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Changes of topographic context of the Yanamarey glaciers in the Tropical Peruvian Andes

KYUNG IN HUH[1], BRYAN G. MARK[1] & CHRIS HOPKINSON[2]

1 Department of Geography and Byrd Polar Research Center, The Ohio State University, Columbus, OH 43210
huh. 26@ osu.edu
2 Applied Geomatics Research Group, NSCC Annapolis Valley Campus, Nova Scotia, Canada

Abstract We use a combination of satellite and airborne remote sensing, digital photogrammetry and geospatial techniques to assess the surface area, volume and topographic changes of Yanamarey glacier in the Cordillera Blanca, Peru between 1962 and 2008. The surface area of Yanamarey glacier lost about 85% from 1962 (1.155 km^2) to 2008 (0.165 km^2). The average surface lowering of the glacier is 144m during this period. The change in surface area and the change in volume have a positive relationship with the correlation coefficient of 0.91 from 6 different year differences. Further investigation is required to explain the scaling of surface area to volume relationship in tropical glaciers in Cordillera Blanca, Peru.
Key words tropical glacier; Cordillera Blanca; LiDAR; surface area and volume changes

INTRODUCTION

Tropical glaciers are very sensitive to changes in climate due to the low latitude radiation regime and steep vertical mass balance gradients (Kaser and Osmaston, 2002; Vuille *et al*. 2008). In fact, tropical glaciers have been rapidly retreating over the 20th century, raising concerns about regional water supplies under continued global climate change (Bury *et al*., 2010; Juen *et al*., 2007). Monitoring glaciers using remotely sensed data has drawn a great attention in physical geography and earth science communities for decades and time-lapse analysis of sensory data has provided important variability information of tropical glacier recession (Racoviteanu *et al.*, 2008). This study focuses on the Yanamarey glacier in the Cordillera Blanca, Peru to assess the volume and topographic changes over the late 20th century using a combination of satellite and airborne remote sensing. High resolution LiDAR (Light Detection and Range) data achieved in 2008 and DEMs (Digital Elevation Models) from vertical aerial photographs taken in 1962 by stereo-photogrammetry reveal both current glacial surface topography and glacial profiles 46 years back, enabling calculation of the total volume loss trend over the last 46 years. And multispectral ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) imagery taken in 2001-2008 is used to estimate loss of surface area as well. Our objectives include: 1) estimating the glacierized area in 2008, 2) computing changes in glacier area from 1962 to 2008, 3) assessing elevation differences between DEMs from LiDAR and stereo-paired aerial photographs, 4) refining a surface area to volume relationship of tropical glaciers for more detailed inventory of glacier volume and water resources.

STUDY AREA

The study area is the Cordillera Blanca of the Peruvian Andes, which is the largest tropical glacierized area on earth, stretching northwest to southeast over 130 km between 8° 30'S to 10°S latitude (Ames, 1998)(Figure1). Based on previous research, the glacierized area of Cordillera Blanca was quantified as 723.37 km^2 from 1970 aerial photography with average thickness of 31.25 m estimated from previously published surface area to volume relationships (Ames *et al*., 1989). The Cordillera Blanca is a high relief region featuring the highest peak in Peruvian Andes, Huascarán south (6768m), and the glaciers span from ~3000 m valley floors to over 6000 m elevation. Dramatic glacier shrinkage in the region due to climate changes has been affecting the hydrologic regime of the glacierized watersheds. Most of the glacierized area flows into the Pacific Ocean via the Rio Santa. The climate of the region varies significantly across the steep altitudinal gradients of the Andes. Compared to the extremely arid desert coastal lowlands, the highlands are relatively moist. Average precipitation rates in the upper Rio Santa basin, where the Yanamarey case-study is located, range from between 800 and 1200 millimeters per year and greater than 80 percent of precipitation falls between October and May. Monthly average stream discharge is also higher during these months, and thus reflects the seasonal variability of precipitation typical of the outer tropics (Mark and Seltzer, 2003).

