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Inventory of glacier-front positions using CBERS-2 data: a case study for the Bolivian Andes

RAFAEL R. RIBEIRO[1], JEFFERSON C. SIMÕES[1], JORGE ARIGONY-NETO[1,2] & EDSON RAMIREZ[3]

1 *Núcleo de Pesquisas Antárticas e Climáticas, Depto. Geografia, Instituto de Geociências, Universidade Federal do Rio Grande do Sul, Porto Alegre, Brazil*
jefferson.simoes@ufrgs.br; rrr.3@pop.com.br

2 *Institut für Physische Geographie, Albert-Ludwigs-Universität Freiburg, Germany*

3 *Universidad Mayor de San Andrés, IHH, La Paz, Bolivia*

Abstract For the first time, products of the China–Brazil Earth Resources Satellite (CBERS) are used for Andean glaciers studies. In this paper we compare results from previous ground studies with our observations using two scenes acquired by the High Resolution Charge Coupled Device (CCD) and the Infra-Red Multispectral Scanner (IRMSS) aboard the second Chinese–Brazilian satellite (CBERS-2), to establish an inventory of glacier frontal positions from 1975 to 2004 in the Cordillera Tres Cruces, Central Bolivia. All studied glaciers have retreated since 1974 (by up to 409 m) agreeing with ground studies. The use of CBERS-2 can contribute to establish an inventory of Andean glaciers as it covers the same area each 26 days.

Key words remote sensing; glacier inventory; CBERS-2

INTRODUCTION

Andean glaciers play an important role in the hydrological and social-economic systems of many countries. For example, they are essential to supply drinking water to local communities; produce energy in hydroelectric power plants; supply water for agriculture; and have scenic values in tourism. In La Paz (Bolivia), for instance, 70% of the water used by the population comes from glaciers.

Mountain glaciers, in general, lost mass during the 20th century (Dyurgerov & Meier, 2000). This is a process that can be attributed both to a general atmospheric warming and to regional climatic variability (Meier, 1984). Altogether, melting of mountain glaciers, ice caps and parts of the Antarctic and Greenland ice sheets, are the main contributors (70%) to sea level rise; the rest is mainly due to the thermal expansion of the ocean water (Church *et al.*, 2001). Though mountain glaciers constitute less than 1% of the cryosphere volume, it is estimated that they contributed with ¼ of the sea level increase between 1988 and 1998 (Dyurgerov, 2003). In short, mountain glaciers are considered by the Intergovernmental Panel on Climate Change (2001) as one of the main contributors to future sea level rise and key indicators of climate change.

Accurate determination of mountain glacier changes may be useful for assessing regional hydrological balance and water supply. One of the methods for these evaluations consists of measuring temporal differences in the frontal part of glaciers (extent and altitude). Unfortunately, the great majority of mountain glaciers are in remote areas where traditional topographic surveys are expensive, if not impossible. The main solution is to integrate the scarce field data obtained by traditional methods with remote sensing data (Reinhardt & Rentsch, 1986).

In recent years, Landsat and Advanced Space Borne Thermal Emission and Reflection Radiometer (ASTER) images data have been used to create a glacier inventory (Kääb *et al.*, 2002), for example, through the Global Land Ice Measurement from Space (GLIMS) programme. Yet, some parts of the Andes do not have good imagery coverage. On the other hand, since 2001, a new opportunity arose from the launch of the China-Brazil Earth Resources Satellites (CBERS). In this paper we compare results from previous studies (Jordan, 1991, 1998) with two scenes acquired by the High Resolution Charge Coupled Device (CCD) and the Infra-Red Multispectral Scanner (IRMSS) aboard the second Chinese-Brazilian satellite (CBERS-2), to establish an inventory of glacier frontal positions over the last 30 years in the Cordillera Tres Cruces, Bolivia (67°22′–67°32′W and 16°47′–16°09'S, Fig. 1).

