Brief communication: Potential of satellite optical imagery to monitor glacier surface flow velocity variability in the tropical Andes

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Abstract

We present the first analysis of glacier dynamics in the tropical Andes of Peru and Bolivia using satellite data from 2013 to
10 2022. Despite the challenges posed by small-size glacier, low velocities and high cloudiness during the monsoon, we map
annually aggregated surface velocities and quantify the seasonal variability in the fastest parts of the glaciers. Limited trends
are observed on the annual velocities over the last decade, but significant seasonal changes between the wet and the dry seasons
are found, likely controlled by the seasonality in melt water production and the related changes in the hydrological conditions
at the glacier-bedrock interface.

15 ## 1. Introduction

Ice flow velocity is a critical variable characterizing the dynamics of glaciers and ice caps, serving as a valuable indicator of
their response to climate change. Ice flow velocity is also of paramount importance as it enables to: (i) infer various other
physical variables of glaciers such as ice thickness distribution, basal sliding or friction; (ii) quantify mass fluxes and loss
through ice discharge into lakes or into the sea; and (iii) study glacial instability phenomena such as ice avalanches, glacier or
20 ice shelves destabilizations (Gilbert et al., 2018; Millan et al., 2023; Jager et al., 2024). Until now, available observations of
flow velocities for mountain glaciers (excluding ice caps) have been limited to large glaciers, temporally averaged (Millan et
al., 2022), quantified at coarse spatial resolutions of hundreds of metres (GoLIVE, Gardner et al., 2024; ITS_LIVE, Scambos
et al., 2016), or at local scale (Van Wyk de Vries et al., 2022). This directly impacts the study of small glacial features in
regions such as the tropical Andes, which experience some of the highest mass losses (Hugonnet et al., 2023). To date, the
25 spatio-temporal variability of glacier flow in the tropical region has never been explored in details. This leaves a significant
knowledge gap in our understanding of glacier dynamics and their response to climate change under tropical conditions, with

direct consequences on ice flow modeling capacities. However, tropical glaciers pose greater challenges than other mountain regions because glaciers are much smaller (a few hundred metres wide), much slower (flow velocity typically <100 m/yr) and in climate conditions that do not favour continuous optical satellite coverage; *e.g.*, high cloudiness during the monsoon season

30   that typically spans from November-December to March-April in the Andes of Peru and Bolivia where our study is focussed (*e.g.*, Rabatel et al., 2012, 2013; Autin et al., 2022).

Therefore, we propose to reconstruct, for the first time, the evolution of the dynamics of glaciers located in the tropical Andes of Peru and Bolivia from the years 2013 to the present. We explore the spatial and temporal variabilities of glacier flow at both decadal and seasonal scales, thus providing the first observations of glacier dynamics variability in a Tropics.

35   ## 2. Methods

2.1. Ice velocity processing

The overall workflow we have developed to retrieve glacier surface flow velocity from satellite imagery has been fully described and validated in Millan et al. (2019), Mouginot et al. (2023) and Rabatel et al. (2023). Here we only present a short description of the four modules: (1) database creation and image preparation; (2) glacier surface displacement calculation; (3)

40   data calibration; and (4) post-processing with data filtering and averaging to obtain glacier surface velocity maps.

The image preparation module automatically downloads Sentinel-2 and Landsat-8 ortho-rectified images and create pairs of images with repeat cycles ranging from 5 to 400 days, matching acquisitions in the same orbits for each satellite to minimize residual stereoscopic effects. Additionally, we enhance surface features using a Sobel filter on Sentinel-2's band #8 and the panchromatic band of Landsat-8. To derive glacier surface displacement, we calculate the standardized cross-correlation

45   between two images within a pair (details on window size can be found in Millan et al., 2019 and Rabatel et al., 2023). We automatically calibrate glacier surface flow velocity using ice-free areas to mitigate potential biases arising from relative geometric distortions or geolocation errors between image pairs (see Millan et al., 2019). Our region of interest (RoI) is shown in Figure 1 and encompasses several glacierized cordilleras in the Andes of southern Peru and northern Bolivia. The RoI is divided into 159 geo-cubes distributed throughout the study region and with an imprint of 250x250 pixels with a spatial

50   resolution of 50 m. As made for the European Alps in Rabatel et al. (2023), this standardized dataset is stored on a common grid to facilitate the extraction of time series of the surface flow velocity or calculate time-averaged maps.

