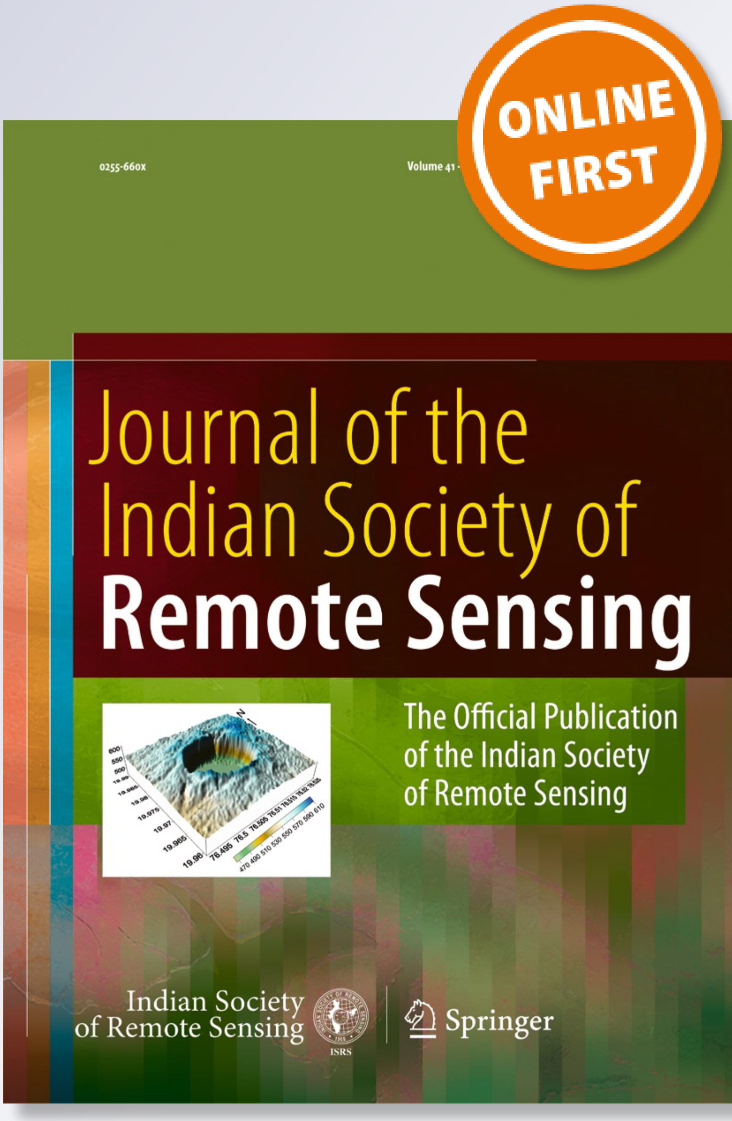
Applying GNSS and DTM Technologies to Monitor the Ice Balance of the Horcones Inferior Glacier, Aconcagua Region, Argentina

M. Gabriela Lenzano, Luis Lenzano, Darío Trombotto Liaudat, Jorge Barón & Esteban Lannutti

Journal of the Indian Society of Remote Sensing

ISSN 0255-660X

J Indian Soc Remote Sens
DOI 10.1007/s12524-013-0294-z



Springer

J Indian Soc Remote Sens
DOI 10.1007/s12524-013-0294-z

RESEARCH ARTICLE

ISRS

Applying GNSS and DTM Technologies to Monitor the Ice Balance of the Horcones Inferior Glacier, Aconcagua Region, Argentina

M. Gabriela Lenzano · Luis Lenzano · Darío Trombotto Liaudat · Jorge Barón · Esteban Lannutti

Received: 29 November 2012 / Accepted: 14 May 2013

Abstract This work provides results and analysis of the behavior in a reconstituted debris covered glacier, Horcones Inferior (HIG). This glacier is located at 32° 41′ S and 69° 57′ W in the Aconcagua region, Mendoza, Argentina. The HIG has experienced surges events in 1984 and 2003. GNSS techniques and Digital Terrain Models (DTMs) derived from ASTER optical imagery, were used to detect movements and altimetric changes of the HIG in the 2001–2012 period. Based on a GNSS semi - continuous station, N and E mean velocities of 0.9 cm/d and 1.1 cm/d and in U direction were 1.1 cm/d and 1.5 cm/d were obtained respectively in 2009–2010 period. Additionally, GNSS profiles showed a velocity range between 0.5 cm/d and 2.8 cm/d. Finally, through a DTM comparison the altimetric change before and after the last surge in 2003 was obtained. The applied techniques allowed accurate and reliable change detection of the HIG.

Keywords GNSS · Digital terrain models · Debris covered glacier · Surging glacier · Aconcagua region

M. G. Lenzano (✉) · L. Lenzano · D. T. Liaudat · E. Lannutti
Instituto Argentino de Nivología, Glaciología y Ciencias Ambientales, (IANIGLA)-CCT, CONICET, 330, PO BOX5500, Mendoza, Argentina
e-mail: mlenzano@mendoza-conicet.gob.ar

L. Lenzano
e-mail: llenzano@mendoza-conicet.gob.ar

D. T. Liaudat
e-mail: dtrombot@mendoza-conicet.gob.ar

E. Lannutti
e-mail: elannutti@mendoza-conicet.gob.ar

M. G. Lenzano · L. Lenzano · J. Barón
Instituto de Estudios del Ambiente y Recursos Naturales (IDEARN), UNCuyo,
Ciudad Universitaria,
Mendoza, Argentina

J. Barón
e-mail: jbaron@uncu.edu.ar

Introduction

Glaciers play a significant role in controlling downstream water supply in arid or semiarid regions, where precipitation is minimal. The Central Andes glaciers are experiencing a recess process since the beginning of the 20th century; a progression that has accelerated during the last decades. This sustained decline of ice covered areas is one of the most reliable indicators of global warming (Haeberli 2005; IPCC 2007). Global warming accelerates the ice melting in Andean covered glaciers (Trombotto and Borzotta 2009) and melting water accumulates in ponds or thermokarst. However, even during this glacier recession period, a few glaciers have experienced front advances, and some of them have shown extraordinary surge episodes.

Surging glaciers are those that are experiencing sudden advances, which are apparently unrelated to climatic changes and/or episodes of exceptionally high flow speed (Meier and Post 1969; Kamb 1985, 1987; Kotlyakov et al. 2004, 2008). Surging, or surge-type, glaciers undergo periodic phases of rapid flow between longer intervals of stagnation. A fast flow may last from a few months to a few years, and then the inactive phase could be 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 in the glacier becomes heavily crevassed.

In this work, results are presented on 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 thus, the glacier's contribution is crucial for this region. A parallel trend is that the demand for fresh water has increased sharply in recent decades, as a result of population growth, and rapidly expanding agricultural and industrial use.

