

# Andean Tropical Glacier Extent from Landsat Imagery

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## Abstract

Current concerns of climate change have led to an increased recognition of the importance of monitoring glaciers throughout the world. Satellite image analysis is a valuable tool in monitoring glacial change. This study examines the recession of tropical Andean glaciers in Bolivia, comparing recent LANDSAT-5 Thematic Mapper (TM) data with historic maps produced by Ekkehard Jordan, compiled during the mid 1970s. Utilizing Geographic Information Systems, the physical maps were digitized into a layer that identifies specific glacier areas. This layer was then compared to previously satellite-based aggregated results of the primary tropical Andean glaciers extents for two dates: ~1986 and ~2006. Further analysis was used to determine total area of glacier change.

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## I. Introduction

Lush tropical forests and warm temperatures are what most people think of the tropics. However, what many do not realize is that the tropics can also contain the opposite of that impression. Tropical glaciers may sound like a nonexistent oxymoron but they are actually present near equatorial areas. The Andes Mountain range is the longest mountain range in the world and holds many mountain glaciers in its high latitudes. These glaciers are not only a key indicator to climate change but provide fresh water for many ecosystems as well as indigenous populations near the Andes Mountains. According to the *National Snow and Ice Data Center* (NSIDC), “currently 10% of land area is covered with glaciers and those glaciers store about 75% of the worlds freshwater<sup>2</sup>” (NSIDC, 2010). They are complex and important in studying climate variation. By recording and monitoring glacier activity, researchers can get an enhanced understanding of regional and global change as well as expose past climate histories.

Due to the current concern that climate change is becoming a more urgent problem, more research is needed to determine what is actually occurring. Thus, my research is on Andean tropical glaciers and their recession in area extent. Specifically focusing on the Bolivian Andes, my work involves comparing ~1975 physical maps of three different mountain ranges with current LANDSAT-5 TM Images. The mountain ranges in question are the Cordillera Apolobamba, Cordillera Real, and Cordillera Tres Cruces (Quimsa Cruz). The goal is determine the amount of melt within specific glaciers and overall mountain ranges between the ~1975 to

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<sup>2</sup> National Snow and Ice Data Center (NSIDC). (2010). *All About Glaciers*. Retrieved on July 20, 2010 from <http://nsidc.org/glaciers/quickfacts.html>

~1986 and the ~1975 to ~2006 using ArcGIS.

## II. Data and Methods

### E. Jordan Maps

The project contained an array of data sources and materials. The baseline dataset was generated from detailed physical maps of Bolivian glaciers created by German researcher Ekkehard Jordan. In 1975, Jordan created a “comprehensive glacial hydrology program with support on the German side from the Geographical Institute of the Technical University, Hannover, and the Kreidlerwerke,

Kornwestheim, and on the Bolivian side, from UMSA La Paz and the Servicio Geológico de Bolivia (GEOBOL)”<sup>3</sup> (Jordan et al., 1978).

Jordan produced comprehensive maps by collecting aerial photographs over three cordilleras- Apolobamba, Real, and Tres Cruces.

In addition, he used aerotriangulation (process of assigning ground control values to points on a block of photographs) as well as graphical and numerical evaluation using a Zeiss-Stereocord instrument (analytical plotting instrument)<sup>4</sup> (Schubert, 1991). These maps outline glacial area extent for specific glaciers as well as elevations, moraines, lakes, rivers, steep rocks,

and ridge lines. Each glacier, colored in blue, was assigned their own identification number and was outlined with a thick black line, indicating glaciers, or a dotted line, indicating snow patches that have lasted for several years. There are a total of 23 maps (including a legend and an aerial photograph). Out of the total maps, 13 were used and compatible with this analysis. There was one map for Cordillera Tres Cruces (Map 16), three maps for the Cordillera Apolobamba (Map 4, Map 5, and Map 6), and nine maps for the Cordillera Real (Map 7, Map 8, Map 9, Map 10, Map 11, Map 12, Map 13, Map 14, and Map 15).

