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Monitoring surface velocity changes of rock glaciers in the Chilean Andes using DINSAR technique with PAZ imagery.

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Vertical deformation associated with the displacement of rock glaciers in the upper Mapocho river basin, in the central Andes of Chile, was monitored using a series of PAZ radar satellite images and the DInSAR technique. Forty-one PAZ images of ascending and descending orbit were processed with the *Small Baseline Subset* (SBAS) technique. Regarding the obtained results, it was estimated that the vertical displacement velocity of rock glaciers between October 9, 2019 and April 22, 2021 reached up to -22 mm/year and the movement in the W-E direction ranged from -47 to 38 mm/year. This remote sensing technique is a useful tool to measure the surface displacement of rock glaciers, compared to conventional techniques such as GNSS point measurements, especially in the semi-arid Andes, which is one of the most important reservoirs of these geoforms worldwide.

Keywords: PAZ images, SBAS, DInSAR, rock glacier.

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1. Introduction

One of the main applications of remote sensing with synthetic aperture radar (SAR) is the monitoring of areas affected by land surface deformation using the *Differential Interferometric Synthetic Aperture Radar* (DInSAR) technique [1,2,3,4,5,6]. This technique exploits the information contained in the radar phase of at least two complex SAR images obtained at different times, over the same area and forming an interferometric pair [1,7]. The DInSAR technique is used for the generation of interferograms, where the contribution of the topographic phase is eliminated by means of a reference DEM [8] to the interferometric phase component associated with the displacement.

One of the algorithms used for the displacement velocity study is the *Small Baseline Subset* (SBAS) technique [9], which is a DInSAR algorithm used to monitor the time evolution of surface deformations. This technique is based on a suitable combination of differential interferograms elaborated with data pairs characterized by having a small orbital separation (baseline), in order to limit spatial decorrelation phenomena [10]. In addition, the key feature of this algorithm is its ability to reduce phase noise and filter out atmospheric artifacts. The SBAS method is a robust algorithm that provides results for both large-scale deformation phenomena and more localized displacement effects [11], allowing the generation of displacement time series maps from a SAR dataset [3].

On the other hand, rock glaciers are defined as *"the geomorphological expression of the reptation of mountain permafrost with high ice content [12,13,14] and have a tongue or lobe-shaped morphology and a frontal and lateral escarpment as a result of slow downslope or valley displacement, presenting ridges and furrows on their surface"* [15]. According to [16], these active geoforms are used as indicators of Andean permafrost and can be considered fossil groundwater bodies, or non-renewable water resources [15], so their study acquires great importance.

There are several methods to monitor the displacement of rock glaciers; with differential GPS [17,18] and remote sensing techniques with LiDAR [19,20] and radar [21,22,23] sensors. However, recently the DInSAR technique allows monitoring the displacement velocity of these geoforms contributing to the elaboration of rock glacier inventories on a large scale and at low cost, due to the availability of free SAR images such as the S1 images of the Copernicus program.

In this context, the displacement velocity of rock glaciers located in the upper Mapocho river basin in the Andes of Central Chile was monitored between 2019 and 2021 using the DInSAR technique and PAZ radar satellite images.

2. Materials and methods

2.1. Study area

The study area corresponds to a sector of the Metropolitan and Valparaíso regions of Chile, located between 33.032640° and 33.507255° south latitude and 70.475131° and 70.020157° west longitude and has an area of 1,655 km^2 and 1,802 km^2 for the ascending and descending orbit, respectively (Figure 1). It has a Mediterranean climate, with an average rainfall of 341 mm concentrated in winter and a prolonged dry season of 7 to 8 months [24]. The relief of the study area corresponds to a mountainous relief of the metropolitan and Valparaíso regions with altitudes ranging from 1,179 to 6,058 m asl (DEM ALOS PALSAR, 12.5 m resolution) where 44.3% of the surface of the study area is above 3,500 m asl. The 43.7% of the slopes are above 40° and the exposure of the slopes is predominantly SW and W oriented (33% of the surface of the study area).