The Horcones Inferior glacier (HIG) originates at the foot range of the Aconcagua south wall (4,300 m a.s.l.) and has experienced surges or extraordinary advances in recently years. During the last two surges experienced by the glacier in 1984 and in 2003, the surface of the GHI has been monitored by satellite images by different authors (Unger et al. 2001; Espizúa at WGMS 2008; Lenzano et al. 2011). The 1984 event was explained by a model of ice extensional deformation and listric faults (Milana 2007) and because of interaction with thermokarst phenomena (Lenzano et al. 2012). During the 2003 surge that endangered the Confluencia Camp (Leiva et al. 2005), field measurements of the ice velocity were performed by IANIGLA's (Instituto Argentino de Glaciología, Nivología y Ciencias Ambientales) glaciological team. This phenomenon is the main motivation to study and monitor the HIG.

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 before and after of this phenomena. Kotlyakov et al. (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 regular photo-geodetic measurements of glacier fluctuations, permanent glacial-meteorological stations, and conducting field studies.

The implementation of the GNSS technology has become an excellent tool to obtain precise information on the time-dependent behavior of glaciers, and, therefore, the deployment of continuous or semi-continuous GNSS stations on the glacier surface provides highly reliable spatial data. The use of GNSS techniques have been reported in previous studies from different regions (Eiken et al. 1997; Tregoning et al. 1999; Lidberg et al. 2006). Remote sensing, in particular, satellite imagery has shown to be a useful tool to monitor and analyze glacier evolution. To monitor glacier altimetric changes, Digital Terrain Models (DTMs) represent the ideal data, as from DTMs, acquired at different epochs, both deformation and movements can be detected, see (Barrand et al. 2009). Obviously, these techniques can be applied on their own or in combination with others, providing a wide range in coverage and accuracy of the extracted geospatial information.

The objective of this study is to investigate the behavior of the HIG surface before and after the 2003 surge in the period 2001–2012 stagnant through a combination of different techniques. The use of satellite image-based digital photogrammetric method represents an efficient technique to estimate the surface before and after the 2003 surge event. ASTER imagery was used to create the DTMs, an inexpensive source of data; though, its use presents a challenge due to its coarse resolution and modest georeferencing accuracy. Stereo ASTER imagery has been frequently used to monitor glaciers since it is available at low cost with worldwide coverage (Etzelmüller and Sulebak 2000; Vignon et al. 2003; Rivera 2004; Miller et al. 2009; Bolch et al. 2011). Additional data of the evolution was recorded by a station located in the ablation zone, where a semi-continuous GNSS station was placed during the ablation seasons of 2009 and 2010. The HISS (Horcones Inferior Semi-continuous Station) was installed on the glacier surface at 3,500 m a.s.l. Finally, to get more complete data in the ablation area, kinematics GNSS profiles were acquired for ablation season during the period 2011–2012.

Study Area

The Horcones Inferior valley shows several types of ice bodies, such as glaciers, reconstituted glaciers, debris covered glaciers, and a periglacial environment represented by numerous rock glaciers and other cryoforms.

The HIG, located at 32° 41′ S and at 69° 57′ W in the Aconcagua Provincial Park, Mendoza, Argentina, see Fig. 1, flows down in a sickle-shaped valley from 4,300 m a.s.l. to a height of about 3,500 m a.s.l. On March 2006, the HIG entirely occupied the Valley, ending at Quebrada de Los Horcones, totaling a length of 11.5 km. In that region, the most frequent precipitation types are sleet, snow and hail. The annual average precipitation for the area, at 4,000 m a.s.l., is above 600 mm (Minetti and Corte 1984). The mean annual air temperature in Cristo Redentor (32° 50′ S, 70° 05′ W) at 3,832 m a.s.l. during the period of 1961–1980 was −1.6 ° C (Servicio Meteorológico Nacional 1986; Trombotto 1991).

The HIG feeds from the ice of hanging glaciers (Superior and Medio Glaciers) of the Aconcagua south wall, and through four avalanche channels that carry snow and ice to the head of the HI valley. This part is the only area without thermokarst, and 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 4,200 m a.s.l. downwards is an ablation zone with debris covered ice (see Fig. 2).

During surge events, the high ice velocity breaks the glacier ice into extremely irregular ice blocks that constitute the HIG body. These blocks generally dip more than 60°, according to Milana (2007), and are oriented almost perpendicularly to the glacier flow and are inclined in opposite direction to the flow. 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, when a new surge advance reached the ice remaining overlapping whole the glacier and sometimes their movement together forward downstream.

Data Sources

Images: To support this study, two Terra Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) scenes were selected; both images were acquired during mid-summer (January 1, 2001, and January 13, 2008). The selection of images was made according to the availability of the closest imagery before and after surge. The images were used to create DTMs to obtain the altimetric differences on the

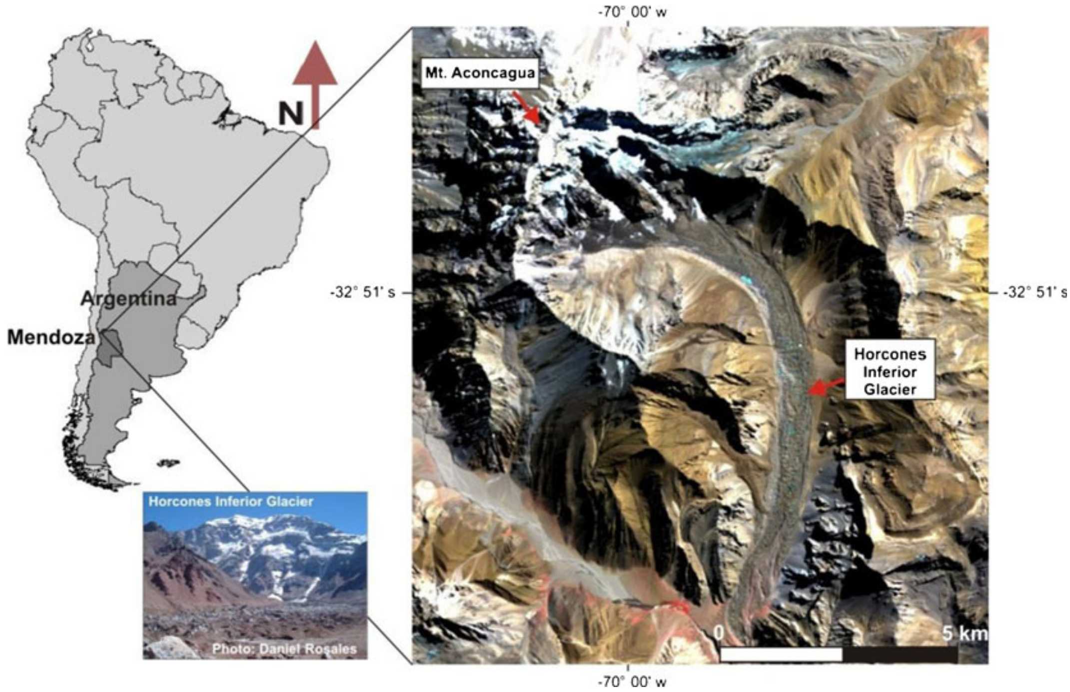


Fig. 1 Map of the study area: *upper left* shows the location in Argentina, *right image* depicts the studied terrain, and *lower left image* provides an impression of the Horcones Inferior Glacier and the south wall of the Aconcagua