In this paper we show results of the first application of CBERS visible and near-infrared imagery for glaciological studies, integrating remote sensing data with the geographic information system (GIS) techniques. Glaciers' features, such as extent and

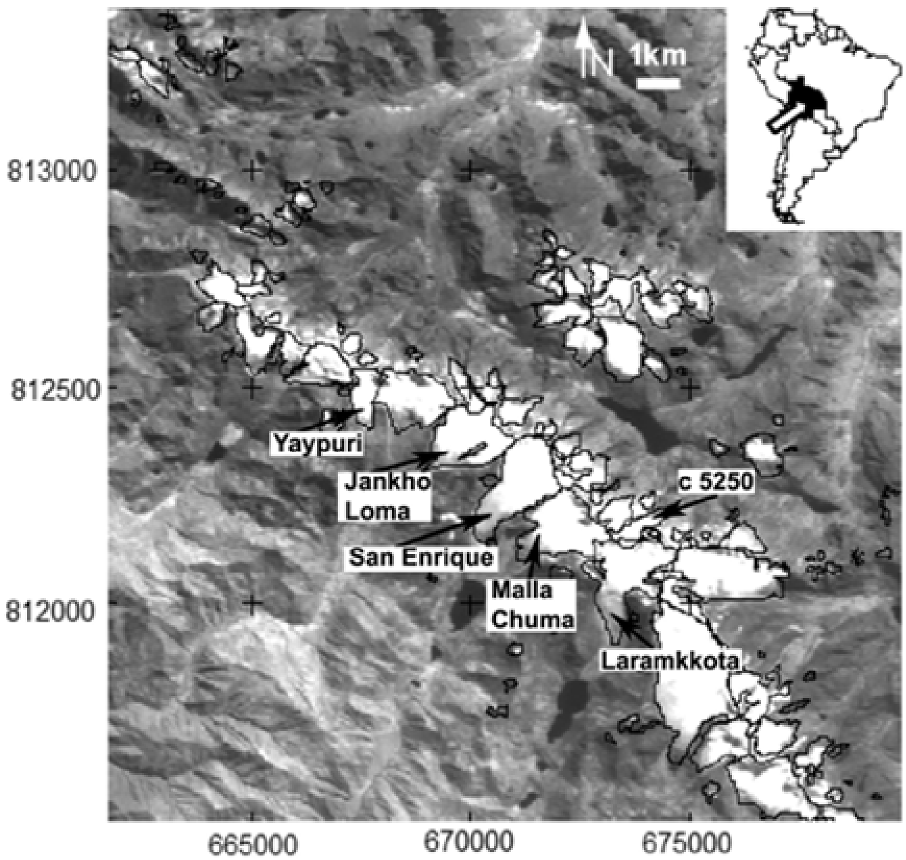

Fig. 1 A CBERS-2 CCD band 3 image (19 May 2004) of Tres Cruces Cordillera (Bolivia), thin black lines outline glacier drainage basins as identify in a 1975 topographic map (Jordan, 1991). The arrow in the inset locates this mountain range in South America (black area marks the Bolivian territory).

terminus altitude, and 30-year trends were computed. Results are then compared with glacier-front position manually digitized from the image.

STUDY AREA

The mountain range Tres Cruces (Quimsa Cruz in Aymara) is approx. 35 km long and 10 km wide; it is about 150 km east of the city of La Paz (16°30′S, 68°09′W). These mountains begin to the southeast of the La Paz River, extending up to the city of Ventillaque. In 1975, the total glacier area was 39 km^2 (Jordan, 1998), distributed in 156 drainage basins. Several peaks reach more than 5000 m above sea level; the highest are the Jachancuncollo (5900 m) and the Gigante Grande (5807 m). Several lakes exist in front of these glaciers, of which the most extensive are Huallatani, Laramkkota, Octa Kkota and Chatamarca. The source of the River Miguillas, where there are four small hydroelectric power plants, forms by melting of some glaciers in these mountains.