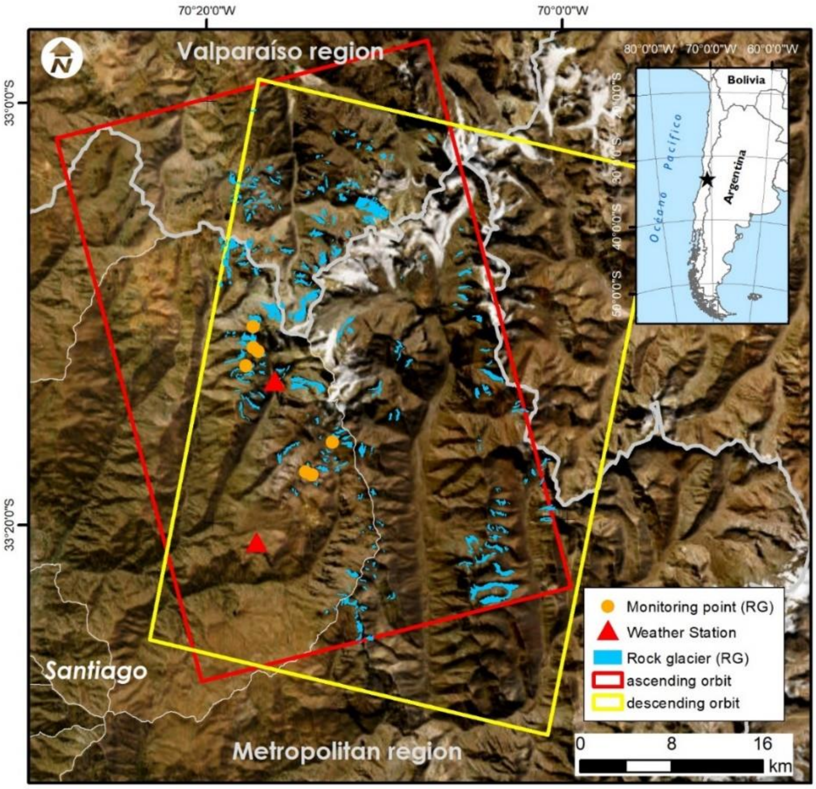

Fig. 1. Study area.

2.2. Data collection

41 PAZ images were used (19 ascending and 22 descending orbit) with VV polarization provided by the National Institute of Aerospace Technology (INTA) of Spain under Announcement of Opportunity AO-001-050. The SAR images of the Spanish PAZ satellite operate in X-band (100/150 MHz) and their acquisition mode is *Stripmap* (SM) and have a *Single Look Slant Range Complex* (SSC) processing level and their coverage is 30 km × 50 km and are obtained with a spatial resolution of 0.90 x 2.04 m (in range and azimuth).

The acquisition date of the ascending orbit PAZ images was between September 17, 2019 and April 24, 2021 and the master image corresponds to November 22, 2019. For the descending orbit, the acquisition of the images was between on September 17, 2019 and June 5, 2021 and the master image corresponds to the image from December 11, 2020.

2.3. SBAS processing

The SBAS algorithm [9] implemented in ENVI SARScape 5.6 software was used to estimate the vertical component, W-E component and velocity of the motion in the study area.

Figure 2(a) and 2(b) shows the connected graph for the ascending and descending orbit images representing the connection between the *master* image (yellow dot) and the rest of the *slaves* images (green dots), where the gray lines show the interferograms that meet the minimum requirements of SBAS processing. The red dot in the connected graph of the descending orbit images represents the image that was not selected to form an interferogram and was therefore left out of the SBAS analysis. The maximum LB_P y for the ascending orbit images was 370.45 meters and 176 days and for the descending orbit was 415.33 meters and 176 days.

The *master* image of the ascending orbit corresponds to that of November 22, 2019 and the connection plot in Figure 2 (a) shows that 77 pairs were analyzed in all combinations. The master image of the descending orbit corresponds to that of December 11, 2020 and 104 pairs were analyzed in all combinations (Figure 2b).