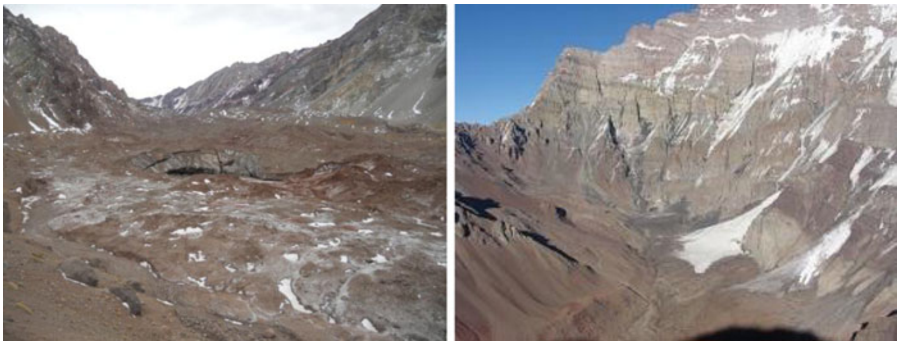


Fig. 2 The pictures, acquired from a helicopter on December, 2011, show the Horcones Inferior glacier; in the left, the glacier surface with thermokarst, and on the right the headwaters with the south wall of Mt. Aconcagua

glacier surface before and after surge event occurred in 2003. The images from the ASTER sensor have a geometric resolution ranging from 15 to 90 m depending on the bands with an area coverage of 60×60 km. The three ASTER telescopes, including the VNIR (visible and near-infrared), SWIR (short wavelength infrared), and TIR (thermal infrared region) sensors, can be oriented in the cross track direction, rotating the camera in the ±24° range. The product level 1A has the stereo pairs 3N and 3B that permit the generation of topographic mapping products, such as DTMs and orthophotos (Iwasaki and Fujisada 2005). The images used in this study show scarce snow cover and the maximum cloud percentage of 20 % has limited or no affect over the glacier areas.

Continuous GNSS data: The Horcones Inferior semi-continuos station (HISS) was installed in the ablation area in the central line of glacier flow to collect data during 2009–2010 period. The main objective of this measurement was to obtain continuous evolution data during ablation seasons. Geo-Tech L1 single-frequency GPS receiver was equipped with an adequate power supply, including two solar panels (20 W, 12 V), and gel batteries. The GPS data acquisition rate was 30″. Vertical errors, produced by displacement and attitude changes of the moving ice, were small enough to be disregarded; in particular, considering that single-frequency GPS equipment was used. Note to restore the vertical orientation, the station was visited almost weekly.

The HISS was used in two seasons. During the first season, it was installed on January 29th, 2009, and was removed from the glacier surface on April 24, 2009. During this time, the system experienced some problems, and hence the receiver recorded data only until March 15. The total recording time was 45 days. In the second season, the equipment was installed at the same location on December 7, 2009 and removed on February 23, 2010. The total recording time was 68 days. The system, improved with new solar panels and a power system programmed with a microcontroller to optimize and ensure data recording, acquired data10 h a day, from 9 am to 7 pm local time.

GNSS Profiles: One transect and three cross-profiles around HISS station were acquired to obtain the altitude change at the ablation zone of the glacier during the seasons 2011–2012 (Fig. 3). One of the cross-profiles (CP3) contains the HISS station. The data acquisitions were made at the beginning and end of both summer seasons. The profiles were surveyed first on May 21, 2011, and then on January 4, 2012 and finally May 9, 2012. The time period between the surveys was 228 and 127 days, respectively. A dual-frequency Trimble 5700 with a data acquisition rate of 5″ was used to acquire the profiles. The antenna height was 2 m above the ground, and the survey area covered the last 1.5 km of the glacier. The transects were repeated at the same locations in both seasons with the exception of those spots where the glacier surface was so rugged that it was impossible to obtain the same profile.

Methods

Digital Terrain Model (DTM) Extraction

As the georeferencing of the ASTER imagery is rather coarse, the image orientation was refined by using GCPs (Etzelmüller and Sulebak 2000). The use of GCPs is important to obtain precise georeferencing

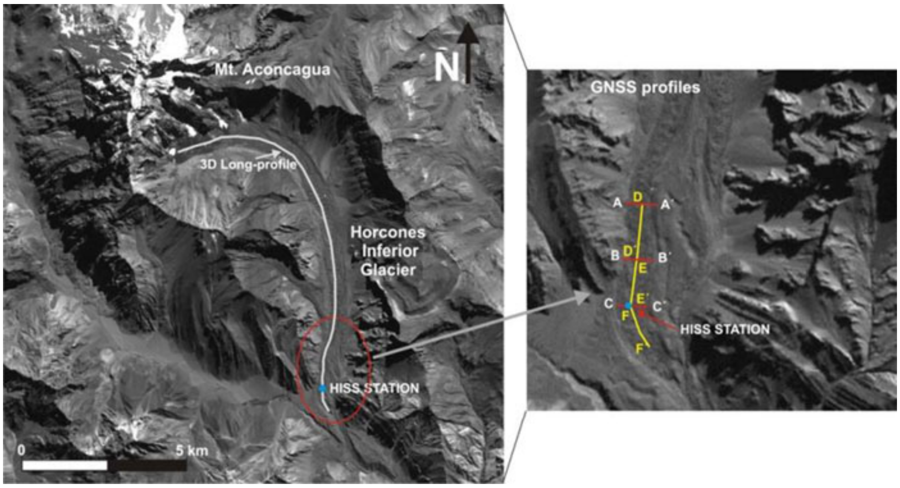


Fig. 3 The map shows the location of HISS Station, and the profiles taken for the altimetric change before and after 2003 surge (*grey color*); the right image shows the position of the GNSS profiles in the ablation area

for the stereo models, as they assure accurate elevation as well as planimetry in the reference frame (Wolf and DeWitt 2000). In this study, 11 GCPs were surveyed and referenced in WGS84, and then projected into the Argentine GK2 local mapping frame. To improve the image georeferencing, and, subsequently, increase the reliability of the DTMs, an additional 25 secondary GCPs, derived from the cartographic database of IGN (Argentinean National Geographic Institute), at 1:50,000 scale, were used. Finally, approximately 100 tie points per scene were used to form strong stereo models. The DTMs with a grid size of 45 m were extracted by the digital photogrammetric software Photomod 4.4 (Rozycki and Wolniewicz 2007; Liba and Jarve 2009).

During the relative orientation, the y-parallax value for the 2001 and 2008 stereo models was 1.1 and 1.2 pixels RMS, respectively. After performing the absolute orientation, the residuals at GCPs for both models are shown in Table 1. According to Toutin (2008), these results range between the acceptable limits of accuracy, given the geometric resolution of the ASTER imagery.