The regional climate is marked by two strongly distinct annual seasons (Kaser & Osmaston, 2002). In summer (October–May), the intertropical circulation influences the meteorological settings, precipitation occurring due to the humid air masses coming from the Amazonian region. Winter (June–September) is the dry season when air masses coming from the southwest predominates and do not bring precipitation. Therefore, the total summer precipitation is the main control of the glaciers annual mass balance.

REMOTE SENSING DATA

CBERS–2

The CBERS program results from a Brazilian–Chinese partnership in the space technical scientific segment. The launch of the CBERS-2 occurred on 21 October 2003. It carries three sensors: a CCD, an IRMSS, and a Wide Field Imager (WFI). Its orbit is helios-synchronous at 778 km of altitude, performs about 14 revolutions a day allowing a complete coverage of the Earth each 26 days (www.cbers.inpe.br). In this study, we use two CCD and IRMSS scenes acquired on 19 May 2004. The Brazilian Instituto Nacional de Pesquisas Espaciais (INPE) provides South American CBERS-2 images free of charge for registered researchers. Table 1 shows the characteristics of these two images.

Table 1 Specifications of CBERS-2 CCD and IRMSS sensors used in this work.

Cameras	Band/Name	Range (μm)	Spatial resolution (m)	Swath (km)
CCD	2	0.52–0.59 μm (green)	20	113
	3	0.63–0.69 μm (red)	20	113
	4	0.77–0.89 μm (near infrared)	20	113
IRMSS	1	0.50–1.10 μm (panchromatic)	80	120
	2	1.55–1.75 μm (middle infrared)	80	120

DEM

A digital elevation model (DEM), based on a topographic map, complements the study. DEM is a representation of the surface by a digital environment. In glaciology it is useful for detecting changes in glacier geometry (e.g. size, slope and orientation). Different algorithms of interpolation can be used to obtain a DEM; the final product quality depends on the density and distribution of reference points used to generate the model. It is important, therefore, to know which interpolation method results in the smallest error.

Digitized topographic data came from a 1:70 000 map, produced from 1975 aerial photographs using stereophotogrammetric methods (Jordan, 1991). It is a work produced by the Institut für Photogrammetrie und Ingenieur-Vermessungen e Geographisches, University of Hanover, Germany.

These data were used to "create" an elevation grid with 20 m of resolution. We tried two interpolation techniques, Triangulated Irregular Network and TOPOGRID (using Arc-Info^{TM} 8.0.1); the latter produced the smallest error (mean of ±4 m). To verify each model, we used control points not employed in the interpolation process, for example, fluvial drainage lines and other water bodies.

METHODOLOGY

The two satellite images used in this work (Table 1) were acquired at the end of the dry season, when the superficial snow pack is at its annual minimum, which facilitates the identification of the glacier limits. A thick seasonal snow cover makes a correct delineation of a glacier front position difficult, especially when rock outcrops are not spectrally identified because of radiative similarities. Furthermore, sensor calibration of the CBERS-2 data is not yet possible (calibrating coefficients, e.g. gain and slope, are not yet available to users).

The 1975 topographic map was taken as the reference for geometric corrections. We used the ERDASTM software for data co-registration, and the two CBERS-2 CCD and IRMSS images were georeferenced using 20 ground control points (GCP), with a first-degree polynomial transformation and nearest neighbour resampling (20 m and 80 m per pixel, respectively, for CCD and IRMSS data). The root-mean-square error (RMSE), obtained from the geometric correction procedure, is 1.88 pixel for CCD and 2.11 pixel to IRMSS image. After this correction, two different methods for glacier front position delimitation were tested (Fig. 2); their results were superimposed and compared with the manual delineation (discussed above).

Ratio bands, combined with the digital elevation model, were used to separate glaciers/snow features from surrounding land (Paul *et al.*, 2002). The DEM is particularly useful in shadowed areas where surface spectral variations are strongly reduced, resulting in difficult target discrimination. To apply this methodology with CBERS-2 data requires the following ratio segmentation: (first method) IRMSS channel 2 and CCD channel 4; (second method) IRMSS channels 1 and 2. To use ratio bands, in the first method, we integrated CCD with IRMSS data (the latter was resampled to 20 m) using bilinear interpolation.