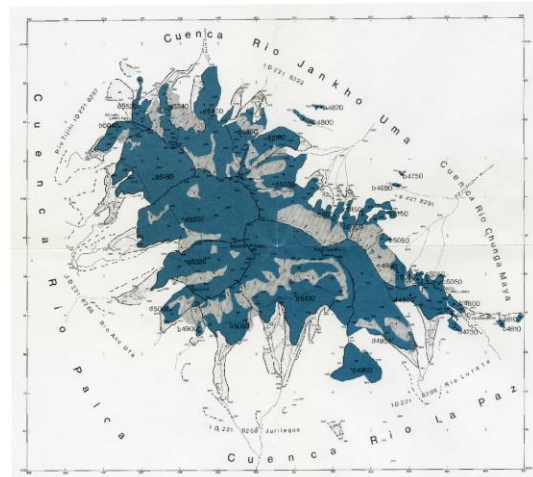


Figure 1. E. Jordan Map of Mt. Illimani (16.39°S 67.48°W) in the Cordillera Real, Bolivia.

The physical maps were converted into a digital format and geo-referenced to match other datasets such as LANDSAT-5 TM images. In order to accomplish this objective, they needed to be scanned each into a TIFF file. However, the scanner that was provided was not sufficient in size. To fix this problem, the maps were sent out to *Kinko's* to be scanned on a larger scanner. The maps were all created into TIFF files and set to 300 dpi. Once the maps were uploaded into

<sup>3</sup> Jordan, E. et al. (1978). World Glacier Inventory — Inventaire mondial des Glaciers. *The Glacier Inventory of Bolivia*. IAHS-AISH Publ. no. 126. Retrieved from: [http://www.itia.ntua.gr/hsj/redbooks/126/iahs\\_126\\_0025.pdf](http://www.itia.ntua.gr/hsj/redbooks/126/iahs_126_0025.pdf)

<sup>4</sup> Schubert, Carlos. (1991) *Book Review: Die Gletscher der bolivianischen Anden*. Journal of South American Earth Sciences. Vol. 4. No. 4, p. 383

the computer, the main glacial areas were sectioned-out of the maps and added into the ArcGIS ArcMap program.

In this program, the scanned images were georeference to their correct spatial region. This was important because the LANDSAT-5 TM images and the scanned maps needed to line up over their corresponding geographic locations. Georeferencing the scanned maps was possible because the physical maps contained UTM coordinates that connected to the spatially correct UTM coordinates using the georeference tool within ArcMap. After connecting 10 to 15 UTM coordinates, the images were then rectified into the correct spatial area. All scanned maps were set with a Projected Coordinate System of WGS\_1984\_UTM\_Zone\_19S and a Geographic Coordinate System of GCS\_WGS\_1984.

### ***Digitization and Data Entry***

After the physical maps were loaded into the program, the next step was to manually create polygon shapefiles, which would be used to represent the glacier areas of the maps. Once

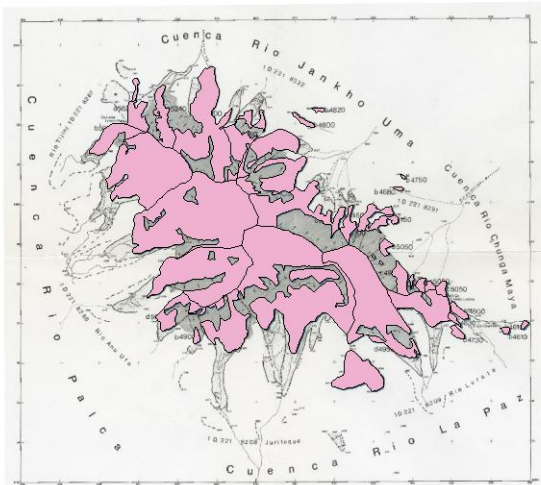


Figure 2. Pink indicates the digitized area of Mt. Illimani (16.39°S 67.48°W) in the Cordillera Real, Bolivia.

