

SATELLITE IMAGES AND GEODETIC MEASUREMENTS APPLIED TO THE MONITORING OF THE HORCONES INFERIOR GLACIER, MENDOZA, ARGENTINA

M. Gabriela Lenzano^{1,2}, Juan Carlos Leiva^{1,3}, Darío Trombotto¹, Luis Lenzano^{1,2}

¹ IANIGLA–Instituto Argentino de Nivología, Glaciología y Ciencias Ambientales. CONICET.

² IDEARN–Instituto de Estudios del Ambiente y Recursos Naturales. UNCuyo.

³ FCA–Facultad de Ciencias Agrarias. UNCuyo.

mlezano@mendoza-conicet.gob.ar

ABSTRACT

This work analyzes the monitoring of the covered and regenerated Horcones Inferior Glacier (HIG) since the implementation of a semi-permanent GNSS station (HISS) on its surface during the summer seasons of 2009 and 2010. The glacier is located at 32° 41's and 69° 57'w, at the foot of the south wall of Mt. Aconcagua, Aconcagua Provincial Park, Mendoza, Argentina. The average velocities obtained from the HISS station were of 1.3 cm/d and 3.5 cm/d during the 2009 and 2010 seasons respectively. The data procured using satellite images during the last surges (1984 and 2003) gave average velocities for the HIG front of 8.7 m/d for the first event and 11.5 m/d for the second one. These results allowed getting accurate and reliable movement tendency at the terminal part of the HIG during the 1984-2010 period.

Keywords: Horcones Inferior Glacier, debris covered glacier, surging glacier, GNSS, Landsat images, Aconcagua.

RESUMEN

El presente trabajo realiza el monitoreo del glaciar Horcones Inferior, cubierto y regenerado a partir de la implementación de una estación GNSS semi-permanente (HISS), instalada sobre su superficie durante las temporadas de verano de 2009 y 2010 respectivamente. El glaciar se encuentra ubicado a los 32° 41's y 69° 57'w, al pie de la pared sur del C° Aconcagua, en el Parque Provincial Aconcagua, Mendoza, Argentina. La estación HISS registró valores de velocidades medias de 1.3 cm/d y 3.5 cm/d durante las temporadas de 2009 y 2010. Se utilizaron imágenes satelitales para el seguimiento del frente del glaciar durante los últimos surges (1984 y 2003), cuyas velocidades medias fueron de 8.7 m/d para el primero y de 11.5 m/d para el segundo evento. Estos resultados permitieron obtener de manera precisa y confiable la tendencia de movimiento de la parte terminal del GHI durante el periodo 1984-2010.

INTRODUCTION

In this work we present some results of the studies carried out at the Horcones Inferior glacier, in the Aconcagua Park, belonging to the Mendoza river basin in the province of Mendoza, Argentina. The Mendoza River is the main water source for agriculture and inhabitants of the province northern oasis and the glaciers contribution is crucial for those years when snow precipitation is scarce or nonexistent.

The Horcones Inferior is a glacier originating at the foot range of the Aconcagua south wall (4300 m a.s.l.) and has experienced surges or extraordinary advances in the past, phenomena that deepens the interest to study and to monitor the glacier. Here we also present results from observing the evolution of one point located nearby the HIG front where a semi-

permanent GNSS station was placed during the ablation seasons of 2008/2009 and 2009/2010 after the last surge experienced by this glacier. Using satellite images both surges were described and the mean ice velocities calculated.

The glaciers of the Central Andes are experiencing a recess process since the beginning of the 20th century, process that has accelerated during the last decades. The degradation of a glacier body is generally associated to climatic changes (Meier and Post, 1969), but in the case of the HIG it is also conditioned by surge events that drastically change the ice morphology and distribution. Surging glaciers are those experiencing sudden advances which are apparently unrelated to climatic changes and/or episodes of exceptionally high flow speed (Meier and Post, 1969; Kamb *et al.*, 1985, 1987; Kotlyakov *et al.*, 2004, 2008). Surging, or surge-type, glaciers are those that undergo periodic phases of rapid flow in between longer intervals of stagnation. A fast flow may last from a few months to a few years, and the inactive phase between 20 and 200 years. Velocities at the ice surface can reach up to more than 50 m day⁻¹ during a surge, and the ice becomes heavily crevassed.