From the two data sets, acquired in 2001 and 2008, the first one, DTM_{01}, was considered as the base or reference in the subsequent analysis; i.e., the DTM_{08} was compared to DTM_{01} with the objective to minimize the residual errors produced by the photogrammetric transformation (Vignon et al. 2003).

The surface of the glaciers, extracted from ASTER stereo imagery, was represented by TIN structures (Triangular Irregular Network). In addition to automatically created surface points, topographic discontinuities, through manually measured breaklines and points, were modeled, further improving the relief forms in areas with complex landscape (Marzolff and Poesen 2009).

DTM Differencing

The difference between DTMs was assessed based on using a variety of topographic features, such as rocky outcrops that are assumed to be static in the proximity of the glaciers under study. Based on comparing 100 points were not in the same altimetric range, the RMSEz for $\Delta H_{01\text{-}08}$ was 26 m. Results may indicate that the mathematical model needed the approach based on minimizing the differences between the two

Table 1 Residuals of GCPs (36 points) in the 2001 and 2008 stereo pairs, respectively

		Res X (m)	Res Y (m)	Res Z (m)
2001	RMS	19.0	20.1	21.8
	Mean	15.3	14.8	18.6
	STD	11.3	13.6	11.4
	Max	39.7	46.8	40.6
2008	RMS	13.1	12.6	23.8
	Mean	10.5	9.6	20.7
	STD	7.3	8.2	11.7
	Max	34.6	29.1	37.8

surfaces in a least squares sense. The significance of those parameters is improve the results of the differences on DTMs considering a physical deformation instead a measurement errors (noise). To approximate both surfaces a three parameters transformation (Xc, Yc, Zc) was done, then they were applied to approximate DTM_{08} to DTM_{01}. The found values are: Xc=0 m, Yc=−18.5 m, Zc=13.2 m, σ=0.35 m.

Profiles on the glacier were generated by manual delineation following the line of the ice central flow on 3D surfaces. Figure 3 shows the location of the flow profile over the glacier. The elevation differences were taken as normal differences between both surfaces. By comparing DTM_{01} and DTM_{08}, the altimetric change ($\Delta H_{01\text{-}08}$) of the glacier was determined.

GNSS Data Processing

HISS data was processed with Bernese software version 5.0. All the data was referenced in the POSGAR98 (Posicionamiento Geodésico Argentino) frame. The HISS was linked to Portillo (PORT) Continuous Station, located in Libertadores, Chile, about 10 km from the HIG. Orbits and orientation parameters preparations were done by POLUPD, PRETAB and ORBGEN routines. Observables processing and control were solved through CODSPP, SNGDIF and MAUPRP routines. Finally, the processing and parameters estimation were done by GPSEST, to estimate all parameters necessary for the processing. As L1 frequency was used and the baseline was shorter than 20 km, the SIGMA algorithm was used to solve ambiguities (see Bernese User Manual 2007). In all the cases, fixed solutions at 95 % confidence level were accepted. Table 2 shows the RMS (root mean square) from the GNSS processing for both seasons.

The processing of kinematics profiles was done with the rtklib software (free source). The data was linked to INCA Continuous Station. Precise ephemerides were used to get more accurate data, ambiguities were fixed in all the profiles at 95 % level of confidence. The accuracy for each profile is shown in Table 4.

Table 2 Accuracy of data processing

Season	RMS_N (m)	RMS_E (m)	RMS_u (m)
2009	±0.004	±0.003	±0.009
2010	±0.002	±0.003	±0.007

Results

Geodetic Ice Balance of the 2001–2008 Period

The Horcones Inferior Glacier has suffered changes in each one of the surges it has experienced in 2001–2008 period. During the last event (2003), the surge traveled 12.3 km in 1,065 days, and the new glacier front reached 3,400 m a.s.l. with 11.5 m/d average speed (Lenzano et al. 2011). The long profile was created using digital terrain models (DTM_{01} and DTM_{08}), and from them the altimetric variation of the ice before and after the surge was obtained. The profile has a length of 11.5 km, and was acquired after the 2003 surge in 2006. Figure 4 shows the glacier topography changes, caused by this sudden event along the valley-long profile. The black line indicates the modeled surface in 2001 and the grey line that of 2008. The mean altimetric difference $\Delta H_{(01-08)}$ was 23 m ±10 m. From the beginning, close to the origin of the Horcones Inferior Glacier, the 2001 surface is kept above the 2008 level until the position where the old front remained after the 1984 surge; approximately (8.5 km from the origin). From there on, the glacier occupied the valley, which was free of ice until then, and the glacier came out of the valley with its front standing close to the Confluencia camp site. The maximum ice altitude in this area from bedrock is approximately 20 m for the year 2008.

HISS Continuous Monitoring

After 3 years of 2003 surge ended when the glacier had very low velocity, the data recorded by the HISS GNSS station during two periods reflect continuous ice degradation during ablation seasons. The topographic relief in this area changes every year as a consequence of this continuous process. This situation is illustrated in the Fig. 5, where the images were taken from the HISS towards the origin of the glacier in February 2009 and in, February 2010, respectively. When comparing both photographs, the surface degradation as a thermokarst without water is evident; the red color circles indicate the identical sites.

The HISS station provided data for two discontinuous seasons. During the first season, HISS moved 0.46 m in planimetry southeastward, see Fig. 6a; this movement is logical as it is towards the front of the glacier. HISS altimetry data showed that ice surface

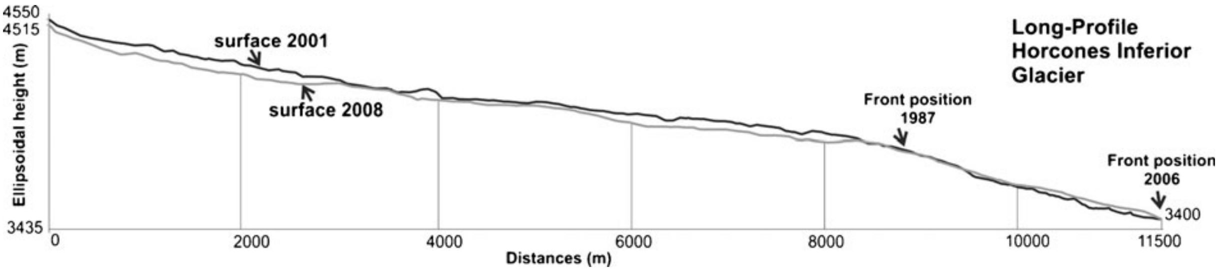


Fig. 4 The figure shows the long-profile in the Horcones Inferior Glacier before and after the 2003 surge event. The surface was modified by the surge, and the glacier passed the 1987 front position occupying the whole valley. The *black line* show the surface in 2001 and the *grey* show the surface in 2008

altitude decreased by 0.50 m in the interval considered, see Fig. 6b. The station remained out of service 273 days during the winter 2009 season. When it was again positioned in the same location in December 2009, the point was located at 1.40 m below the last registered altitude. During the second season, the movement in NE was 0.70 m in the same direction of the previous season, see Fig. 6d, and the altimetry showed a decrease of 2.12 m, see Fig. 6e.