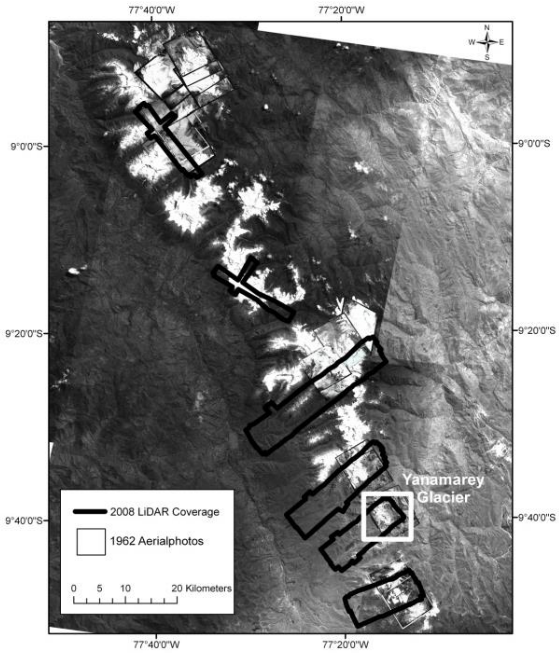

Figure 1 Coverage of 1962 aerial photographs and 2008 LiDAR flights over Cordillera Blanca, Peru. Background is ASTER mosaic image. Black boxes show the LiDAR flight coverage in 2008. 1962 aerial photo coverage is also shown in the figure. White box shows the location of Yanamarey glacier.

The Yanamarey glacier is one of the most studied sites of glacier hydrology in Peru (center coordinate of 9°39'S and 77°16W). Compilations of historical photographs and maps have quantified mass changes of the glacier over time (Ames *et al.*, 1989; Georges, 2004; Kaser *et al.*, 1990). Since 1968, a routine (monthly to inter-annual) surveying program was started to monitor four target glaciers, including the Yanamarey glacier, for observations of glacial extent and climate variables, providing an important glacial database (Ames, 1998; Francou *et al.*, 1995).

DATA AND METHODS

High-resolution airborne LiDAR data were acquired over select glaciers during July 2 - 16, 2008 (black boxes in Figure 1). Vertical the black- and - white aerial photographs taken on June 17, 1962 over Cordillera Blanca, Peru on a scale of 1:60,000 were acquired by USAF-AST-9 and provide our earliest epoch of glacier surface information. Stereo- paired images covering the selected glacier areas were purchased from the Peruvian Geographical service, Instituto Geografico Nacional in Lima, Peru (also in Figure 1). Multispectral ASTER imagery (background mosaic image in Figure 1) and derived DEMs spanning 2001 – 2008 were used for the calculation of the surface area changes and the total volume loss. All the ASTER images and DEMs were provided from LP DAAC (The Land Processes Distributed Active Archive Center) in Sioux Fall, SD.

Airborne LiDAR data covered 564 km^2 of targeted glacial and hydrological study areas in the Cordillera Blanca. LiDAR DEMs were extracted from the high density LiDAR surface elevations in LAS format to recreate the 2008 glacier surfaces.

Generating DEMs from aerial photography requires preliminary digitizing and orthorectification, which were accomplished using ERDAS Leica Photogrammetry Suite. Generating the DEM is challenging because of the high-relief mountain terrain, the old film used in the aerial photographs, a lack of camera information and difficulties in matching control points in snow and ice covered steep slope environments between stereo pairs of aerial photographs. Based on the aerial DEMs, an orthophoto was generated.

The glacier boundary of each image (1962 orthophoto and ASTER images) was extracted as a polygon using ArcGIS. These glacier polygons were used to calculate both glacier surface area and glacier volume changes in combination with the images and DEMs, respectively. Surface area change was calculated for the 1962 epoch and each year of six available ASTER images: 2001, 2002, 2004, 2005, 2007 and 2008. Volume changes were computed between 1962 and both the 2008 LiDAR DEM and select ASTER DEMs (2001, 2005, 2007 and 2008).

