Semi-automated reconstruction of glacier extent in the Cordillera Blanca, Peru (1989 – 2007) using ArcMap

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Abstract

Glaciers are known to be very sensitive when climate changes. The variability in temperature and precipitation has a great effect on the position of the glaciers in the past. With the data of images of 1989, 1991, 1999 and 2007 a classification as well a reconstruction of the past position is made. A methodology, based on a semi-automated classification, has been made within ArcMap (figure 1a) . And a three dimensional view of the final product is created in ArcScene (figure 1b). With different tools in ArcMap, a reconstruction has made of the former position of the glaciers in four different years whereby the DEM is used as background. A fully automated classification model was not possible since there were a few fault classified patches. But the final product (figure 1a) was mainly automated and properly created
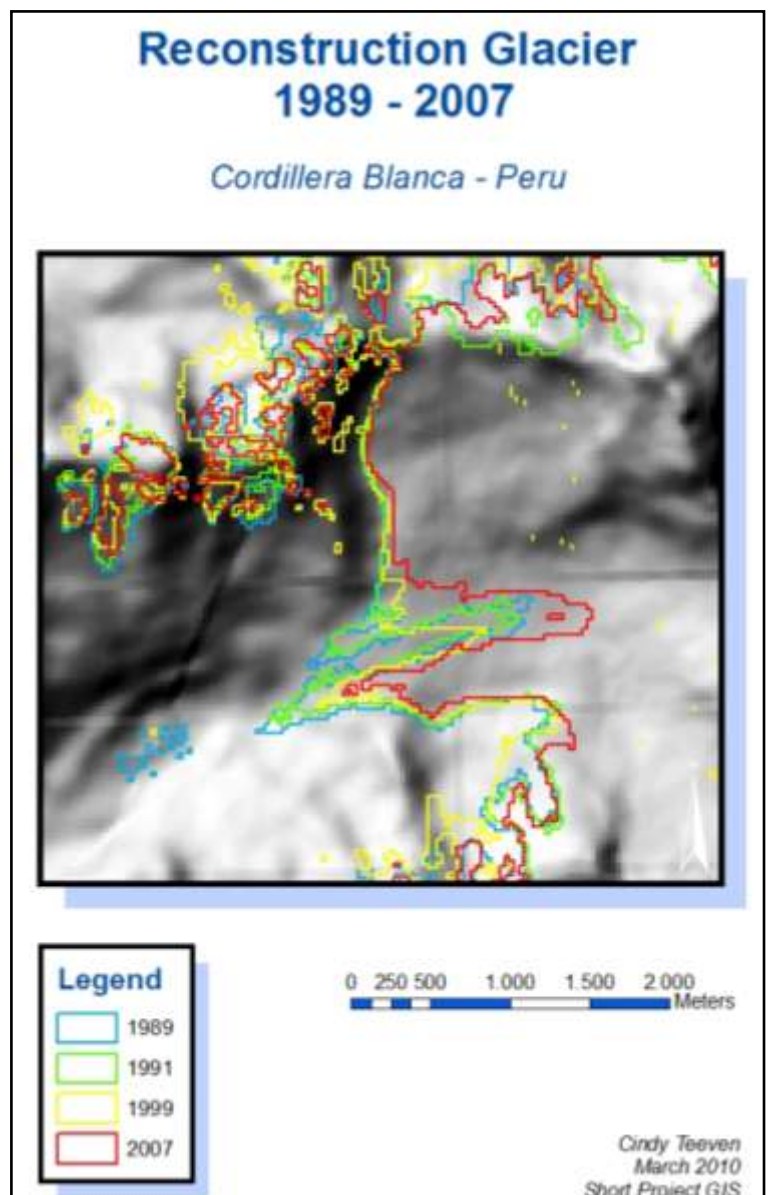
Figure 1: reconstruction of the glacier of 4 year with a DEM clipped on the Study Field of the Cordillera Blanca

Introduction

Many earth surface processes are affected when climate changes. Glaciers are the most visual indicators when climate variables like temperature and humidity are changing (Vuille et al., 2008). Traces of advance and retreat document the position of the glacier in the past. As a consequence of projected climate change glaciers may retreat or advance. Therefore it is important to investigate the behaviour of the glaciers. The two main objectives for this project are:

1. To reconstruct the position of the glacier from Landsat-7 satellite images of 1989, 1991, 1999, 2000 and 2007 and
2. To determine the loss of ice surface (m^2) over these periods

Only the snow covered area is taken into account. Also a maximum is set for cloud cover, since clouds prevent an accurate reconstruction of the glaciers.
Three research questions have been formulated to meet the objectives:

1. *Which methods and tools have been used for identifying the glaciated area?*
2. *What is the best way of projecting the glacier in 3D with ArcScene?*
3. *Which problems occur during the project and what were the solutions?*

This glacier reconstruction will be fully automated for it is not the intention to determine and digitize the outlines of the glaciers manually. Therefore a GIS-based model will be designed which can be applied to other areas.