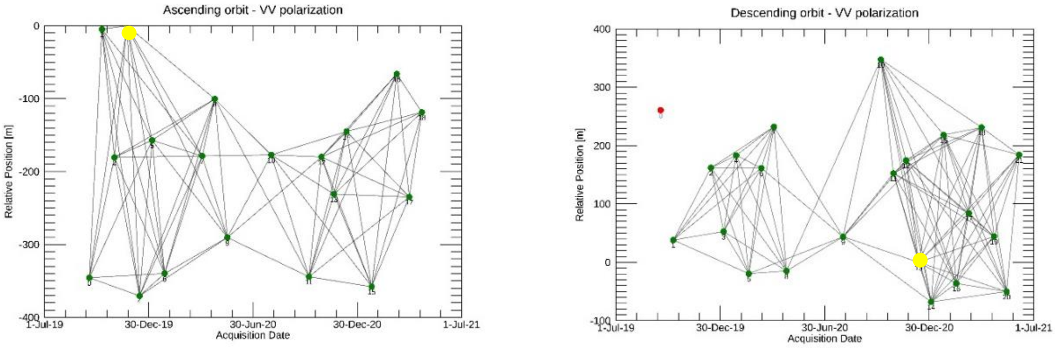

Fig. 2. (a) Connected graph of the PAZ images of ascending orbit; (b) Connected graph of the PAZ images of descending orbit.

3. Results

3.1. Spatial distribution of rock glacier vertical displacement.

As a result of the calculation of the vertical component of the movement using the SBAS technique, Figure 3 shows the vertical displacement velocity between October 9, 2019 and April 22, 2021 in the rock glaciers located in the study area. According to the Glacier Inventory of the General Water Directorate (DGA) updated to the year 2022, 301 rock glaciers are located in the area covered by the PAZ images, however, only 37 recorded displacement velocity information (12.3% of the units). The cumulative vertical displacement values of rock glaciers reach a minimum of -31.6 mm in the study period where positive values show an uplift and negative values show a subsidence of the geoforms surface. The positive values could indicate the uplift of some furrows and lobes of rock glaciers due to the melting of the glacier's subsurface ice [25] as well as snow and detrital accumulation processes, and seasonal saturation of the active layer [26]. Regarding the estimated displacement velocity, it reaches a minimum of -22 mm/year in the study period.

On the other hand, the estimated displacement velocity in the EW direction (Figure 4) ranges between 38 (E) and 47 (W) mm/yr and the accumulated displacement in the same direction varies between a minimum of 62 (E) and a maximum of 65 (W) mm. Positive (+) values indicate movement of the geoforms in the E direction and negative (-) values in the W direction. In general, the vast majority of rock glaciers located on W and E oriented slopes show a displacement in the direction of the slope.

In the sector studied, which corresponds to a complex high mountain topography, 86.8% of the area has no information because the SBAS processing yielded a low coherence (less than 0.2 according to the threshold used in the processing).

Figure 5 (a) shows a photograph of the rock glacier located in the sector of point 1 where the vertical displacement velocity recorded ranges between 0.07 and -22 mm/year in the study period analyzed.

Figure 5 (b) shows a photograph of the rock glacier located in the sector of point 2 and the vertical displacement velocity recorded ranges between 8 and -15 mm/year in the study period analyzed.