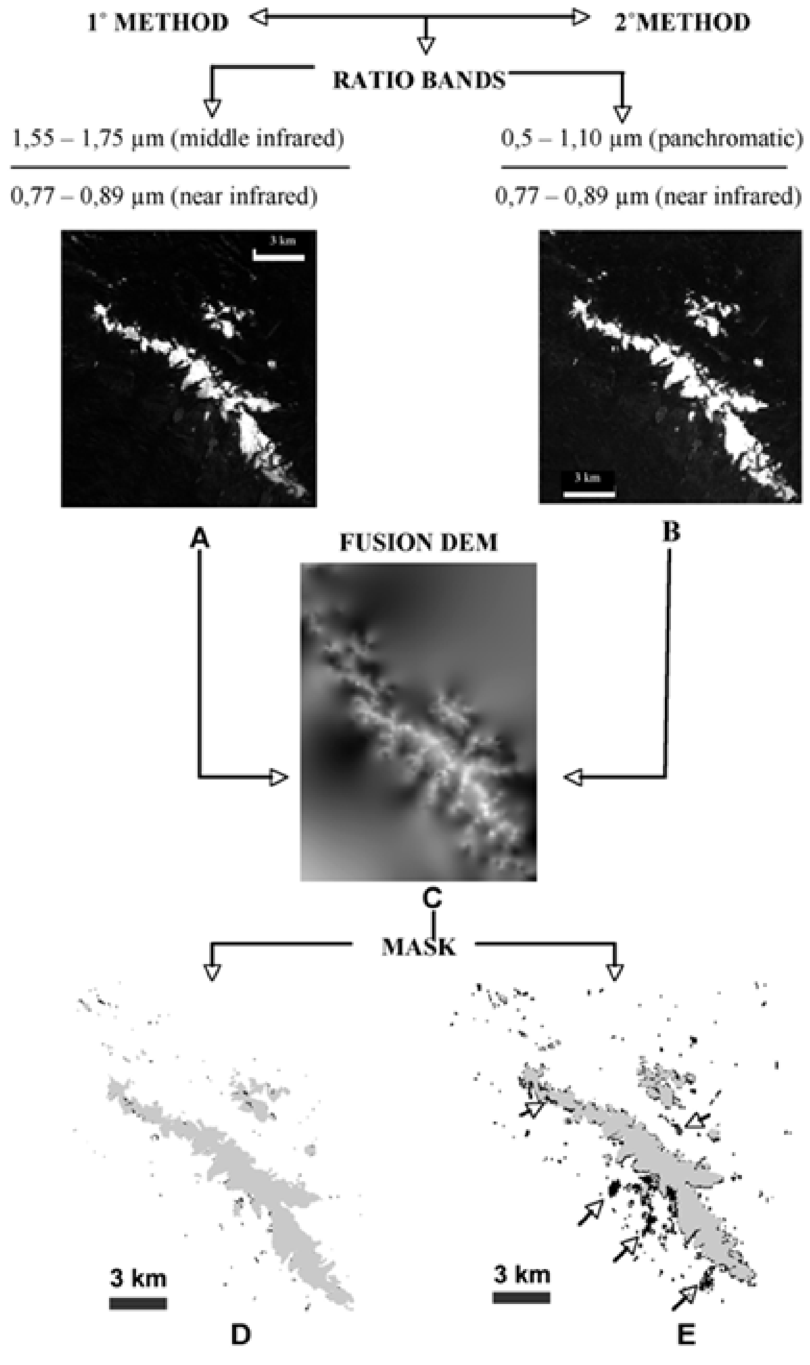

Fig. 2 Glacier masks workflow obtained from IRMSS band 2/CCD band 4 (a,c,d) and IRMSS band 1/IRMSS band 2 (b,c,e). Grey areas mapped by manual delimitation, only ratio bands map black ones. Arrows in "e" indicate where shadows and water were mapped as glacier area by the second method (only corrected identified by visual inspection of the image).