Given the catastrophic characteristic of surges, it is crucial to understand and record the changes produced on the glacier ice, and to observe how the surface is suddenly affected by a surge event, during and after the phenomenon. Kotlyakov (2008) proposed: “a system of regular monitoring of changes to sizes and forms of surging glaciers and of their dynamic behavior through ground, aerial and space observations”. Ground observations include setting up regular photogeodetic measurements of glacier fluctuations, permanent glacial-meteorological stations, and conducting field studies.

Field measurements of the ice velocity were performed by IANIGLA's (Instituto Argentino de Glaciología, Nivología y Ciencias Ambientales) glaciological team during 2003 surge that endangered the Confluencia Camp (Cabrera & Leiva, 2005). The surface of this glacier has been monitored by the authors since 1984 with the help of Landsat images including the 1984 and 2003 surge events (Unger, *et al.*, 2001; Pitte *et al.*, 2009, Lenzano, 2011). The satellite image interpretation of archive images has shown to be a useful way to monitor and analyze glacier evolution during and after surges.

The data from a semi permanent GNSS station named “HISS” (Horcones Inferior Semi-permanent Station) installed on the glacier surface at 3500 m a.s.l. were used for monitoring the HIG terminal part behavior during a stagnant period between surges with a high degree of precision. Similar GNSS measurements techniques have been carried out in previous studies within different regions (Eiken *et al.*, 1997; Tregoning *et al.*, 1999, Lidberg *et al.*, 2006).

STUDY AREA

The Horcones Inferior valley shows several types of ice bodies such as: glaciers, reconstituted glaciers and debris covered glaciers and a periglacial environment represented by numerous rock glaciers and other cryoforms. The HIG is located at 32° 41's and at 69° 57' w (Figure 1) in the Aconcagua Provincial Park, Mendoza, Argentina. The HI glacier flows down, in a sickle-shaped valley, from 4300 m a.s.l. to a height of about 3500 m a.s.l. On March 2006 the HIG occupied entirely the Valley, ending at Quebrada de Los Horcones, 750 m downstream totaling a length of 11.25 km.

The HIG feeds from the ice of hanging glaciers (Superior and Medio Glaciers) of the Aconcagua south wall (Figure 2), through four avalanche channels that carry snow and ice to the head of the HI valley. This part of the HI glacier is the only area without thermokarst and is easily identified in aerial photographs and satellite images. The new ice incorporated to the

reconstituted glacier is quickly covered by cryosediments proceeding from talus and snow avalanche channels. The rest of the glacier, from the 4200 m a.s.l. downwards is an ablation zone with debris covered ice.