2.2. Time series extraction

For each geo-cube, a temporal pixel-by-pixel filtering is first performed based on different criteria described in Rabatel et al. (2023). Then, the filtered maps are aggregated into annual mosaics, which are spatially filtered following the procedure

55   described in Rabatel et al. (2023). To aggregate the individual velocity measurements, we used the Ordinary Least Square

(OLS), also called linear regression method (Mouginot et al., 2023). Unreliable pixels are flagged if they present a large variability after filtering, using a coefficient of variation above 75%, or if the standard deviation on the surface flow direction exceeds 2.5°. The trend is considered significant according to a Mann–Kendall test (Rabatel et al., 2023) and a mask is generated on this basis (Fig. 1B, D, F). The hypothesis of the presence of a monotonic trend in the time series is accepted with

60   a p-value of the test is below 0.05. Finally, a spatial filtering on the trend map that uses either a 3×3 Gaussian or a median filter is applied. To extract the seasonal signal from time series data, we use a Locally Weighted Scatter-plot Smoothing (LOWESS) method. The principle is to perform regression on a certain number of points using a linear or quadratic function over a sliding window, the size of which is determined based on the availability of observation data (Derkacheva et al., 2020). This method is used to automatically determine the approximate dates of seasonal peaks from year to year. We only derived

65   the LOWESS fit when we have a sufficient density of observations, more often during dry seasons after 2016 (Fig. 2).

3. Results

3.1. Overall description and decadal trend

Surface flow velocity maps reveal flow patterns on the smallest glacial features (*e.g.*, 1 km^2 on average), where this variable has been measured using medium-resolution satellites (10-15 meters pixel size) with global coverage. Generally, surface

70   velocity rarely exceeds 50 m/yr. However, locally, in the steepest parts of the glacier tongues, velocities can exceed 80 m/yr, such as on Ausangate South Glacier (Cordillera Vilcanota, Peru) with velocities beyond 100 m/yr (Fig. 1A), or the lower part of Ancohuma Glacier (Cordillera Real, Bolivia), the main tongue of Ancohuma West (Fig. 1C), or on the Chaupi Orco North-west Glacier located in the Cordillera Apolobamba at the border between Peru and Bolivia (Fig. 1E). We have evaluated our results by comparing the annually aggregated velocity values with annual *in situ* d-GNSS measurements of ablation stakes

75   displacement located in the lower tongue of the Zongo Glacier in Bolivia where surface flow velocities range between 5 to 25 m/yr (Réveillet et al., 2015). D-GNSS data are within the level of error of the annually aggregated data (between 10-15 m/yr standard deviation). Nonetheless, the same kind of comparison was made in the Alps with a larger dataset of d-GNSS measurements made at locations where velocities reach up to 120 m/yr, and we obtained a very high performance of satellite-derived glacier flow velocity with a root mean squared error of 10.5 m/yr and a coefficient of determination of 0.92 (Rabatel

80   et al., 2023).