For each method, threshold values were estimated by visual inspection, using ratio bands with a DEM fusion to obtain a glacier mask. The margins of glaciers were identified by converting data from raster to vector format. Data were then transferred to Arcview^{TM} GIS 3.2 software, to construct polygons of glacier termini changes.

Glacier front positions changes can then be observed in the overlay map using different time polygons. Integration of glacier maps with the DEM allowed determination of a glacier terminus altitude. Figure 2 shows the workflow used in this work to determine glacier front position from CBERS-2 satellite image ratio bands.

RESULTS AND DISCUSSION

The difference of reflectivity between the visible (high for snow and ice) and middle infrared (low for the same targets) allows glacier classification from segmented glacier map CBERS–2 data, applying the methodology of Paul *et al.* (2002).

The two methods (Fig. 2) were superimposed and compared with the manual delineation results, in combination with band 3 CCD image equalized histograms, allowing us to determine termini position changes of six glaciers for the period 1975–2004: Yaypuri, Jankho Loma, San Enrique, Malla Chuma, Laramkkota and c 5250 (Fig. 1). The best results are provided by the use of IRMSS channel 3 with CCD channel 4 (Fig. 3). It is not possible to clearly discriminate shadows/water from ice/snow targets using the IRMSS band 2/CCD band 4 ratio due to the lower spatial resolution (80 m).

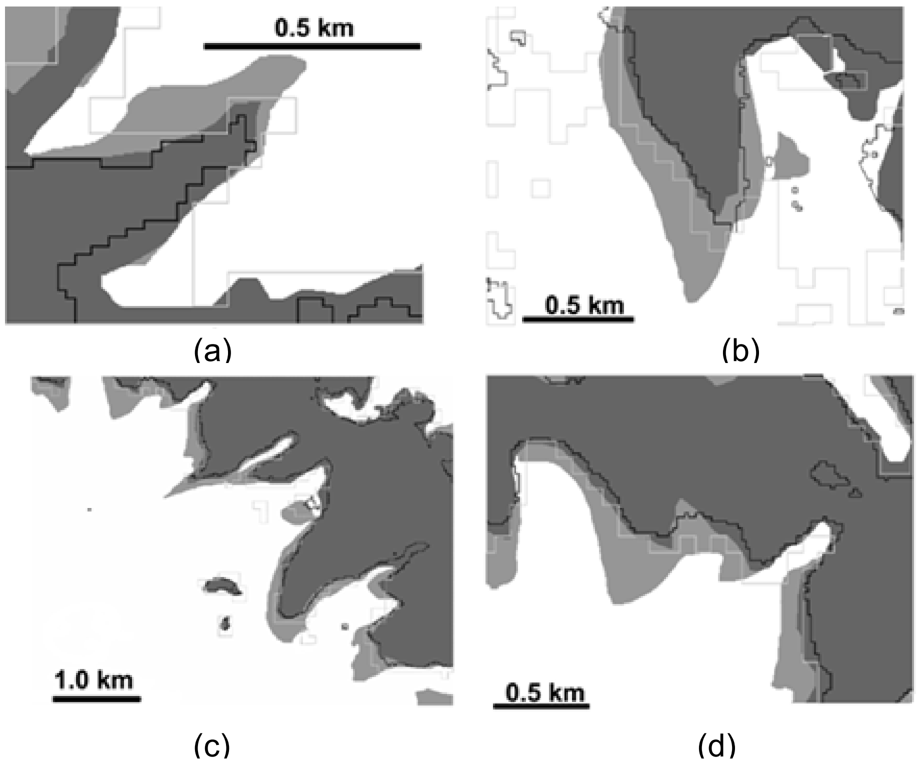

Fig. 3 The six glaciers fronts studied in this work: (a) c 5250; (b) Laramkkota; (c) Malla Chuma, San Enrique, Jankho Loma; (d) Yaypuri. Light grey areas are glacier terminus as found in 1975 (Jordan, 1991), manual delimitation over the 2004 CBERS-2 images are in dark grey. The thin light grey line represents ice front positions as determined by the band IRMSS band 2/CD band 4 ratio; the thin black line represents delimitation using IRMSS channel 3 with CD channel 4, used for the Tres Cruces Cordillera glaciers inventory.