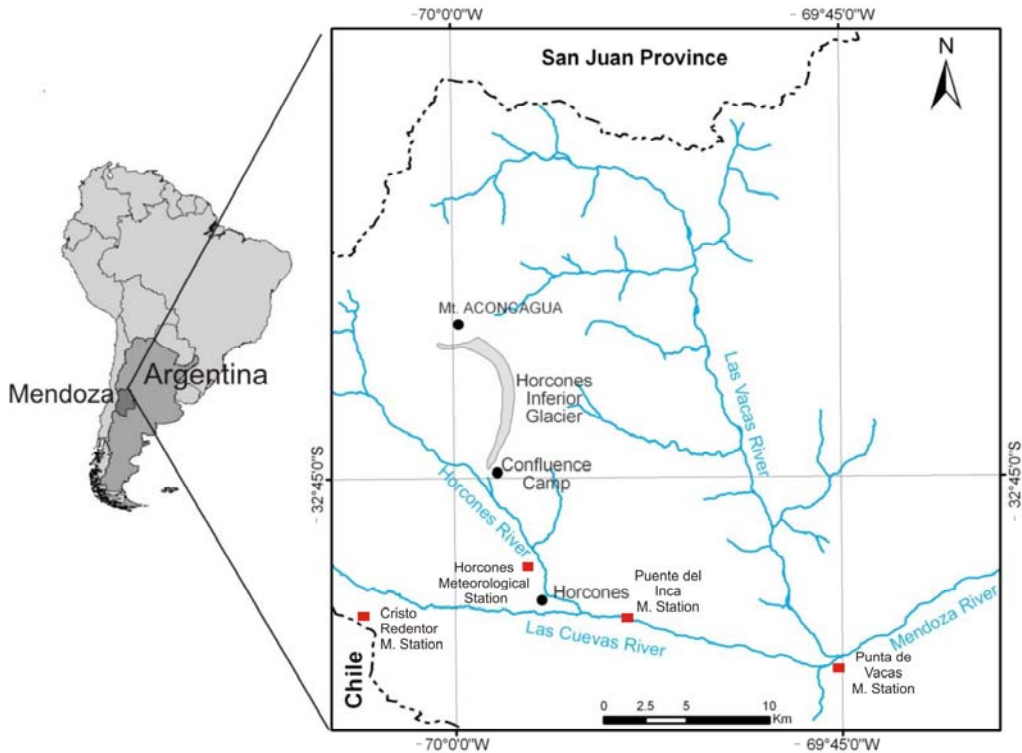


Figure 1. Map of the study area showing the weather stations.

During the surge events the high ice velocity breaks the glacier ice into extremely irregular ice blocks that constitute the whole HIG body. These blocks generally dip more than 50° , according to Milana (2007), and are oriented almost perpendicularly to the glacier flow and are inclined in inverse direction to the flow sense. This characteristic turns the surface structure of the glacier almost chaotic.

Usually when the surge advance ends the ice body begins undergoing a strong ice ablation in an almost stagnant situation. The ablation rate weakens with the increasing thickness of the debris cover toward the front. After this quiescent period, a new surge advance reached the remaining ice of the previous surges and set it in movement also up to the old and static front that sometimes even moves forward downstream.

Table I shows data and a climatic description, obtained from the weather stations of the Argentinean side of the Andes (Cabrera, 2009) in an altitudinal range between 2400 – 3830 m a.s.l. Cristo Redentor (1956 – 1985), Horcones and Puente del Inca (1951 – 1976) stations are within a circle of a radius of less than 15 km from the HIG front. The most frequent precipitation types are sleet, snow and hail. The annual precipitation values for the area (at 4000 m a.s.l. approximately) are above 600 mm (Minetti and Corte, 1984).

Table 1. Climatic data of study area (modified from Cabrera, 2009).

Location Station	Height (m a.s.l.)	Averages Temperatures (°C)				Precipitation (mm/year) ***	Climatic Description
		Máxima (January)	Mínima (July)	Anual	Ampl.		
Punta de Vacas (1998-2007)	2400	24.6 (January)	0.5 (July)	11.5	12.5	47.4	Desert climate, cold winter and mild summers.
Puente del Inca (1951– 1976)	2720	20.3 (January)	-5.2 (July)	7.3	14.2	314.3	Mild, dry and mild summer, cold winter.
Horcones (2000-2007)	3090	14.2 (February)	-1.3 (July)	----	n/d	707.5	Mild, dry and mild summer, cold winter.
Cristo Redentor (1956– 1980)	3830	9.9 (January)	-10.1 (July)	-0.9	11.7	n/d	Polar high mountain climate