Figure 6c and f show the velocities of HISS station in NE and Up direction for 2009 and 2010 period. Both graphs not show that the velocity keeps the same tendency, during the 2010 season the trend experience an increase that could be explained due the station was placed in early December, while in 2009 was located in later January. Table 3 show horizontal and vertical mean velocities obtained by HISS during each period. The V_{NE} value is larger by 22 % in the second season than the first one. The V_U change occurring in the second season (2010) is notorious; the increase of change altimetric rate is to 35 % approximately with a consequence of the glacier ice thinning at that area.

Altimetric Changes by GNSS Profiles

The GNSS profiles provide accurate data to assess the surface changes and movements. The results obtained show a clear evidence of the continuous ablation process, the glacier is experiencing, following the negative tendency of ice meltdown at the position of the HISS station. The glacier center profile was divided in three parts LP1, LP2, LP3 see Fig. 3. The last part cannot taken in account because there was a discontinuity in the data produced by the fact that the glacier surface in that area experienced a considerable change from one season to the other, and it was not possible to be located exactly the transect in the same position. The only data that was possible to correlate was that of the 2012 season (January–May), with the exception of the long profile LP-3 where it was possible to process the 2011–2012 (May-January) period (Fig. 7).

The profile values obtained after an intense ablation summer indicate that the surface in this area has experienced a differential behavior of the ice degradation of the Horcones Inferior Glacier. Table 4 shows the min, mean and max values that were found for each

Fig. 5 The pictures show the glacier surface from the HISS station, the left was taken on February 2009 and the right on February 2010; the *red circles* show the same place in both pictures

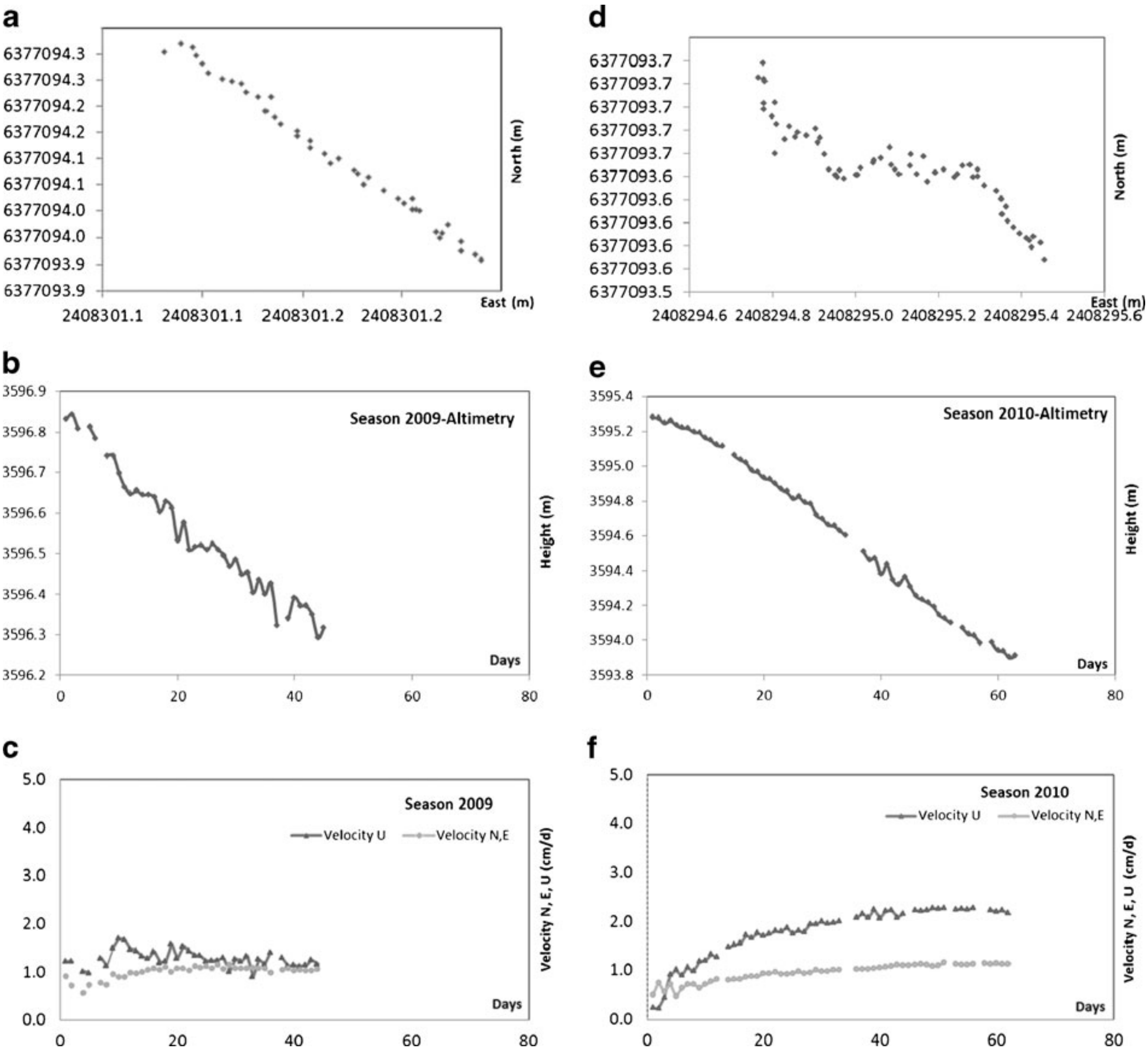


Fig. 6 The graphs show the evolution of the HISS station during the 2009 and 2010 period. First Season (2009): **a** Movement in N, E direction. **b** Displacement in Up direction, **c** Velocity in North, East and Up direction. Second Season (2010): **d** Movement in N, E direction. **e** Displacement in Up direction. **f** Velocity in North, East, and in Up direction

profile, together with the standard deviation and the seasonal mean velocity for this period.

The profile values reach maximum ranges of −5.89 m in the 127 day period and the minimum values were of a few centimeters. LP-3 represents the part which is closer to the glacier front, and it shows the dramatic change that the ice body is suffering due to the low altitude above sea level that got positioned

Table 3 The HISS velocities

Period	Velocity $_{NE}$ (cm/d)	$\sigma_{NE\ (m)}$	Velocity $_{U}$ (cm/d)	$\Sigma_{U\ (m)}$
2009 (January–March)	0.9	±0.002	1.1	±0.004
2009–2010 (December–February)	1.1	±0.005	1.5	±0.009