In order to characterize decadal velocity trends, we analyze the regression coefficient values pixel by pixel (Fig. 1 B, D, F). We observe very low trends over the period 2013-2022, with values mostly ranging between -2 and +2 m/yr^2. Some exceptions can be highlighted, notably with an increase in velocities exceeding 6 m/yr^2 on the Glacier Chaupi Orco North West (Fig. 1F) located on the Nevado Chaupi. On the detailed time series (Fig. 2, bottom), we shown that this glacier underwent a sudden

85   "surge-type" acceleration in 2020-2021, to reach a maximum velocity on May 2022 at 160 m/yr. During about 18 months, the

velocity on the glacier tongue continuously exceeded 100 m/yr, which is more than twice the average of the period 2013-2020. Glacier surge is a phenomenon quite unusual on tropical glaciers but that has already been mentioned on one of the glaciers on the Antisana Volcano in Ecuador (Basantes-Serrano et al., 2022).
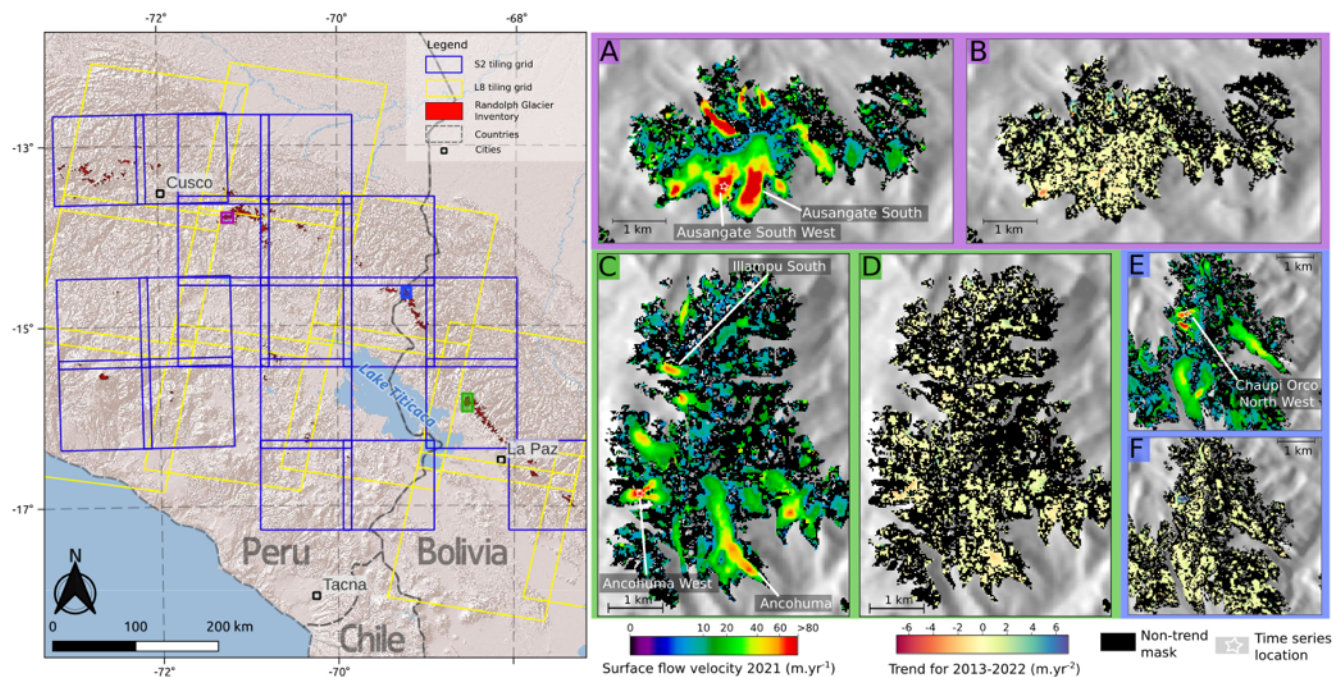
Figure 1: *Sentinel-2 and Landsat-8 tiles covering the glaciers in the tropical Andes considered for glacier surface flow velocity mapping. Inset boxes show the mapped ice flow velocities field for 2021 (left) and velocities trends for the 2013-2022 period (right), for three areas: (A, B) Nevado Ausangate (C, D) Ancohuma region; (E, F) Cordillera Apolobamba region.*