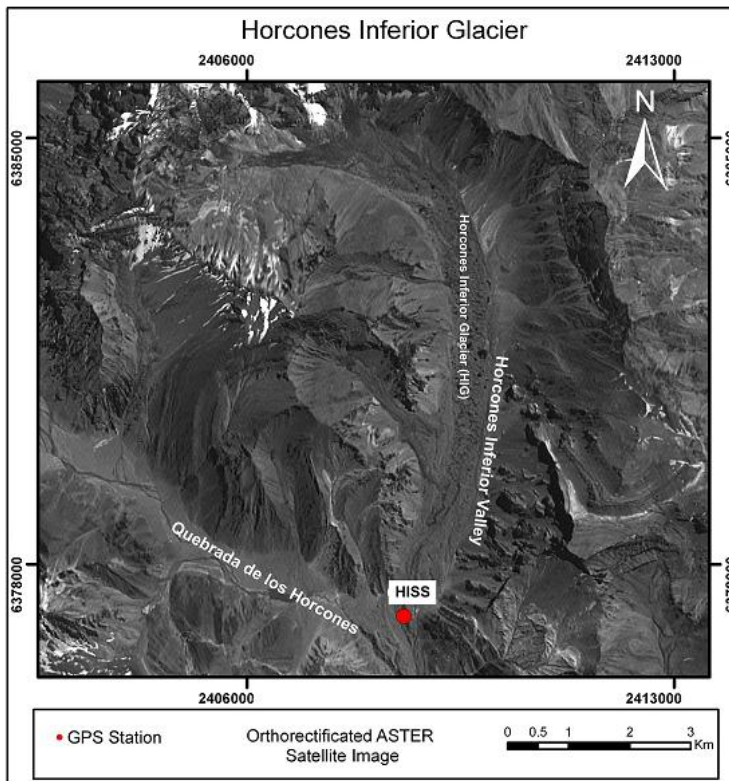


Figure 2. Satellite images showing Horcones Interior glacier and the HISS station.

OBSERVATIONS AND ANALYSIS OF HISTORICAL SURGES

Image treatment

We used Landsat images to obtain information of the GHI evolution during the 1984-2006 period. The images were selected according to their availability in the archive. The dates of scenes taken into account for the analysis of the Landsat sensor are shown in Table 2.

Table 2. List of the LANDSAT scenes used in this work.

Type of sensor	Date
Landsat 7, 4-5 TM, 4-5 MSS. (Path:232, Row: 83)	1984.10.22, 1985.01.25, 1986.02.22, 1987.02.9, 2003.10.19, 2003.11.20, 2004.02.08, 2005.01.25, 2006.02.13.

The Landsat scenes were geometrically treated to eliminate the produced deformations. Thus, the images behave with the properties of a cartographic map. All of the process described below was done using PHOTOMOD 4.4 software (Liba and Jarve, 2009). Georeferencing of each scene was done starting from 13 ground control points (GCP). The planimetric coordinates (X,Y) of these points were obtained from the ASTER 1B scene. The reference frame was that of the POSGAR98 (Posicionamiento Geodésico Argentino) (Moirano, 2000) and the projection system was the official Argentine system, Gauss Krüger, band 2. For the coordinates adjustment we obtained an average RMSE (root mean square error) of 22.4 m (1.4 pixels). Once the previous steps were achieved, we orthorectified the scenes using a digital elevation model (DEM) obtained through digital photogrammetric process with ASTER 1A Level stereo scenes (Hirano *et al.*, 2002).

The HIG front position during the 1984–2006 period was digitalized as per the different glacier stages during the two surge events recorded. We applied the manual digitalization method in each of the selected scenes (Paul, 2000), through photo interpreting of the phenomenon, thus marking the HIG different advances. We calculated the front velocities for both events. The average front velocities were obtained during the two surges from the (X,Y) planar coordinates, Gauss Krüger, band 2, projection system, taking into account years of 365 days.

Analysis of surges

1. Surge 1984 -1987

A surge event was recorded in 1984. The satellite image of October 1984 shows a bulging of the ice surface at the glacier headwaters. The glacier length was of 9.4 km before the surge. This surge traveled 9.8 km downstream in a time interval of approximately three years (1123 days), with 8.7 m/d average speed. The old glacier front was pushed by the surge wave and the new front became stable 350 m downstream.

