ID 251: Applications of the continuity equation to derive targets for glacier models

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Cryosphere-hydrosphere interactions of the Asian water towers: using remote sensing to drive hyper-resolution ecohydrological modelling

Abstract

In this study, we leverage high-quality digital elevation change and glacier surface velocity datasets along with multi-model ice thickness estimates to isolate the annualized local glacier mass balance (hereafter surface mass balance, SMB) for glaciers. Our implementation of the continuity equation builds on recent advances and is applicable to derive altitudinal or distributed mass balance profiles at local and regional scales. We demonstrate the applicability and utility of this approach for several case studies, yielding understanding for glacier health and vital target datasets for improved glacier model calibration and validation.

Introduction

Recent advances in remote sensing approaches have enable large-scale and glacier-specific assessments of glacier volume changes in response to climatic changes. However, these geodetic-differencing thinning patterns integrate the distinct influences of mass balance processes (ie ablation and accumulation) and ice dynamics (advection and flux divergence), rendering them useful for glacier model calibration or validation only at the glacier or larger scales. Furthermore, direct glaciological measurements are available for only a small subset of size-biased glaciers due to logistical and cost constraints (WGMS, 2021). New datasets are needed to bridge the gap between field and geodetic measurements.

Objective

In this study, we aim to progress the development of the continuity method and demonstrate its application for glaciological problems at multiple scales. We seek to:

1. Determine glacier 'health' at the regional scale leveraging multidecadal RS data
2. Assess 5-year mass-balance gradients from remote sensing datasets
3. Use high-precision stereo photogrammetry to derive 2-year mass balances for comparison to glacier mass balance modelling results.

Methods

The tool we use is the continuity equation, here simplified assuming that changes in firn density are negligible, and that englacial and subglacial mass losses are dominated by changes at the ice surface (Miles et al., 2021).

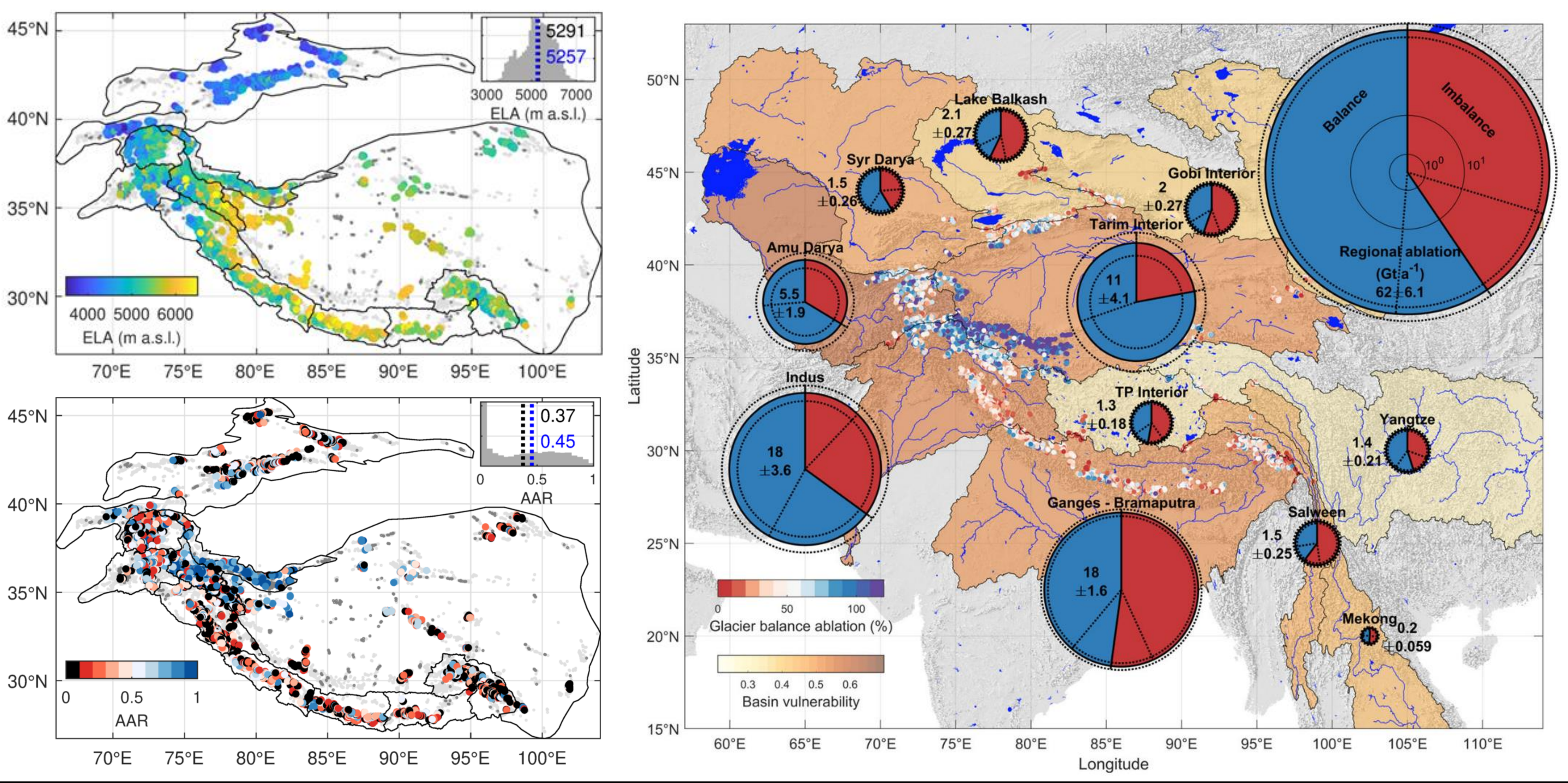
$$\frac{dH}{dt} = SMB - \nabla * \boldsymbol{q}$$