3.2. Seasonal changes in surface flow velocities

For the glaciers presented in Figure 2, we observe a strong seasonality in the surface velocities, particularly between the wet season (from approx. November to March) and the dry season (from approx. April to October). For the Ancohuma West Glacier, the surface flow velocity decreases from 120 m/yr in May to 20 m/yr in September, representing a reduction of over 80%. Similar variations are observed throughout the study area, with, for example, a decrease in surface velocities of 60% for the glaciers located on the southern flank of the Ausangate summit (see Fig. 1). This seasonality repeats year after year and is observed for a large number of other glaciers in the RoI (not shown). However, it is important to note that the glaciers of Ancohuma and Ausangate are among those where it is possible to observe the beginning of the acceleration marking the transition to the wet season in 2021 and 2022, generally occurring in September-October (Fig. 2).
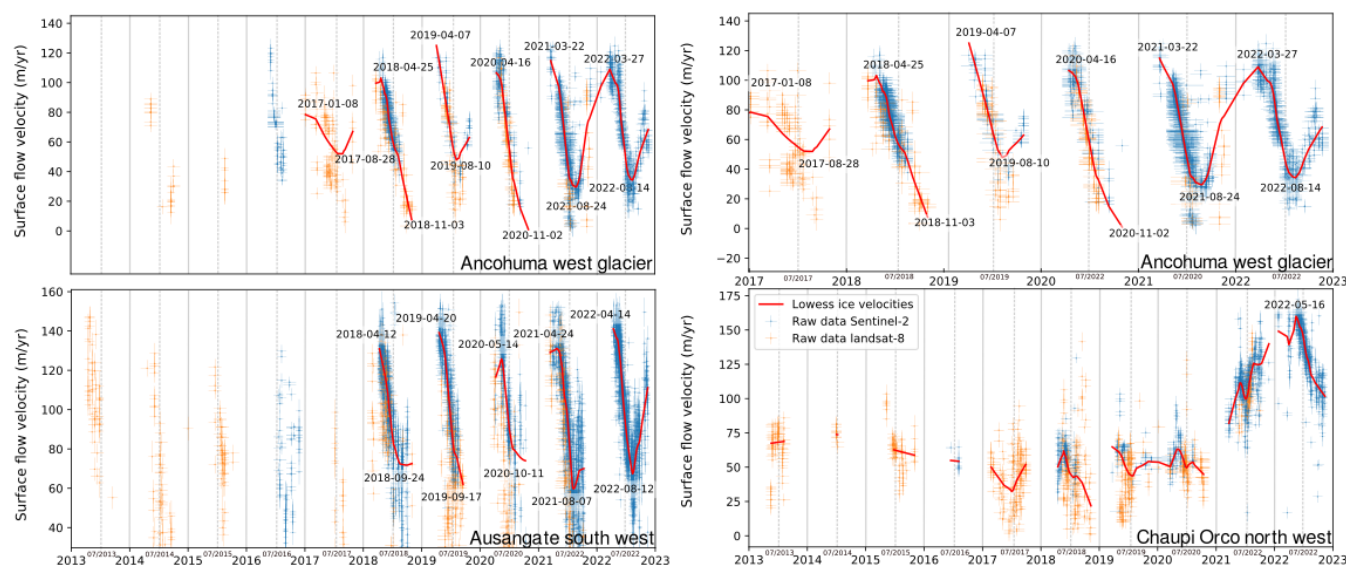
Figure 2: *Time series of glacier surface flow velocities on Ancohuma West between 2013 and 2022 (top left), and zoom into the 2017-2022 period (top right), Ausangate South West (bottom left) and Chaupi Orco North West (bottom right). Location of the plotted time series can be found in Figure 1.*

4. Discussion

For the first time, we highlight the spatio-temporal variability of glacier dynamics in the tropical Andes. In addition to the decadal changes, we also identify the existence of a seasonal cycle in velocities between the wet and dry seasons that has never been observed before (Fig. 2). We measure a unique dynamical behaviour with significant velocity variations over scales ranging from 4 to 5 months, with reductions of up to 80% (Fig. 2). It is worth noting that we only observe the glacier surface flow velocities over the period between March-April to October-November (*i.e.* between the end of the wet season and beginning of the next one). Indeed, the very high cloudiness of the monsoon regime affecting South America during the wet season (*i.e.* between November-December to March-April) strongly limits the use of optical satellite imagery.