Once this surge event ended, the glacier reached an almost quiescent state and the ablation process begun until the new surge event started in 2003. During the 1987-2003 period the satellite images shows almost no change in the glacier front position. Milana (2007) described the 1984 surge with a model of extensional deformation as a listric rotational curve thrust.

2. Surge 2003 - 2007

During the 2003 surge, advances at a speed of up to 35 m per day were registered at the glacier front in situ in the summer of 2004-2005 (Leiva *et al.*, 2006). It is interesting to associate this event with the observations made by a park ranger on duty in the Aconcagua Park who speaks of “...*great noise provoked by the downfall of part of the hanging glacier in April of that year...*” (pers. com.). This was identified as the onset of the HIG chaotic movement. Leiva *et al.* (2005) showed a photo with the scar left by the ice mass that fell off from the hanging glacier (Figure 3).



Figure 3. Mt. Aconcagua South Wall with the Superior and Medio Glaciers. The Aconcagua South Wall (3 000 m fall) seen from the left margin of Horcones Inferior glacier. The red arrow points to the origin of the Jan 8th 2004 ice-fall.

The 2003 surge traveled 12.3 km in 1065 days or in almost two years and the new glacier front reached 3400 m a.s.l., with 11.5 m/d average speed. In this environment temperatures are above the 0° C isotherm and therefore the ice melts more quickly; it also absorbs higher temperatures due to the fact that the layers of cryosediments and dark till of the body surface are rather thin (0.5 m). After this new surge ended the ablation process took over again and the satellite images showed an increase in the number and surface of the thermokarst lakes on the HIG glacier (Lenzano, 2011). The figure 4 shows the HIG front positions from 1985 up till the end of the most recent event in 2006.

A SEMI PERMANENT STATION HISS

The Horcones Inferior semi permanent station (HISS) was set near the front glacier to obtain data of its evolution during the glacier quiescent period (Figure 2). The HISS station with an adequate power supply was placed in a point of the central line of glacier flow close to its front. It has a TECH-GEO GPS, with single-frequency, with an adequate power supply to ensure continuous data acquisition during the field seasons. The power supply includes two solar panels of 20 W, two 12 V and 7 A gel batteries a solar charge regulator (Figure 5).