This requires estimation of the flux divergence, which we accomplish by first estimating the column-averaged ice velocity, leveraging remote sensing data products of glacier surface velocity and ice thickness estimates, and determining the local flux divergence based on the pattern over a radius of several ice thicknesses (e.g. Van Tricht et al., 2021) . This is then combined with remotely-sensed products of thinning patterns and a spatially-varying density assumption. We assess different uncertainty sources and the overall uncertainty through a Monte Carlo ensemble.

An advantage of the approach is that it can be used with a variety of standard data products, or with self-generated remote sensing results. Here we demonstrate three use-cases.

Case 1: Regional climatic SMB patterns

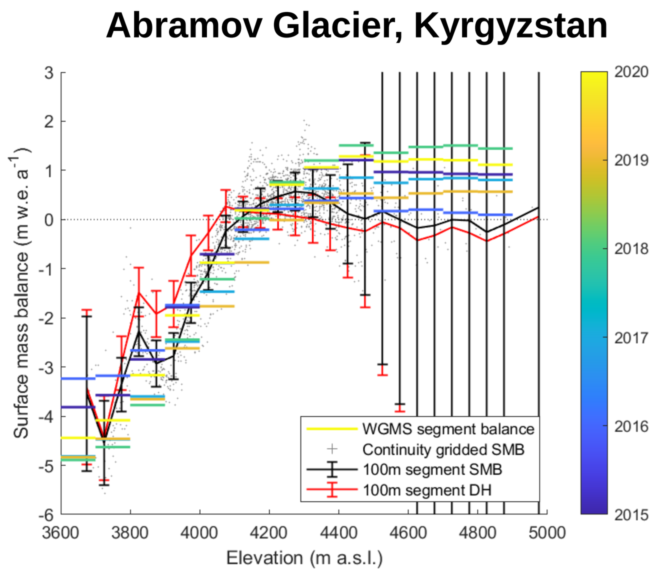
In this case, we simplify the glacier geometry to derive altitudinal mass balances and leverage thinning, velocity, and thickness data products relevant for the 2000-2016 period. This allows us to analyse over 5000 large glaciers across High Mountain Asia and to quantify their 'health' in terms of Equilibrium Line Altitude (ELA), Accumulation Area Ratio (AAR), and Ablation Balance Ratio (ABR). See details in Miles et al., (2021).