Therefore, there are uncertainties concerning the timing and magnitude of maximum velocity peak, which may occur earlier in the wet season. The use of radar interferometry would be required to measure these flow changes more accurately, specifically for small moving regions (*e.g.*, on ice cap) and during the wet season. However, this remains very challenging due to the pronounced topography (shadowing/layover), climatic conditions favouring temporal loss of coherence (high precipitation rates and surface melting). These difficulties in recovering phase coherence are illustrated on interferograms examples provided in Figures S1 and S2.

The strong seasonal cycle observed in the glacier surface velocity data can be explained in the light of the glaciological regime of the tropical glaciers. On the basis of 27 years of continuous monthly measurements of the surface mass balance of Zongo

Glacier (Bolivian Cordillera Real), Autin et al. (2022) have shown that the surface mass balance is strongly negative during the transition period between and dry and the wet seasons, *i.e.* from September to December with the most negative values reached in November. Melting remains high during the wet season counterbalancing in the ablation area of the glacier the

125   intense snowfalls occurring during the monsoon. From April to August, ablation is limited and largely occurs through sublimation thus strongly limiting the water production. Therefore, the progressive increase in melting at the glacier surface from September to November leads to a strong water inflow inside and at the bedrock interface of the glacier when the drainage system is particularly inefficient after the dry season. This leads to increasing water pressure and progressively increasing basal sliding which results in an increase in surface flow velocities as seen in Figure 2 for Ausangate and Ancohuma glaciers,

130   particularly for the last two years of observation. Then, the strong surface melt rates during the wet season maintain high meltwater discharges that promote the development of efficient subglacial drainage networks. At the end of the wet season (*i.e.* in March-April) decreasing melt rates at the glacier surface limit the water discharge thus explaining the large slowdown in glacier flow velocities. Even if the glaciological regime differs in the tropics in comparison to the mid-latitudes, such seasonal pattern is consistent with what has been described by Gilbert et al. (2022) on the Argentière Glacier in the French

135   Alps.

The changes in glacier flow in the Andes are close to the limits of what can be accurately measured using Landsat-8 and Sentinel-2 satellites (Millan et al., 2019). This is due to the very small size of the glaciers, as well as their very slow flow velocities, typically lower than 50 m/yr. High-resolution measurements of glacier flow (*e.g.*, SPOT, Pléiades), as well as continuous field measurements (*e.g.*, d-GNSS) would be useful for strengthening the analysis presented here. However, our

140   study shed light on previously unexplored dynamics processes in tropical glaciers with implications for understanding their response to climate change.

Author contribution

R.M, A.R designed the study. R.M, E.D and J.A developed the code, processed and analyzed the data. E.D prepared the manuscript with contributions from all co-authors.

145   ## Competing interests

The authors declare that they have no conflict of interest.

Acknowledgments

This work was performed at the *Institut des Géosciences de l'Environnement* and at the University of Copenhagen. E.D., R.M. and A.R. acknowledge funding from the OSUG LabEx OSUG@2020 (*Investissement d'Avenir*, ANR-10-LABX-56). J.A. acknowledges funding from the Villum Foundation (Villum Young Investigator grant no. 29456). We acknowledge the *Service National d'Observation* GLACIOCLIM (UGA-OSUG, CNRS-INSU, IRD, INRAE, Météo-France, IPEV) and its counterpart in Bolivia (UMSA-IGEMA, Dr. Alvaro Soruco) for the long-term monitoring of Zongo Glacier. This work is dedicated to Jérémie Mouginot, co-PI of the LabEx project, who passed away in September 2022.

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