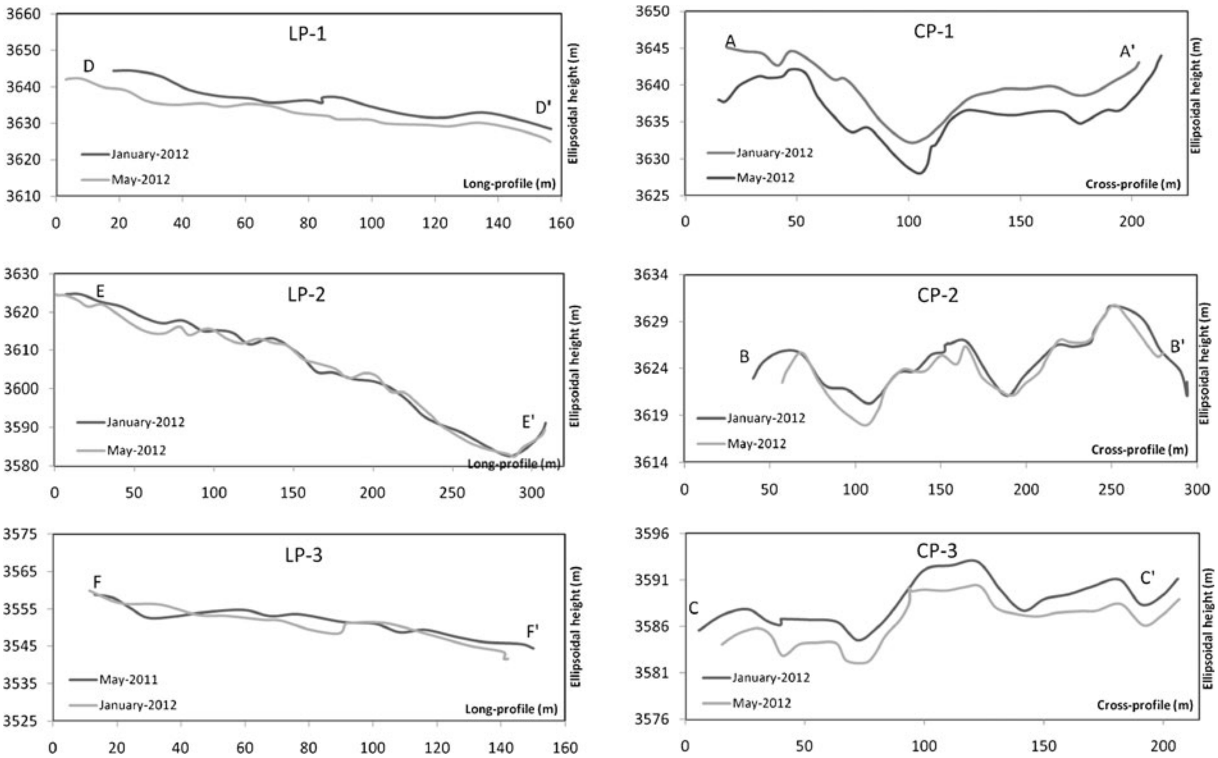


Fig. 7 The graphs show the altimetric position of the long and cross profiles on the glacier surface. The *black line* show the surface in January 2011 and the *grey* show the surface in May 2012, with an exception in the LP-3 profile where the data was correlated between May 2011 and January 2012

after the 2003 surge. The three cross profiles were named as CP1, CP2 and CP3. They showed a maximum of −7.28 m and a minimum of a few centimeter changes in altitude in the period of 127 days. The CP-2 a little change in the surface is observed, just −0.67 m. This can be related to the fact that in this sector a till thicker layer exists, and therefore the influence of the solar radiation could be smaller. In the other profiles, both surfaces did change in altimetry but in topography there were almost no changes.

The results of the seasonal mean velocities in the longitudinal profiles show an increasing trend from the first (LP1) to the last (LP3), the closest to the tongue of the glacier. Comparing this first two, there was a significant variation in the speed being 2.61 cm/d far away to the tongue, and 0.35 cm/d in the middle. For the third profile (LP3), we obtained the balances that include the winter and even spring seasons. Unfortunately on May, 2012, the last profile could not be acquired

Table 4 The min, mean and max ΔH, the standard deviation of each profile and the up mean velocity of each profile in every period

Profile	Period	Min ΔH (m)	Mean ΔH (m)	Max ΔH (m)	SdU (m)	VelU (cm/d)
Long-profile LP1	Jan2012–May2012	−1.03	−3.32	−5.89	0.04	2.61
Long-profile LP2	Jan2012–May2012	−0.19	−0.44	−2.57	0.02	0.35
Long-profile LP3	May2011–Jan2012	−0.47	−0.55	−4.11	0.03	0.24
Cross-profile CP1	Jan2012–May2012	−0.96	−3.55	−7.28	0.02	2.79
Cross-profile CP2	Jan2012–May2012	−0.07	−0.68	−3.35	0.03	0.54
Cross-profile CP3	Jan2012–May2012	−1.15	−2.37	−3.97	0.01	1.87

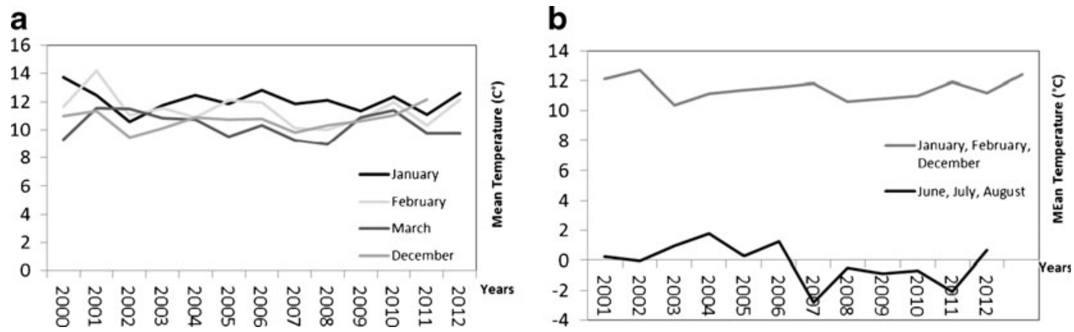


Fig. 8 **a** Mean monthly temperature for the ablation season in 2000–2012 at the Horcones weather station. **b** Mean temperature for ablation and cold season during 2001–2012 period

for the same place due to substantial changes occurred in the area during the summer.

The results obtained in the cross profiles keep the same trend as in the long profiles. In all three cases the change from the left border to the right of the glacier remained virtually constant. In the CP1, the speed was 2.79 cm/d, which is consistent with LP1. Similarly, the CP2 recorded an average speed of 0.54 cm/d which corresponds to the value of LP2. Finally, the CP3, that contained HISS, had a value of 1.87 cm/d that matched the HISS tendency obtained in 2009 and 2010 summer seasons.

Temperature data of the Horcones weather station located approximately 5 km from HIG front and at an altitude of 2,800 m a.s.l. were analyzed. Figure 8a shows the mean monthly temperature of January, February, March and December during the period 2000–2012, and Fig. 8b shows the mean temperature for ablation season between December, January, February and March), and also during the cold season (June–August). The Fig. 8b shows a small negative tendency in the temperature data during the cold season.

Data from meteorological stations of Central Chile show a warming of 0.3 °C to 0.7 °C over the last hundred years with an increment of temperature in winter (Escobar and Aceituno 1998; Carrasco et al. 2008). On the other hand, the analyses of the 0 °C isotherm at the Quintero station (32°47′S, 71°33′W) indicated a vertical rise of it of 150 m in winter and 250 m in summer over the last 25 years. This suggests that a similar trend must have affected the snow line in this part of the Andes. These facts may explain loss of ice mass in the glacier.