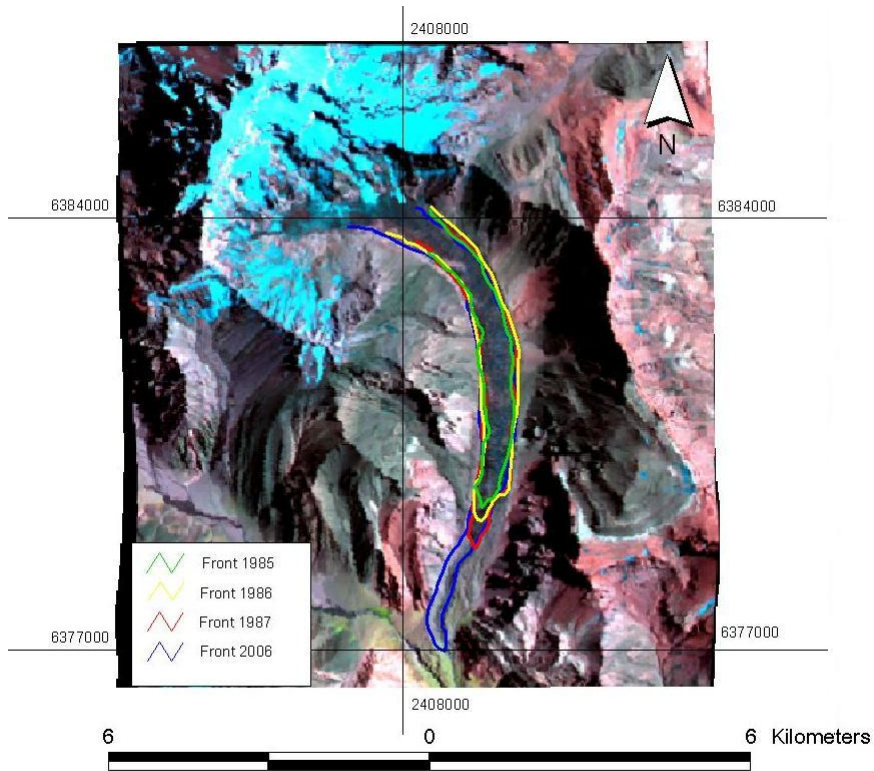


Figure 4. The front evolution of Horcones Inferior glacier during the 1984 and 2003 surges. January 1985 position in orange; February 1986 in yellow, and February 1987 in red. The area marked green shows the glacier front position between the end of the 2003 surge till present.



Figure 5. The HISS station.

The HISS was installed on January 29th, 2009, and was taken from the glacier surface on April 24, 2009. During this time interval acquiring data, called “*the first season*”, the power supply system underwent some problems; hence the receiver recorded data only until March 14. The total recording data comprises 44 days, from January 29th (GPS day 29) until March 14th (GPS day 73). We installed the equipment in the same place on December 7, 2009 (GPS day 341) and took it out on February 23rd, 2010 (GPS day 54). For this “*second season*” of data acquisition the equipment had been improved with new solar panels and a power supply with on and off system (a power system programmed with microcontroller), to optimize the power supply and to ensure data recording. The equipment recorded data 10 hours a day, from 9 am to 7 pm LT.

The HISS station was fixed to the glacier surface, its antenna was 0.32 m over the debris-covered glacier surface so that the verticality errors produced by its displacement were small enough to be disregarded, considering that we used single-frequency GPS equipment. Nevertheless, we visited the station almost weekly restoring its verticality.

We processed the HISS data from the 2009 season in the POSGAR98 reference frame. For this the HISS was linked to two permanent stations Mendoza Centro (MZAC) and Santiago (SANT) and using the DGPS (differential GPS) static positioning method it was possible to give higher accuracy to the final coordinates. These permanent stations (PS), belonging to the SIRGAS (Sistema de Referencia Geocéntrico para América del Sur) net (Drewes, 1998, Fortes *et al.*, 2006), were those closer to the HISS. The MZAC station is placed in the Province of Mendoza and SANT is located in the city of Santiago de Chile, both included in the IGS (International GNSS Service). These public continuous stations with free access are located at a distance no bigger than 75 km from the HISS. The position of the HISS was solved by adjusting closed figures generated by GNSS vectors: SANT-HISS; HISS-MZAC; MZAC-SANT. We worked with fixed solutions at 95% confidence level. The coordinates adjustment was done with the constraints adjustment (Leick, 2004).

The data from the second season (2009-2010) were processed with the data from the Portillo (PORT) PS. The station is about 10 km from the HIG at Libertadores in Chile. We gave the coordinates to the HISS using the PORT as the fiducial one. When working with closer permanent stations, the resolution of the positioning with single-frequency receptors is more accurate. To measure with the carrier frequency L1 and solved ambiguities the maximum distance should be 100 km. The most accurate positioning is obtained when the vectors do not exceed 30 km (Marquez *et al.*, 2009).

Table 3 shows the RMS (root mean square) from the GNSS processing for both seasons. They denote the differences between the resulting precision estimates for bases greater than 50 km and close bases such as PORT.

Table 3. RMS of the HISS data processing.

Season	RMS _{x(m)}	RMS _{y(m)}	RMS _{h(m)}
2009	± 0.026	± 0.031	± 0.039
2010	± 0.002	± 0.003	± 0.007

RESULTS

Data recorded in the HISS station by the direct GNSS method reflect the continuous ice degradation in the terminal part of the HIG during a period of time in the ablation seasons of two years after the 2003 surge ended when the glacier ice had very low or null velocity.

The HISS position data show that during the first season it moved 0.50 m towards southeastward (Figure 6a), while during the second season the HISS displacement was of 0.70 m in the same direction (Figure 6b).