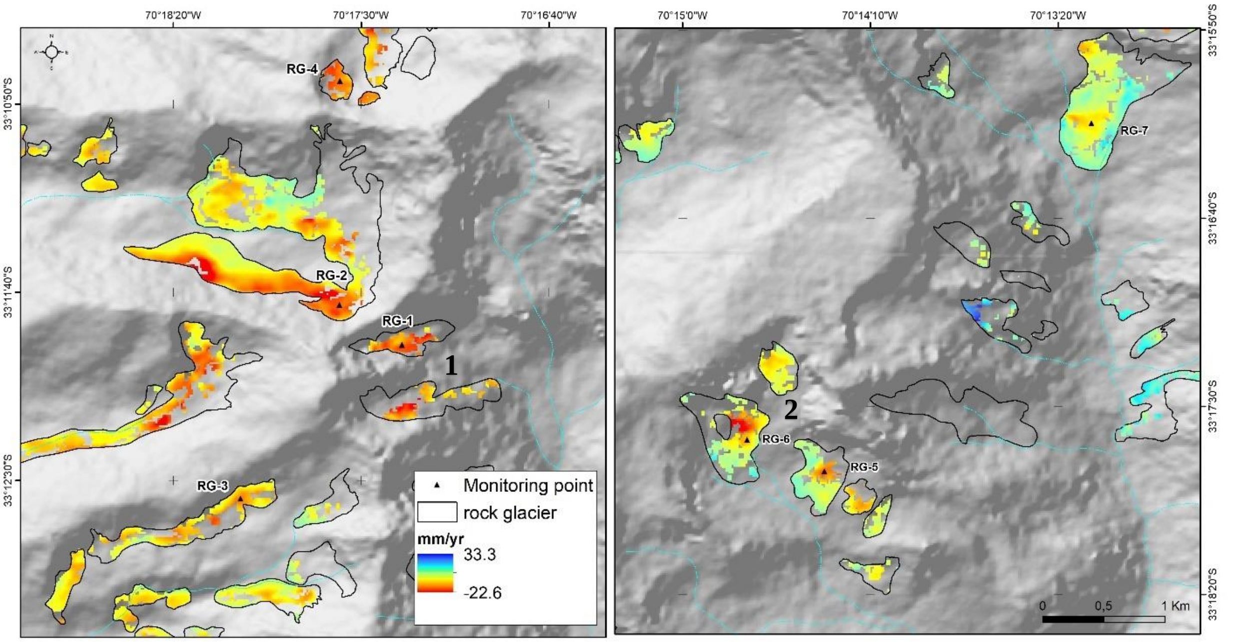

Fig. 3 Vertical displacement velocity of rock glaciers in the study area (mm/year) in the analyzed time period (2019-2021).