Discussion

The Horcones Inferior Glacier represents a highly unstable glacial environment, with degrading ice which is indicated by each one of the methods implemented in the present work in the period 2001–2012. When the glacier movement is in a quiescent period establishes again the ablation mode, then caused by the intense ice melting the glacier initiates a fast collapse. In the study area, temperatures are above of 0 °C isotherm, and therefore the ice melts more quickly; note the ice also absorbs more radiation due to the fact that the layers of cryosediments and dark till of the body surface are rather thin of 0.50 m approximately, according to measurements taken in the field. After the surge ended the ablation process took over again and the surface showed an increase in the number of the thermokarst lakes, and the topography started to smooth again.

We maintain the hypothesis that the melting water of the thermokarst drains through fractures and cavities in ice. If permafrost exists at that height a soft bed due to cryoweathering would probably be formed and *eisrinde* (Büdel 1981) effect would also be active. This layer might represent an unconsolidated and discontinuous layer that would be impermeable in depth.

If cavities are disconnected but full with water, this water increases the ice strength and its downward movement. In this case, the glacier is temperate and there may also be water on the glacial basal bed, which enhances the transfer of the strength. We suppose that in the future the cavities might join and favour the homogenization of the glacier where ice blocks are embedded by melting water. Water outlet has to stop the surge.

The irregular topography of the Horcones Inferior Glacier before and after surges makes it difficult to access its surface, and therefore using satellite images is an adequate tool obtain information of larger areas. In this study the generation of DTMs from ASTER optical images, in areas with topographic complexity such as the Mt. Aconcagua region, proved feasible to estimate elevation change in glaciers. The adjustment between two DTMs helped to reduce the noise between DTM_{01} and DTM_{08} and improving the quality on the results. DTMs applied to this type of covered glaciers have produced good results, possibly due to good image correlation which is due to the detritic coverage, just the opposite to the situations in calving glaciers, in areas with snow and ice where lack of contrast results in poor correlation performance (Lenzano 2013).

The importance of DTMs is that it allows obtaining glacier surfaces before and after surges. The $\Delta H_{01\text{-}08}$ altimetric change in the HIG was obtained by the altimetric profile over DTM_{01} and DTM_{08} from ASTER images. The 2008 profile was acquired 2 years after the surge ended in 2006, and it is smoother than that of 2001. This can be explained by the fact that 2 years of intense ablation occurred, affecting the ice transported by the surge in 2003, and this is may also indicate that the altimetric differences in the ice should have been larger in 2006 when the surge ended.

The HIG average velocities recorded during 1984 surge is 8.7 m/d (Lenzano et al. 2011), while during the 2003 surge, rates of 12 m/d were obtained during 2003–2004 period (Lenzano et al. 2012). In the summer of 2004–2005, surveys were conducted *in situ* and velocities were recorded up to 35 m/d (Leiva 2006). According to the values of the ratios obtained from the previous studies and relating them to those obtained from the present study during a quiescent state plus taking into account the size of the HIG, HIG may be classified as a type II surging glacier, according to Meier and Post (1969).

The study on the monitoring the North, East and Up velocities of the HISS GNSS station generated the first kind of this data in the HIG, clearly proving the feasibility of the GNSS approach. The L1 single-frequency GPS equipment linked to near GNSS Permanent Station provided accurate N, E and Up seasonal velocities for 2009 and 2009–2010 period, confirming the fact that the ice in the ablation zone is subjected to a continuous degradation process and this is could be an increasing tendency.

The long and cross profiles taken at the end of the 2010 and 2012 summer seasons provided complementary information on the behavior of the HIG, which allowed for a verification of the data from the 2009–2010 season at the HISS. These profiles provided different values, where the Up velocities ranged from scarce millimeters to almost 3 cm a day during the analyzed periods. This differential behavior on the variability of the reduction of the altitude can be attributed to the different detrital thickness coverage on the surface of the glacier. This shows and asserts if compare the results to the HISS that the glacier moves downhill, but with a smaller velocity than areas farthest from the front.

Conclusions

This study demonstrates that the applications of GNSS semi-continuous station and DTMs from ASTER optical images produced good results in glaciers as HIG. In the future work, the authors will add 4 GNSS semi-continuous station located along the glacier surface to obtain reliable velocities model of the HIG.

Acknowledgments This work was possible thanks to program SIGMA (Sistema de Investigaciones Geodinámico Monte Aconcagua) and Argentina National Council for Science and Technology (CONICET) funding. We thanks to Dr. Charles Toth for his comments and reviews, and Dr. Silvain Bonvalot IRD (Institute de Recherche pour le Développement, France) for providing PORT station data. Also we thanks to Departamento General de Irrigación, Mendoza, to provide the meteorological data, and Tec. Adalberto Ferlito, Andrés Lovecchio for their help in the fieldworks.

References

Barrand, N. E., Murray, T., James, S. L., & Mills, J. P. (2009). Optimizing photogrammetric DEMs for glacier volume change assessment using laser-scanning derived ground-control points. *Journal of Glaciology, 55*(189), 106–111.

Bernese User Manual. (2007) GPS software Version 5.0. Ed. by Dach, R, Hugentobler, U, Fridez, P., Meindl, M. Copyright Astronomical Institute, University of Bern.

Bolch, T., Pieczonka, T., & Benn, D. I. (2011). Multi-decadal mass loss of glaciers in the Everest area (Nepal Himalaya) derived from stereo imagery. *The Cryosphere, 5*, 349–358.

Büdel, J. (1981). Klima-Geomorphologie. Gebrüder Borntraeger, 304 p., Salzweg-Passau.

Carrasco, J. F., Osorio, R., & Casassa, G. (2008). Secular tren of equilibrium line altitude on the western side of the southern Andes, derived from radiosonde and surface observations. *Journal of Glaciolology, 54*, 538–550.

Eiken, T., Hagen, J. O., & Melvold, K. (1997). Kinematic GPS survey of geometry changes on Svalbard glaciers. *Annals of Glaciology*, 24.

Escobar, F., & Aceituno, P. (1998). Influencia del fenómeno ENSO sobre la precipitación Nival en el sector andino de Chile central durante el invierno. *Bulletin de l'Institute Francais d'Etudes Andines, 27*(3), 753–759.

Etzelmüller, B., & Sulebak, J. R. (2000). Developments in the use of digital elevation models in periglacial geomorphology and glaciology. Physische Geographie. *Jahrestagung Winterthur*, 41.

Haeberli, W. (2005). Mountain glaciers in global climate-relate observing systems. In U. M. Huber, H. K. H. Burgmann, & M. A. Reasoner (Eds.), *Global change and mountain regions (a state of the knowledge overview)* (pp. 169–175). Dordrecht: Springer.

IPCC (2007). Intergovernmental Panel on Climate Change. 26th Session of the IPCC, Bangkok, Thailand.