created, the polygons would digitally represent specific glaciers that have been defined mostly by mountain ridges. Furthermore, this would allow the insertion of specific data corresponding to that specific polygon or glacier. This was done by creating a polygon shapefile in ArcCatalog and assigning the file the same coordinate systems as the scanned images. Then it was imported into ArcMap with the scanned image. From there, the Editor Tool was used to digitize features or create glacier polygons. The Editor Tool was traced over the outline of the glaciers by connecting points together. The Snapping setting was used so that the vertexes or points created would correctly line up with neighboring points. By double clicking, the

program created an individual polygon in the shape of the glacier traced (*Figure 2*). On average each map contained about 250 polygons defined for glaciers. This does not include digitized lakes, rivers, moraines, and steep rock areas. For rivers, a line shapefile was created with the same coordinate information as the scanned images. This procedure was repeated with all the maps. Please note that remote sensing software could not be used to classify the image because the map quality was too poor to be processed.

I continued to create multiple glacial polygons within the shapefile as well as record the specific glacial information to each polygon within the Attributes Table of the shapefile. The information recorded was as follows:

*Glacier Id*

*Sub Id*

*Elevation:* at gravity-center of glaciers

*Surface Area*

*Type:* indicating a glacier or snow lasting several years

*Feature:* Glacier, Moraine, Steep Rock, Lake

*Notes:* indicating problems or names indicated on the Maps

*X Shift:* distance shifted from original Map on x-axis

*Y Shift:* distance shifted from original Map on y-axis

*Map Id:* Map Number

### LANDSAT-5 Thematic Mapper (TM) Data

After completing the digitization, four LANDSAT-5 Thematic Mapper (TM) scenes were obtained from Dr. Daniel Slayback, covering Apolobamba, Real, Tres Cruces, and Munecas (province containing Lake Titicaca). Each scene was set to a 7, 4, 2 band composite, so that the images would maintain a "natural-like" composite as well as penetrate atmospheric particles and smoke. This combination also made the ice and snow turn a light blue color, which made it easy to validate the digitized glacier correct location (*Figure 3*). The Apolobamba scene (top scene) is a 30 meter by 30 meter cellsize taken on July 12, 2006 (path2 row70). The Real scene (middle right scene) is a 30 meter by 30 meter cellsize taken on July 21, 2006 (path1 row71). The Tres Cruces scene (bottom scene) is a 28.5 meter by 28.5 meter cellsize taken on July 1, 2007 (path 233 row72). Lastly, the Munecas scene (middle left scene) is a 30 meter by 30 meter cellsize taken on August 3, 1985 (path2 row71). These scenes were used to further help validate glacial areas and extents with the digitized glaciers.

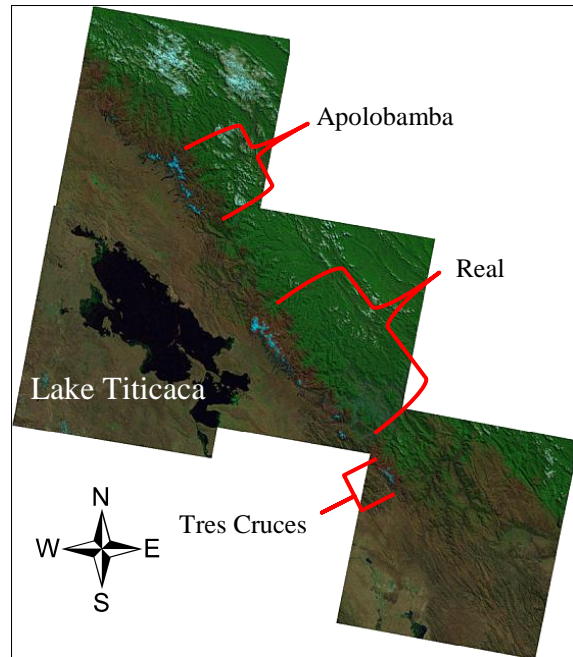


Figure 3. LANDSAT-5 Thematic Mapper (TM) mosaic of analyzed regions.

The digitized glaciers were compared to the LANDSAT-5 Thematic Mapper (TM) aggregated results, previously compiled by Dr. Daniel Slayback. Unfortunately, there are errors in the Apolobamba results and could not be analyzed in this research.