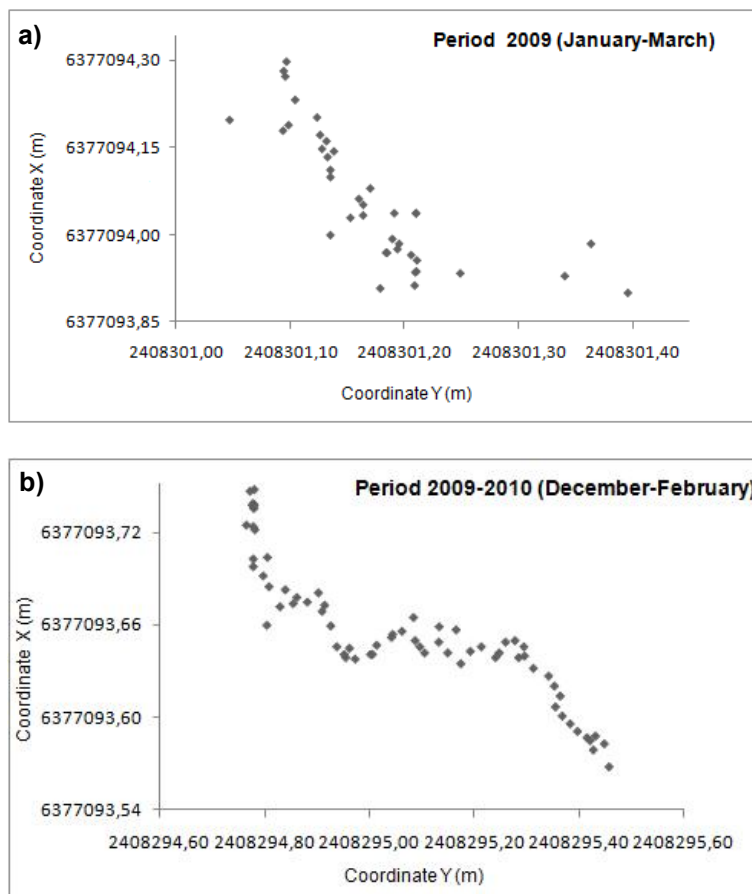


Figure 6. Planimetric evolution of the HISS station. a) Season 2009. b) Season 2010.

The HISS altimetry data showed that the ice surface altitude decreased in the time interval considered (Figure 7a and b). The upper graph shows the evolution of the Z coordinate in the first season and shows the ice thickness decreasing 1.20 m. The smoothed curve shows the effect of data noise by linking to far away PS. The second season, lower graph, shows the station decrease during the 2010 period of 2.10 m. The process of the recorded data during the second season denotes a better definition in the movement trend.

Table 4 shows horizontal and vertical mean velocities obtained from the HISS data for the two seasons. The V_{XY} value is greater in the first season while the V_Z is smaller than the second season one. The V_Z values show that the ablation rate is greater during the first

Table 4. The HISS velocities

Period	Velocity XY	σ_{xy} (m)	Velocity Z	σ_z (m)
2009 (January-March)	1.3 cm/d	± 0.002	1.3 cm/d	± 0.04
2009-2010 (December-February)	0.03 cm/d	± 0.005	3.5 cm/d	± 0.030