RESULTS AND DISCUSSION

Glacier surface area and volume changes

Calculated surface area and volume changes are displayed in Table 1. The Yanamarey glacier shows dramatic glacier shrinkage over the 46 years. Specific glacier surface areas are 1.155 km^2 in 1962, 0.671 km^2 in 2001, 0.547 km^2 in 2002, 0.474 km^2 in 2004, 0.347 km^2 in 2005, 0.259 km^2 in 2007 and 0.165 km^2 in 2008. These results show that the Yanamarey glacier lost about 85% of its total surface area between 1962 and 2008. The glacier recession accelerated during more recent spans of years 2005-2007 and 2007-2008. On average, the glacier surface lowered 144 m over the 46 years. At this rate of volume loss, the Yanamarey glacier may disappear within a decade.

Table 1 The results of the changes of surface area and volume in Yanamarey glacier

Data Source	Year	Area (km^2)	Year diff	dA(km^2)	Year diff	dV (km^3)
Aerialphoto	1962	1.155				
ASTER	2001	0.671	1962-2001	0.484		
ASTER	2002	0.547	2001-2002	0.124		
ASTER	2004	0.474	2002-2004	0.732		
ASTER	2005	0.347	2004-2005	0.127	1962-2008L	0.123
ASTER	2007	0.259	2005-2007	0.882	2001-2005	0.013
ASTER	2008	0.165	2007-2008	0.939	2001-2007	0.011
LiDAR	2008	-			2001-2008	0.014

Year diff: year difference between images; dA: surface area difference; dV: volume difference; L: LiDAR

Surface area and volume scaling

Figure 2 plots the change in surface area versus the change in volume calculated between: 1962 and the 2008 LiDAR DEM, 2001 and 2005, 2001 and 2007, 2001 and 2008, 2005 and 2007, and 2007 and 2008 from ASTER DEMs, respectively. Calculated glacier volume differences were 0.123 km^3 (1962-2008), 0.013 km^3 (2001-2005), 0.011 km^3 (2001-2007), 0.014 km^3 (2001-2008). Several authors (Chen and Ohmura, 1990; Bahr *et al*. 1997) have shown that the volume of mountain glaciers is either proportional or exponential to the surface area. Here, the change in surface area and the change in volume shows very similar pattern to the relationship of surface area and volume shown in Chen and Ohmura (1990). Using remotely sensed data to quantify glacier mass changes over time in remote, high elevation tropical mountains has great potential but also faces uncertainties in volume scaling and interpreting climatic forcing given complexities of topography. Further investigation is required to explain the scaling of surface area to volume relationship in tropical glaciers in Cordillera Blanca, Peru.

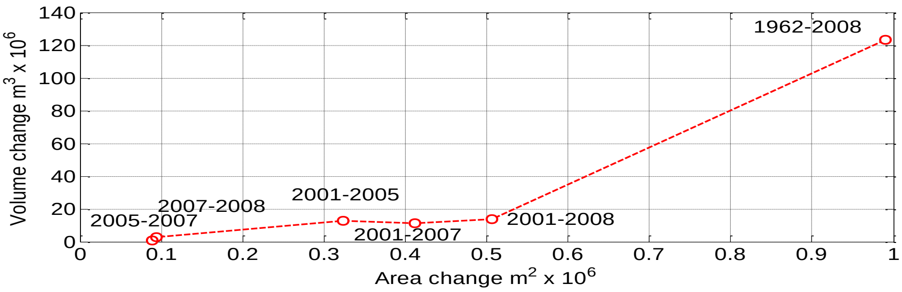

Figure 2 The relationship of surface area changes and volume changes

CONCLUSION

This study represents the first effort to integrate high-resolution airborne LiDAR technology, satellite remote sensing and geospatial analysis to investigate the volume and spatial nature of late-glacial and modern tropical glacier recession over the world's largest concentration of tropical glaciers. This research will answer the important research question of what changes are occurring in the mass of the Earth's tropical glaciers in response to climatic variables and energy flux in tropics. Furthermore, the high accuracy mapping of glacier surface elevations allow for volume changes to be directly measured allowing for explicit testing and refining of scaling relationships between changes in glacier surface area and volume changes that is necessary for inventorying remaining glacier mass with remote imagery.

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