### III. Analysis and Results

Once the digitization was completed on all the maps, a comparison was made between the ~1975 area extents and a GeoTIFF satellite-based aggregated image, previously compiled by Dr. Daniel Slayback, from ~1986 and ~2006.

Table 1. GeoTIFF Satellite-Based Aggregated Image Index

1: Non-Glacier for either ~1986 and ~2006
2: Water or Shadow
3: Unchanged Glacier in both ~1986 and ~2006
4: Glacier Melt in ~1986, not in ~2006
5: New Glacier in ~2006 (non-glacier in 1986)

To begin, there needed to be a conversion of the GeoTIFF results (raster) into features using the Spatial Analyst tool. Then it was able to select an individual section out of the image. These sections are given in *Table 1*. From here, values 3 and 4 were selected out to give the total area of the all glaciers in ~1986. Then by

merging all the attributes together, a solid polygon was created. This is important because comparing the digitized glaciers with multiple polygons would cut the polygons into smaller sections that will be assigned duplicate information. Then the ArcGIS Symmetrical Difference analysis tool was applied to compute the geometric intersection of the digitized glaciers, and the sectioned-off GeoTIFF. The program extracts the area wherever intersections occur. When this takes place, the area of difference, or melt, is left from ~1975 to ~1986. Repeating this process with only value 4 sectioned-off gives the area difference, or melt, from ~1975 to ~2006. Further use of the ArcGIS Symmetrical Difference analysis tool was used to extract the area of error occurred. The error was based on differences between the GeoTIFF results and E. Jordan maps. The area was then calculated using the geometry calculation tool that provided the overall area of difference, or melt, for each digitized polygon or glacier. *Figures 4 and 5* show the sections of melt as well as year range in the Cordillera Real Illimani Mountain area (Map 15).

Map of Mt. Illimani in the Cordillera Real, Bolivia  
16.39°S 67.48°W

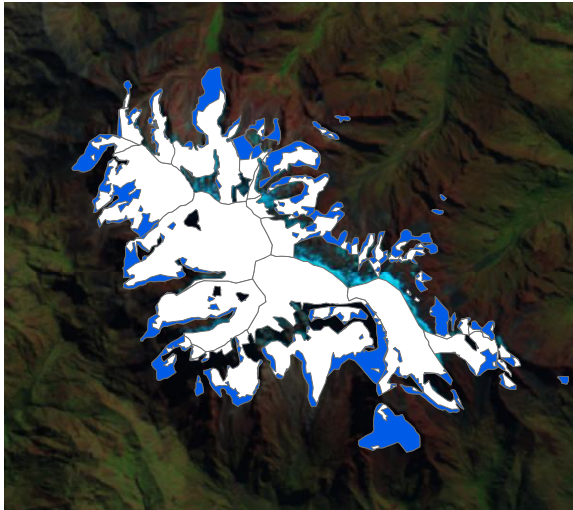


Figure 4. Blue represents the area of Melt that occurred from ~1975 to ~1986. The area of glacier loss was 24.8890% since ~1975.

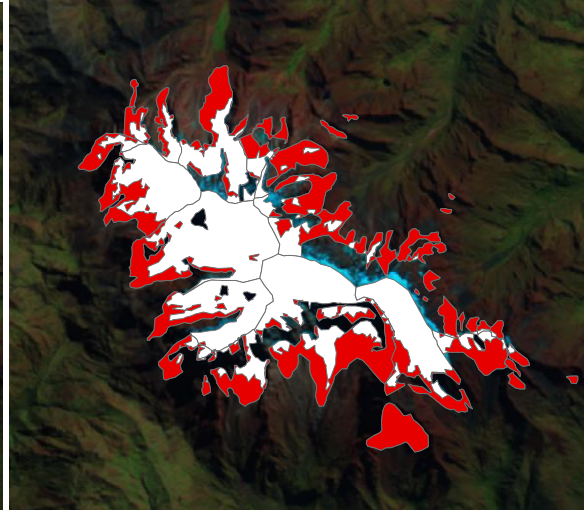


Figure 5. Red represents the area of Melt that occurred from ~1975 to ~2006. The area of glacier loss was 43.5346% since ~1975.

