glaciers near Puncak Jaya	Aug 8, 1980	4	MSS 60	110 063	6.34	0.63
	Sept 8, 1982	2	MSS 60	103 063	6.07	0.61
	Nov 3, 1988	5	TM 30	103 063	4.67	0.23
	Nov 17, 1993	5	TM 30	103 063	3.36	0.17
	Oct 9, 1999	5	TM 30	103 063	2.74	0.14
	Oct 14, 2004	5	TM 30	103 063	1.88	0.09
	Oct 28, 2009	5	TM 30	103 063	1.29	0.06
	Oct 13, 2015	8	OLI 30	103 063	0.56	0.03
	Mar 11, 2018	8	OLI 30	103 063	0.47	0.02

[#]Area value from Ye et al. (2006), Table 5
[&]Composite image with one from Jul 29, 1975 (002 070)

S3. A local account of a GLOF in 2007 in Phaco, near the Quelccaya ice cap in southern Peru

The following ethnographic vignette introduces briefly how the complexity of the retreat of the Quelccaya ice cap unfolds in everyday life in Phinaya, an Andean village located near it. Figure 7 in the main text shows the locations described in these accounts.

The night the flood happened, almost everyone was out of Phaco, one of the most remote sub-sectors of the Phinaya Andean village, attending a community meeting in central Phinaya. Communal meetings play a key role in the social life in rural Andean communities and, as attendees tend to engage actively in the discussions, they frequently extend until late at night. This was not an exception that day.

Among the few who stayed in Phaco that night was *Luisa*, a neighbor from Phaco, who witnessed that everything started by midnight with an intense sound: *Brrrr, brrrr, brrrr brooooom*, as she later told *Domingo*, one of her neighbors in Phaco. At that point, she could not determine that all that noise was linked to a flood that was about to change her life forever. *How could she know that a landslide was coming to Phaco, anyway? Domingo* continues. *Can you imagine all that noise? Brrr brrrrr brrr, brooooom… and then the water, the mud, and the stones…. Plajjj, plajjj, plajjjj…. What could it be? Where was all that water coming out from? We didn't even know that there was a lake up there!* He confronts us.

As we can learn from *Domingo's* testimony, glacial lakes remain typically unknown for the locals until they flood. When those who spent the night in central Phinaya returned to Phaco early the next morning, they also could not understand what was going on. The landscape they were used to see every day was suddenly almost unrecognizable. *Greywater was coming out from all the streams and canals – that at that point were almost destroyed—, and the whole grasslands were covered with a grey mud that almost looked like lava, Domingo* remembers. Furthermore, their grazing infrastructure, which they had been patiently implementing and expanding during the last decades, was destroyed as the force of the water pulled it out of the ground, broke it in parts, and dragged the pieces very far away into the valley.

Among the most affected by this flood were *Maria*, one of the few who stayed in Phaco that night, and *Luis*, her husband. The flood changed their lives dramatically. It affected their livelihoods, as it destroyed most of the grass in their lands that still, more than ten years after, have not fully recovered. As *Javier*, another local herder from Phaco explained to us in detail:

> *The flood deposited a large amount of grey sand to their land, and a strong rotting smell started coming out of it after a few days but lasted for weeks. This killed the grass that still today has only been able to regrow in specific small patches in their land. You can still see today a big grey colored area in their land, the grey sand that came with the flood and doesn't let the grass grow anymore. A short time after the flood, Luis and his wife just ended selling their cattle; and later, they decided to rent their land and move to Sicuani (a small city located 4 hours away from Phinaya). Since they had moved, they have only come to visit and check their land a very few times."*

Furthermore, as Javier also highlights, the flood also affected *Maria* emotionally: *Maria was always* asustada *[frightened] after [the flood]. What might she had felt? Total fear, right?*

The community president at the time of the flood also provides some insights into this issue. As we were told by him, besides understanding the causes of the flood, one of their biggest concerns after this event was to verify that the community was not in danger of being affected by a larger flood in the following days. For that reason, they sent letters and visited different branches of the National Institute of Civil Defense (INDECI), the official body in charge of the response to disaster events in Peru, requesting that an expert team to evaluate the causes of these events and to investigate if more of these events could not occur in the future. However, they never received a response.

Before the flood, locals in Phaco were not used to visiting the land near the ice cap. It was only after weeks of not receiving a response from INDECI that the community organized an expedition to visit the base of the glacier and document the situation themselves. *Domingo*, who was part of the delegation who visited the lake, explained this in detail: *We are not used getting very close to the ice cap. What for? There is no grass there. Before the flood, we sometimes approached that area only if a llama had escaped, but never that close to the ice cap. That's why none of us knew that there was a lake there until then.* The expedition, however, allowed them to discover that there was a new lake at the foot of the Quelccaya. As *Domingo* remembers, that day they saw pieces of ice floating on the lake, which allowed them to understand that a big piece of ice had fallen into the lake and made it overflow.

Fortunately, there have been no floods in Phaco since that event. However, after the flood, local lakes and glacier retreat, have become a topic of major concern for the locals, and now are frequently raised in the community meeting debates.

References

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