Iwasaki, A., & Fujisada, H. (2005). ASTER geometric performance. *IEEE Transactions on Geoscience and Remote Sensing*, 43(129).

Kamb, B. (1985). Glacier surge mechanism: 1982–1983 surge of variegated glacier, Alaska. *Science, 227*, 469–479.

Kamb, B. (1987). Glacier surge mechanism based on linked cavity configuration of the basal water conduit system. *Journal of Geophysical Research, 92*, 9083–9100.

Kotlyakov, V. M., Rototaeva, O. V., Desinov, L. V., & Osokin, N. I. (2004). Causes and effects of a catastrophic surge of Kolka Glacier in the Central Caucasus. *Zeitschrift für Gletscherkunde und Glazialgrologie, 38*(2), 117–128.

Kotlyakov, V. M., Osipova, G. V., & Tsvetkov, D. G. (2008). Monitoring surging glaciers of the Pamirs, Central Asia from space. *Annals of Glaciology, 48*, 125–133.

Leiva, J. C. (2006). Assesment climate change impacts on the water resources at the Northern Oases of Mendoza Province, Argentine. In M. Price (Ed.), *Global change in mountain regions* (pp. 81–83). Wiltshire: Sapiens Publishing. 343 p.

Leiva, J. C., Mackern, M. V., Cabrera, G. A., & Lenzano, L. E. (2005). Global change impacts on mountain hazards and tourism in the Aconcagua Region, Mendoza, Argentine. In M. Price (Ed.), *Global change in mountain regions* (pp. 259–260). Wiltshire: Sapiens Publishing. 343 p.

Lenzano, M. G. (2013). Assessment of using ASTER-derived DTM for glaciological applications in the Central Andes, Mt. Aconcagua, Argentina. *Journal of Photogrammetry, Remote Sensing and Geoinformation Processing*.

Lenzano, M. G., Leiva, J. C., Trombotto, D., & Lenzano, L. (2011). Satellite images and geodetic measurements applied to the monitoring of the Horcones Inferior Glacier, Mendoza, Argentina. *Revista de la Asociación Argentina de Geofísicos y Geodestas (Geoacta), 36*, 13–25.

Lenzano, M. G., Trombotto, D., & Leiva, J. C. (2012). Monitoreo de la superficie del Glaciar Horocnes Inferior y sus termokarst, antes, durante del surge de 2003–2006. Andes Centrales Argentinos. *Revista de la Asociación Argentina de Geofísicos y Geodestas (Geoacta), 37*(2), 1–4.

Liba, N., & Jarve, I. (2009). Making orthophotomosaic about Tartu city with PHOTOMOD Program and its geometrical quality. FIG 2009, Working Week Report (Fédération Internationale des Géomètres–International Federation of Surveyors) Surveyors Key Role in Accelerated Development, Eilat-Israel, 3–8 May.

Lidberg, M., Johansson, J. M., Scherneck, H. G., & Davis, J. L. (2006). An improved and extended GPS-derived 3D velocity field of the glacial isostatic adjustment (GIA) in Fennoscandia. *Journal of Geodesy, 81*(3), 1394–1432. ISSN 0949–7714.

Marzolff, I., & Poesen, J. (2009). The potential of 3D gully monitoring with GIS using high-resolution aerial photography and a digital photogrammetry system. *Journal of Geomorphology, 111*(1–2), 48–60. doi:10.1016/j.geomorph.2008.05.047.

Meier, M. F., & Post, A. S. (1969). What are glacier surges? *Canadian Journal of Earth Sciences., 6*(807), 807–817.

Milana, J. P. (2007). A model of a Glaciar Horcones Inferior surge, Aconcagua region, Argentina. *Journal of Glaciology, 53*, 183.

Miller, P. E., Kunz, M., Mills, J. P., King, M. A., Murray, T., James, T. D., & Marsh, S. H. (2009). Assessment of glacier volume change using ASTER-based surface matching of historical photography. *Geoscience and Remote Sensing, IEEE Transactions, 47*(7), 1971–1979.

Minetti, J., & Corte, A. (1984). Zonificación latitudinal del clima en la zona andina y su relación con el límite inferior del hielo perenne (LIHP) y del límite inferior geocriogénico (LIG). *Acta Geocriogénica, 2*, 129–143.

Rivera, A. (2004). Mass balance investigations at Glaciar Chico, Southern Patagonia Icefield, Chile. Ph.D. Thesis. School of Geographical Sciences. University of Bristol.

Rozycki, S., & Wolniewicz, W. (2007). Assessment of DSM accuracy obtained by High resolutions stereo images. ISPRS Hannover Workshop 2007 High Resolution Earth Imaging for Geospatial Information, Universitat Hannover, Leibniz, Germany, 29 May–1 June.

Servicio Meteorológico Nacional. (1986). Estadísticas Meteorológicas 1971–1980. Buenos Aires, Argentina.

Toutin, T. (2008). ASTER DEMs for geomatic and geoscientific applications: a review. *International Journal of Remote Sensing, 29*, 1855–1875.

Tregoning, P., Twilley, B., Hendy, M., & Zwartz, D. (1999). Monitoring isostatic rebound in Antarctica with the use of continuous remote GPS observations. *GPS Solutions, 2*, 70–75.

Trombotto, D. (1991). Untersuchungen zum periglazialen Formenschatz und zu periglazialen Sedimenten in der 'Lagunita del Plata', Mendoza, Argentinien. Heidelberger Geographische Arbeiten. Heft 90: 171 p, Heidelberg, Germany.

Trombotto, D., & Borzotta, E. (2009). Indicators of present global warming through changes in active layer-thickness, estimation of thermal difussivity anf geomorphological observations in the Morenas Coloradas rock glacier, Central Andes of Mendoza, Dry Andes, Argentina. *Cold Regions Science and Technology, 55*, 321–330. Elsevier, The Netherlands.

Unger, C., Espizua, L. E., & Bottero, R. (2001). Untersuchung von Gletscherständen im Tal des Río Mendoza (zentralargentinische Anden) - Kartierung auf eines Surge-vorstosses des Horcones Inferior. *Zeitschrift für Gletscherkunde und Glazialgeologie, 36*, 151–157. 1480 p.

Vignon, F., Arnaud, Y., & Kaser, G. (2003). Quantification of glacier volume change using Topographic and ASTER DEMs. A case study in the Cordillera Blanca. Proceedings of IGARSS' 2003, 21– 25 July 2003, Toulouse, France, IEEE 2003, 2605–2607.

WGMS, (Espizúa) (2008). Fluctuations of glaciers 2000–2005, volume IX. Haeberli, W., Zemp, M., Kääb, A., Paul, F. and Hoelzle, M. (eds.), ICSU(FAGS)/IUGG(IACS)/ UNEP/UNESCO/ WMO, World Glacier Monitoring Service, Zurich, Switzerland.

Wolf, P. R., & Dewitt, B. A. (2000). Elements of photogrammetry with applications in GIS, chapter 5, 3rd edn. New York: Mc Graw Hill.