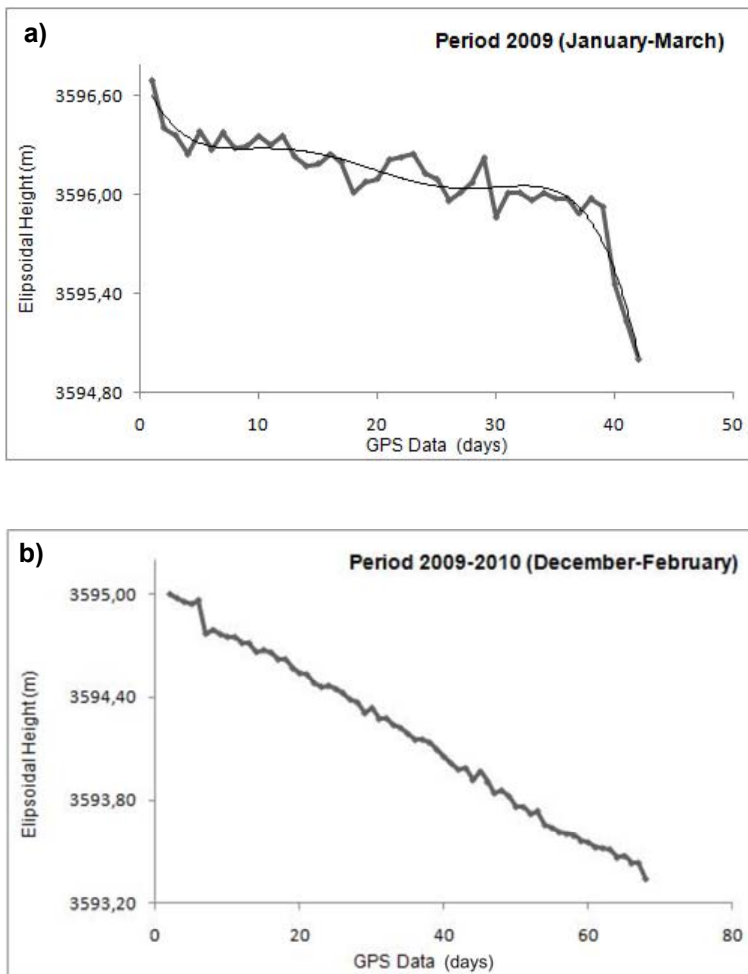


Figure 7. Altimetric evolution of the HISS station. a) Season 2009. b) Season 2010.

season period and so consequently is the thinning of the glacier ice at the site. This could be explained regarding the Horcones weather station mean maximum and minimum temperatures data for both periods (Table 5).

Figure 8 shows the evolution of the HISS Z coordinate and the corresponding daily mean temperature data obtained at the Horcones weather station, located about 410 m below HISS station.

Table 5. Horcones weather station temperature data.

Horcones Station Temperature (°C)	Mean	Maximum	Minimum
First Season	10.9	14.2	6.0
Second Season	11.4	15.4	7.3

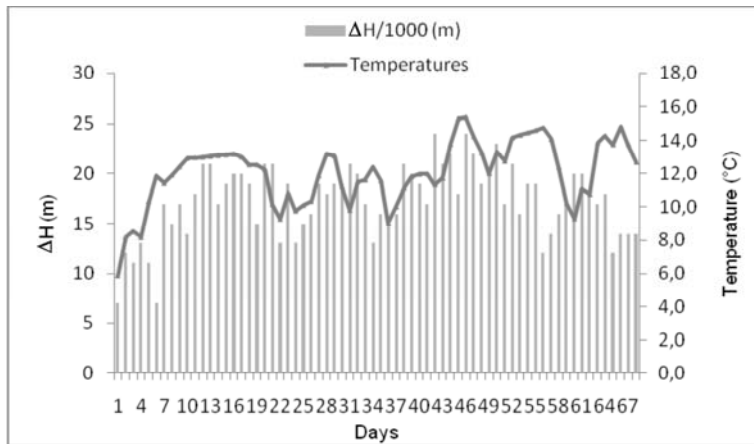


Figure 8. The HISS station altitude evolution and the Horcones Weather station mean daily temperatures. The Horcones station is located at 4 km from the HISS station at an altitude of 410 m below it.

CONCLUSIONS

Satellite images proved to be an appropriated tool to describe surges events and the glacial behavior between them; even if we used images with geometric resolution of 30 m.

The HISS data precision was estimated and analysed (Table 3). From them it may be concluded that glacier evolution could be monitored with single-frequency GPS equipment by linking the observations to nearby or far away GPS Permanent Station. The use of far away GPS PS only gives the point movement tendency for a period of time, while the nearby ones (< 30 m) allow to consider the daily changes of the site. This is a good solution for the study of glacier evolution given that GNSS PS are not always available in high mountain areas close to the study area of concern.

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