Case 2: Five-yearly altitudinal mass balance gradients

Here we apply the continuity equation to derive mass balance gradients, as continuity approaches have shown skill in reproducing this even for problematic data inputs (Pelto et al., 2021). For this, we leverage new higher-quality large-scale glacier change datasets relevant for the recent five-year period (2016-2020). Over this timeline, firn density profiles and mass balance gradients generally remain stable, making these results suitable for large-scale glacier model calibration. We first demonstrate the method's ability to represent ablation gradients at Abramov Glacier, where high-quality monitoring data are available, and then apply the approach across the region.

Abramov Glacier, Kyrgyzstan

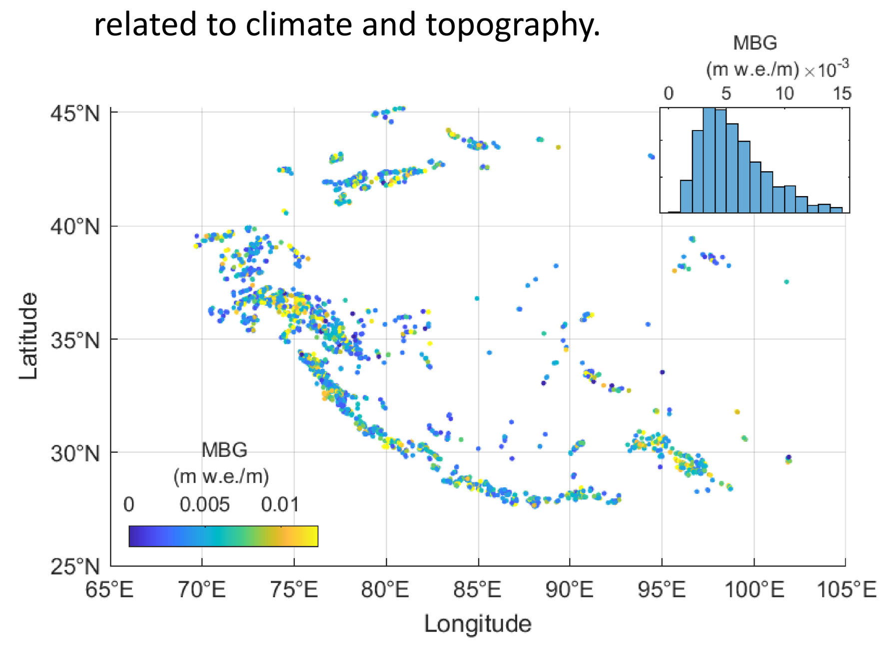


	ELA (m a.s.l.)	MB grad (m w.e./m)
WGMS 2015	4130+/-20	0.008+/-0.001
WGMS 2016	4175+/-20	0.0066+/-0.0007
WGMS 2017	4191+/-20	0.0092+/-0.0006
WGMS 2018	4160+/-20	0.0095+/-0.0012
WGMS 2019	4248+/-20	0.0084+/-0.0003
Avg 2015-2019	4169+/-44	0.0087+/-0.0018
Continuity	4119+/-30	0.01+/-0.0016

Mass balance gradients are variable in space and time. Analyzing WGMS data:

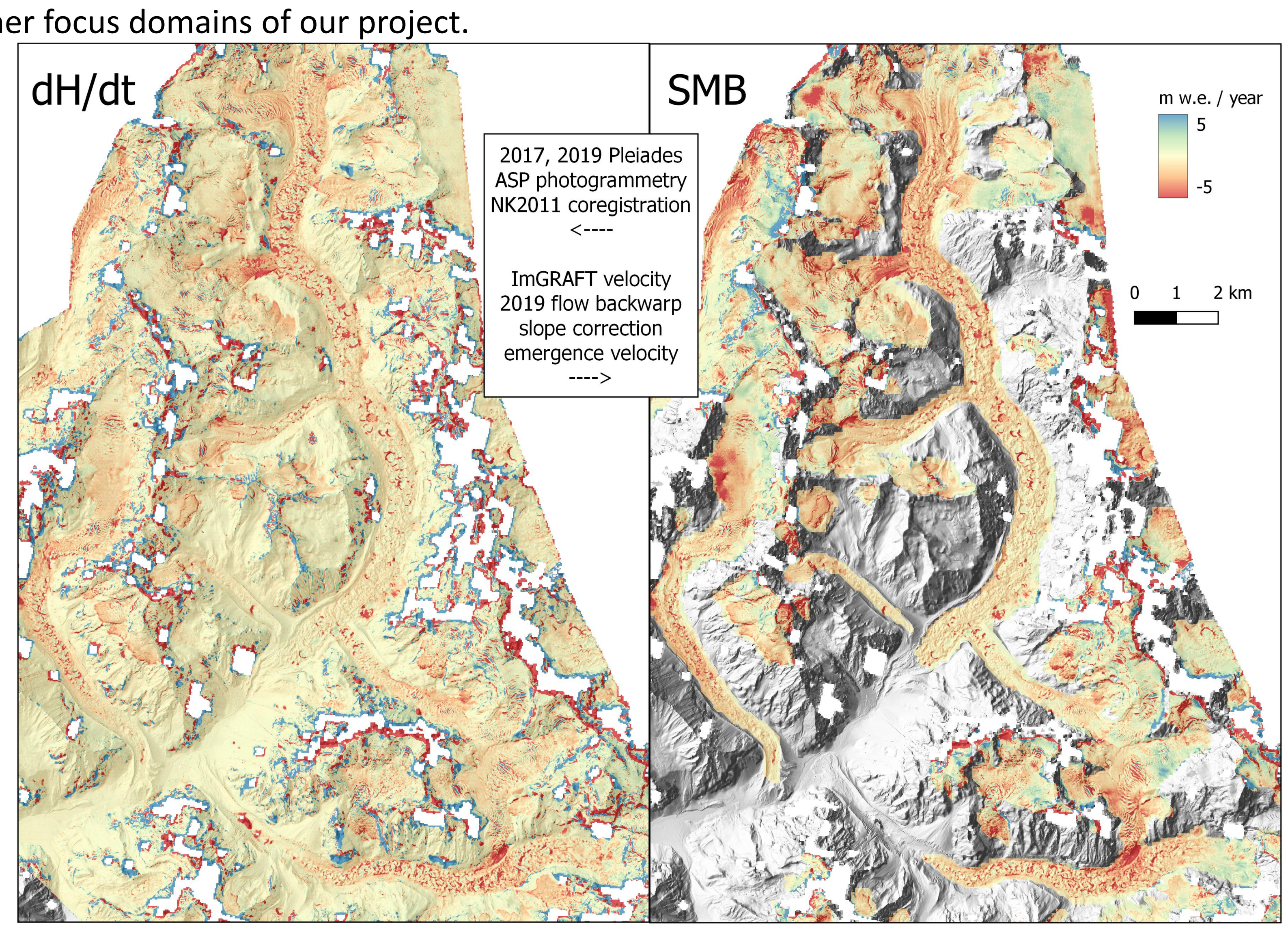
- Median year-to-year variability of 32%
- Median 20% variability for 5-year periods
- 68% of glaciers show average agreement of 5-year and annual gradients within 30%

With this in mind, we present gradients across HMA for glaciers with a clear gradient. This is closely related to climate and topography.