For the first method we integrated CCD with IRMSS images, after a 20-m resampling of the latter. We estimated the uncertainty between the images (Table 2) using the formula by Hall *et al.* (1992), as we do not have any ground topographical survey which prevents verification of our results:

Uncertainty = (IRMSS pixel resolution after resampling)^2 + (CCD pixel resolution)^2]^{½} + registration error

We have:

Uncertainty = $[(20)^2 + (20)^2]^{½} + 40 = 80$ m

Table 2 Uncertainty of the CBERS-2 CCD and IRMSS sensors.

Methods	Cameras/Channels			Uncertainty (m)
	IRMSS	IRMSS/Resampling 20 m	CCD	
1	–	2	4	±80
2	1	–	–	±160
	2	–	–	
DEM	–	–	–	±4

For the second method of construction of ratio bands no resampling of the images is needed, both have a spatial resolution of 80 m.

Table 3 shows the results of the glacial inventory for Tres Cruces Cordillera. All studied glaciers have retreated since 1974. On the east side of the Cordillera, glaciers retreated from 279 to 422 m (i.e. Malla Chuma Glacier); in general, the higher the 1974 ice front elevation, the greater the changes. The San Enrique Glacier is the only one on the west slope that does not follow this behaviour. The only glacier on the eastern slope (c 5250) had the smallest changes (an ice front retreat of 184 m), which is not an unexpected observation as the main source of precipitation is the Amazon basin. In all, our observations confirm results from other investigations concerning a general retreat of Bolivian glaciers during the last 30 years (Francou *et al.*, 2005).

Table 3 Changes in glacier length and terminus elevation between 1975 and 2004 in the Tres Cruces Cordillera (Bolivia).

Glacier	Year	Length (m)	Length Change	Elevation (m)	Elevation Change
Yaypuri	1975	1306	394 ± 80	4901	143 ± 4
	2004	912		5044	
Jankho Loma	1975	2263	409 ± 80	4890	135 ± 4
	2004	1854		5025	
San Enrique	1975	2443	279 ± 80	4943	128 ± 4
	2004	2164		5071	
Malla Chuma	1975	1727	422 ± 80	4946	182 ± 4
	2004	1305		5128	
Laramkkota	1975	2215	330 ± 80	4884	125 ± 4
	2004	1885		5009	
c 5250	1975	1248	184 ± 80	5050	62 ± 4
	2004	1064		5112	

CONCLUSIONS

This is the first application of CBERS data for glacier studies. The analysis of two satellite images gave satisfactory results in the ratio bands used (IRMSS channel 3 with CCD channel 4) for the delimitation of glacier frontal positions in Cordillera Tres Cruces. There is a 40-m mean difference between results using this method and those obtained from manual digitization. Normalized bands differences (e.g. Normalized Difference Snow Index) were not established because CBERS-2 calibrating coefficients are not yet available to users and we do not have ground observations.

The use of CBERS-2 can contribute to establishing an inventory of glaciers from space, through an integration of remotely sensed data with a GIS. The great advantage of using CBERS-2 data is the no-cost policy. Furthermore, CBERS-2 revisits the same area each 26 days, allowing monthly monitoring of Andean glaciers.

All glaciers studied in the Tres Cruces Cordillera, in Central Bolivia, have retreated since 1974 (up to 409 m until 2004). This observation agrees with ground monitoring studies that found a general reduction of the Bolivian glaciers over the last three decades.

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