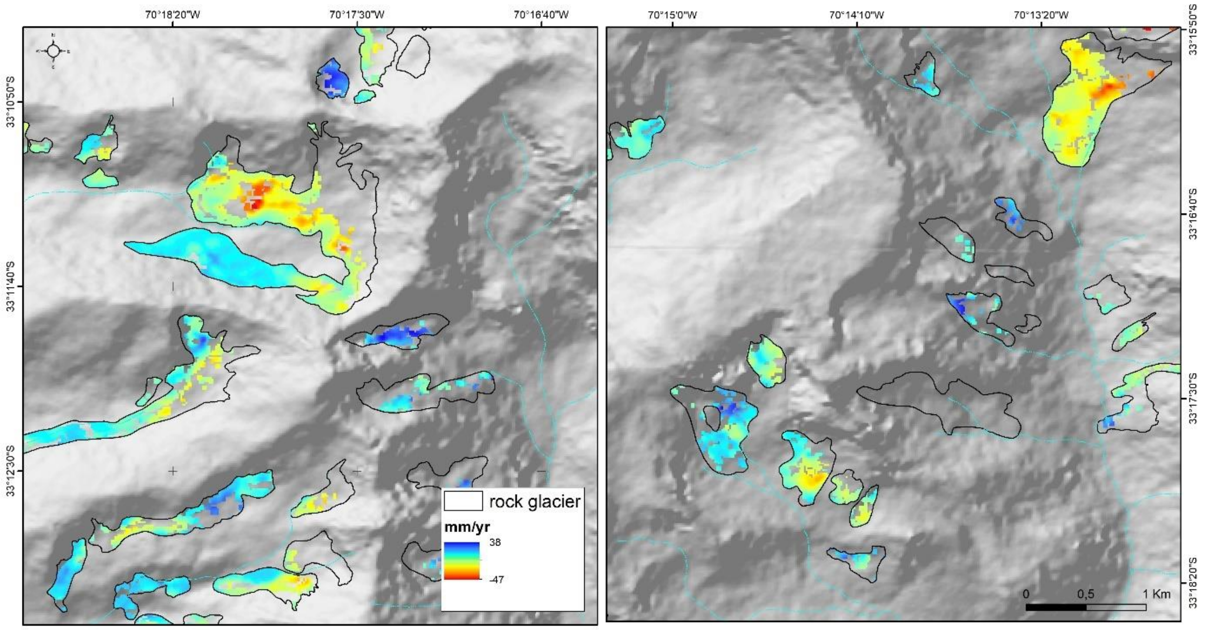

Fig. 4. Displacement velocity in EW direction of rock glaciers in the study area (mm/year) in the analyzed time period (2019-2021).

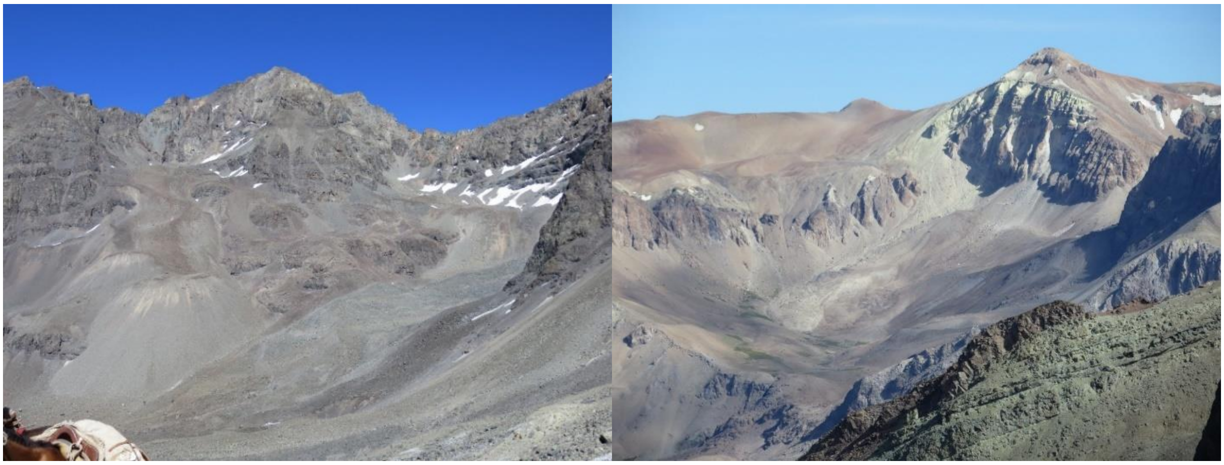

Fig. 5 (a). Rock glacier photography in point 1 sector, captured on January 18, 2016 [27]. Fig. 5 (b) Rock glacier photography in point 2 captured on February 25, 2016 [27].

Figure 6 shows the vertical displacement trend at different points located on the surface of some of the rock glaciers (Figure 3) that present information during the study period.