Table 2. Total Melt Area

<u>Glacial Range</u>	<u>Year (s)</u>	<u>Total Area (km)</u>	<u>Percent Glacial Loss</u>
<u>Cordillera Real</u>	1975	321.0814	N/A
	1975 - 1986	269.5551	16.0478%
	1986 - 2006	195.0817	23.1945%
	Total glacial loss from 1975 to 2006	125.9997	39.2423%
<u>Cordillera Tres Cruces</u>	1975	48.1245	N/A
	1975 - 1986	35.7168	25.7826%
	1986 - 2006	28.3962	15.2118%
	Total glacial loss from 1975 to 2006	19.7283	40.9944%

After calculating the total area loss in the Cordillera Real and Cordillera Tres Cruces, the percentage of melt was calculated. *Tables 2* contains the total melt areas (km) and melt percentages for both mountain ranges.

#### IV. Error

This research was not without its challenges. A few errors occurred during the process of the geo-referencing and analysis. Also, complications arose when recording the information from the physical maps produced by E. Jordan. The Cordillera Apolobamba research analysis is being re-evaluated and will be included in future analysis.

##### *Georeferencing Error*

As stated, all scanned maps and digitized glaciers were set with a Projected Coordinate System of WGS\_1984\_UTM\_Zone\_19S and a Geographic Coordinate System of GCS\_WGS\_1984. However, even with every map in the same coordinate system, the glaciers were not lining up over the glaciers of the LANDSAT-5 Thematic Mapper (TM) scenes. So many coordinate systems and methods were implemented to try and line up the glaciers. In the end, physically manual relocation was performed on the digitized images over their corresponding glaciers. To get the correct location, geographical features were used to reference the maps to make sure all features were overlaying in their proper location. These features were mountain ridge lines and lakes.

##### *Map and LANDSAT Image Error*

The maps by E. Jordan produced questions about the glacier identification method. On a given map, there would be two to four duplications in glacier ids. To specifically identify each individual glacier, a Sub- Id field was added to give each duplicate id a defining alphabetical letter. In addition, there were glacier ids on the map that were not given a defined boundary or color. For each glacier id and for those that were not given a defined boundary or color, they were marked as undefined.

Another error in the research was that the LANDSAT-5 Thematic Mapper (TM) scenes showed glaciers and the physical E. Jordan's maps did not. This could be human error or an error in the process taken in identifying glaciers in the LANDSAT-5 Thematic Mapper (TM) scenes. Either way, the error was accounted for by sectioning-off the error area by performing another Symmetrical Difference analysis on the finish results. By comparing the finished results with the original satellite-based

aggregated results, the error area was able to be a separate shapefile and calculated. *Table 3* shows the amount of error area in the two analyzed mountain ranges.

*Table 3. LANDSAT and Map Error*

<u>Glacial Range</u>	<u>Year Range</u>	<u>Error Area (km)</u>
<u>Cordillera Real</u>	1975 to 1986	22.2840
	1975 to 2006	8.0946
<u>Cordillera Tres Cruces</u>	1975 to 1986	2.5571
	1975 to 2006	1.9490

## V. Conclusions

This research has led to a better understanding of the impacts of climate change on Andean tropical mountain glaciers in Bolivia. Specifically, the results of this research show that both the Cordillera Real glacier range and the Cordillera Tres Cruces glacier range have undergone a reduction in total glacier area by about 40 percent from ~1975 to ~2006. Future analysis will be conducted on the Cordillera Apolobamba, as well as on more recent Landsat images.

## Acknowledgments

Throughout this project, I have received great support and encouragement from the entire staff of the Hydrospheric and Biospheric Science Laboratory and would like to express my deepest gratitude for the welcome I have received. I would like to recognize my mentors Dr. Daniel Slayback and Dr. Karina Yager, who have aided and supported me throughout this project. I hold them in the utmost respect and thank them for their unfailing belief in the importance of this project as well as in myself.

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