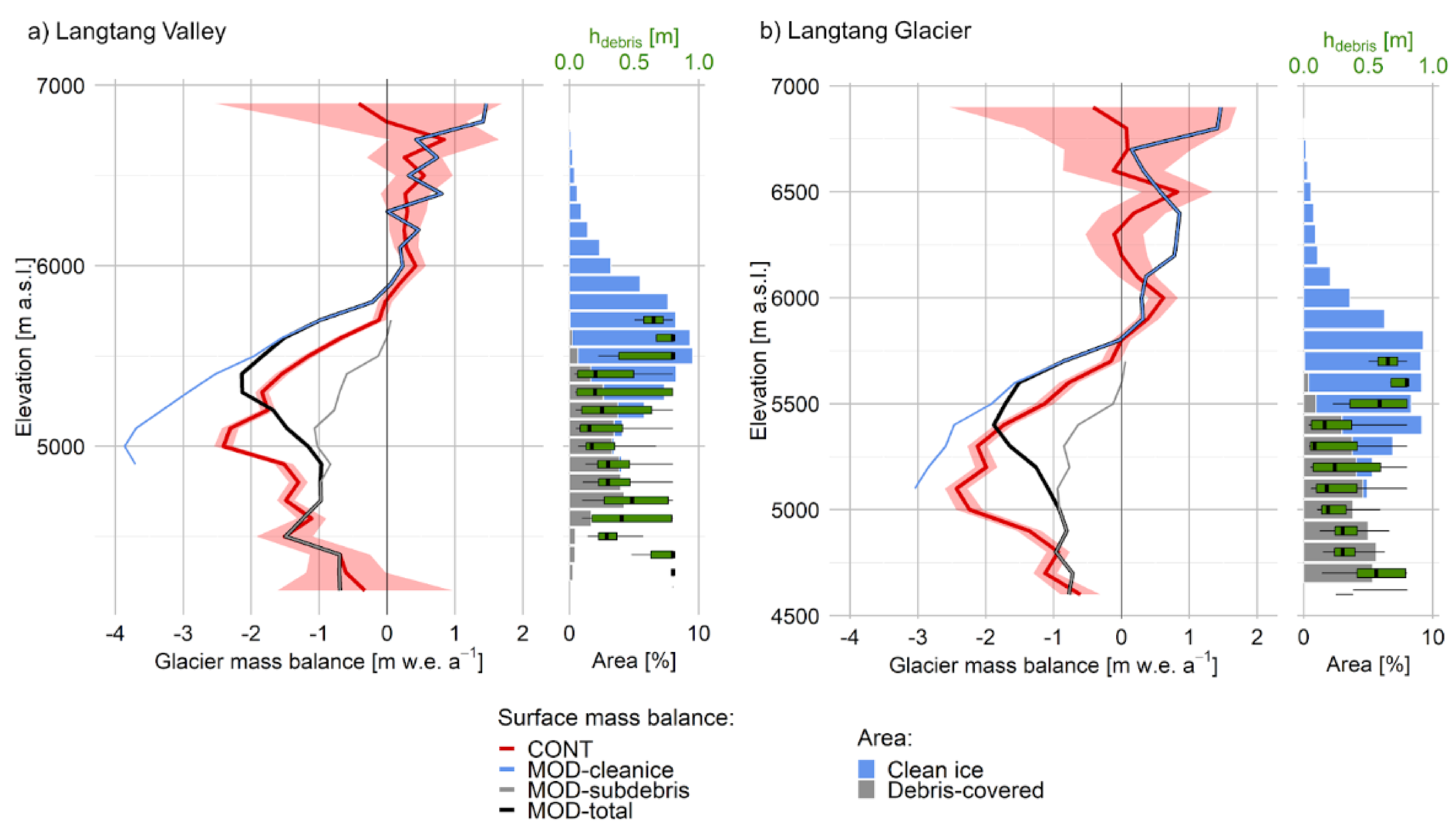


Case 3: Precise SMB for glacier model evaluation

Here, we leverage high-quality Pleiades DEMs to produce high-precision surface mass balance estimates, in this case for 2017-2019 in the Langtang catchment of Nepal. These results are suitable for comparison to independent modelling of glacier mass balance, in this case using the Tethys-Chloris land surface model (Buri et al., in review). See also the poster by P Buri. Comparable datasets have been derived using UAV, Pleiades, SPOT and Deimos datasets for the other focus domains of our project.



Comparison to Buri et al. (in review) model results:



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Conclusions

Taken together these three examples showcase the utility of the continuity equation to complement traditional glaciological measurements and new remote sensing datasets. The approach can estimate fully-distributed net annual mass balance at high spatial resolution and over broad domains, independent of traditional melt and mass balance models. As such, our results provide vital new, extensive calibration targets that reduce equifinality risk posed by models calibrated to geodetic measurements alone. These target datasets (e.g. ELAs, AARs, mass balance gradients, local mass balance) are suited for glacier models of varying complexity and process representation, showing great promise to effectively bridge the observational data gap.