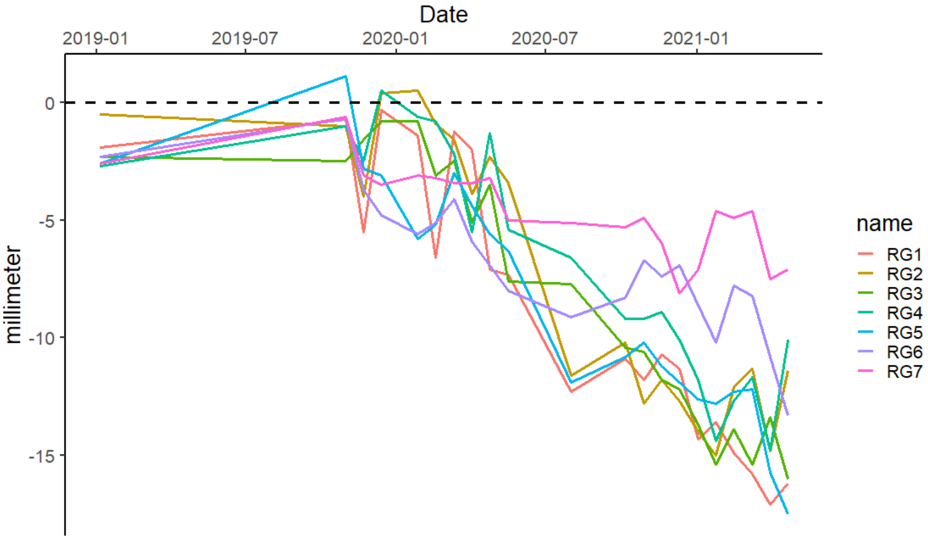

Fig 6. Vertical displacement trend at points where rock glaciers are present.

4. Conclusions and Discussion

As a result of the analysis using the SBAS DInSAR technique with images from the Spanish radar satellite PAZ with VV polarization, an estimation of the vertical component and EW and speed of movement of rock glaciers in the central Andes of Chile was obtained. The results showed a cumulative vertical displacement reaching a minimum of -32 mm between October 9, 2019 and April 22, 2021 and a displacement velocity reaching a minimum of -22 mm/yr in the same study period. Regarding the accumulated displacement in the EW direction varies between 62 mm (E) and -65 mm (W) and the displacement velocity in the same direction ranges between 38 (E) and 47 (W) mm/year in the same study period. [26] points out that the different deformation processes of rock glaciers are influenced by the internal structure and melting of the permafrost and active layer, as well as the underlying bedding and topographic control factors. [12,25,28] indicates that on average it is estimated that a rock glacier can experience a surface velocity variation between 100 and 1,000 mm/year, so the deformation measurements of this work are close to the displacement rates measured in other studies. [25] indicate when rock glaciers are active, these geoforms move downhill. Furthermore, understanding interstitial ice affected by temperature variation would generate grooves, which may explain the negative vertical displacement in this study and the E-W displacement.

[17] determined through differential GPS monitoring (measurements in December 2008, April 2009, January 2010 and April 2010) on the slope of the Punta Negra Bajo rock glacier (33° S) an average vertical displacement of 80 mm/year (SD 30 mm/year). [28] estimated an average rate of displacement in the slope of rock glaciers in the Andes of central Chile of 60-70 mm/year and [23] obtained values of displacement velocity between 22 mm/year to 1700 mm/year in 2,116 inventoried glaciers using S1 radar images. The measurements made by [17,29] correspond to measurements of the glacial slope and are higher than those estimated in this research. However, the measurements recorded in this work are located on the surface of the rock glacier (not on the slope), so the difference in velocities could be due to the fact that, because of the loss of coherence in the study area, the movement of the rock glaciers that show greater displacement was not recorded. However, it is proposed to compare in the future the information provided by the PAZ images with data from the Valle Nevado GNSS seismological station (the only one in the study area coincident with the PAZ images) and to use the multidimensional small baseline subset (MSBAS) technique [30,31,32] which allows projecting the movements along the relief gradient and thus obtaining 3D movement components. In this context, this work focuses on the study of the 7 (figure 6) rock glaciers and it is proposed to extend the study to the rest of the area in the future.

The DInSAR technique is an important tool for monitoring active geodynamic processes in mountainous areas, because it is an efficient, fast and low-cost technique to generate regional-scale inventories in areas of difficult access [23] such as the Andes of Central Chile, however, there are limitations (such as those found in this work) as the loss of coherence (consistency in the phase relationship between the signal of two SAR images) due to spatial decorrelation due to changing atmospheric conditions in mountain environments (the variation of the ionosphere affects the propagation of the radar pulse, generating distortions in the image) and the geometric effects inherent in radar images (layover, shadow, foreshortening).

Finally, in the context of climate change, where precipitation in central Chile is expected to decrease by 5 to 15% by 2030 [33], it is recommended that active rock glaciers be monitored because these geoforms are considered reservoirs of frozen water accumulated during the postglacial period [15], so their monitoring is relevant to study their dynamics and their importance in mountain ecosystems.

Acknowledgements

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