Location

The tropical glaciers in Peru in the Cordillera Blanca are situated in the Andes in the north-western part of South-America (Map 1). Glaciers here take up about a quarter of the mountain range (Kaser et al., 2003). According to Mark and Seltzer (2005), the Cordillera Blanca of the Peruvian Andes has the greatest concentration tropical glaciers on earth. It is a region with large seasonal differences in precipitation, whereas the most precipitation falls during October till April, when the Inter Tropical Convergence Zone is located near the Cordillera Blanca. Ames et al. (1989, cited from Mark and Seltzer, 2005) show that the most numerous glaciers are orientated in southwest. The Equilibrium Line Altitude ELA is lower in the eastern part than in the western part of the mountain range as well as the precipitation. Most of this precipitation is orographically enforced.
Three main rivers drain into three different directions in the Pacific and Atlantic Ocean: the Santa River, Marañon River and the Pativilca River.

For identifying the snow, the full satellite image can be used. However due to false NDSI classification and long processing of the model of a large image, only a small part ('Study Field') was used for the final result.

Map 1: Cordillera Blanca in northwest Peru (GoogleEarth, 2009, GoogleMaps, 2010 and Kaser et al., 2003)

Data

From the Earth Sciece Data Inface (ESDI, 2010)[1] our TM Landsats-7 could be downloaded. The data has a resolution of 30 meters (cell size) with the coordinate system WGS_1984_UTM_Zone_18N. With the Map Search, the following photos were downloaded from path 8 and row 67 (Table 1):

Table 1: metadata for satellite imagery used

ID Number ESDI	Acquisition Date
032-368	30-12-1989
032-369	15-09-1991
207-014	18-12-1999
221-600	22-05-2007

The DEM was downloaded from the site of NASA[2] (2010). The data also has the coordinate system of WGS_1984_UTM_Zone_18N but a slightly different cell size: 30.3 meters.

Table 3 represents a shorten work flow of the method with ArcMap. The paragraphs 1 to 4 in the table are also written in the following method description.
The following files in table 2 are used in the model for glacier reconstruction:

Table 2: required datafiles for the model of glacier reconstruction

	File Name	File Type
Original	p008r67_5t19891230_nn5	Tiff/Raster Dataset
	p008r67_5t19891230_nn4	Tiff/Raster Dataset
	p008r67_5t19910915_nn5	Tiff/Raster Dataset
	p008r67_5t19910915_nn4	Tiff/Raster Dataset
	L5008067_06719990601_B50	Tiff/Raster Dataset
	L5008067_06719990601_B40	Tiff/Raster Dataset
	L5008067_06720070522_B50	Tiff/Raster Dataset
	L5008067_06720070522_B40	Tiff/Raster Dataset
Self Created	Study_Field	Polygon/Shapefile
	1999_Bypass_Polygon	Polygon/Shapefile
Adjusted	Polygon 1999_Adjust	Polygon/Shapefile
	All_Years_Adjust	Polygon/Shapefile
	Mosaic_Clip_ProjectR	Img/Raster Dataset

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[1] *http://glcfapp.glcf.umd.edu:8080/esdi/index.jsp*
[2] *https://wist.echo.nasa.gov/api/*

Method

1. Identifying snow cover

| 7 .tif bands 30-12-1989 | 7 .tif bands 15-09-1991 | 7 .tif bands 18-12-1999 | 7 .tif bands 22-05-2007 |

Composite
band sequence 5,4,2
4 composites

: Tool from ArcMap

: Out or input for a tool

2. Classifying snow cover

Reclassify
Glaciated and non-glaciated - Break values → Ratio

Study Field *Shapefile* → **Clip**

3. Changing steep dark patches

Select layer by attribute
Query Builder → **Eliminate** *Convert dark patches* → Shapefiles of all years

Append *Combines shapefiles of all years*

4. Projecting into ArcScene

Separate DEM of region → **Append** *Combines shapefiles of all years*

Study Field *Shapefile* → **Clip**

Convert to Raster

Table 3: Short schematic method flow in ArcGIS

1. Identifying the snow coverage (figure 2)

1.1   Each of the 7 Landsat bands were downloaded separately from the ESDI site.

1.2   With 'layer stack' in ERDAS and 'composite bands' in ArcMap different bands were combined into a false color composite image. Dependent on the sequence in which the bands could be set, different features can be detected. In a composite of TM band 5, 4 and 2 (figure 2) glacier area appears to be bright and bluish (Hall et al., 1988 and Paul et al., 2002).
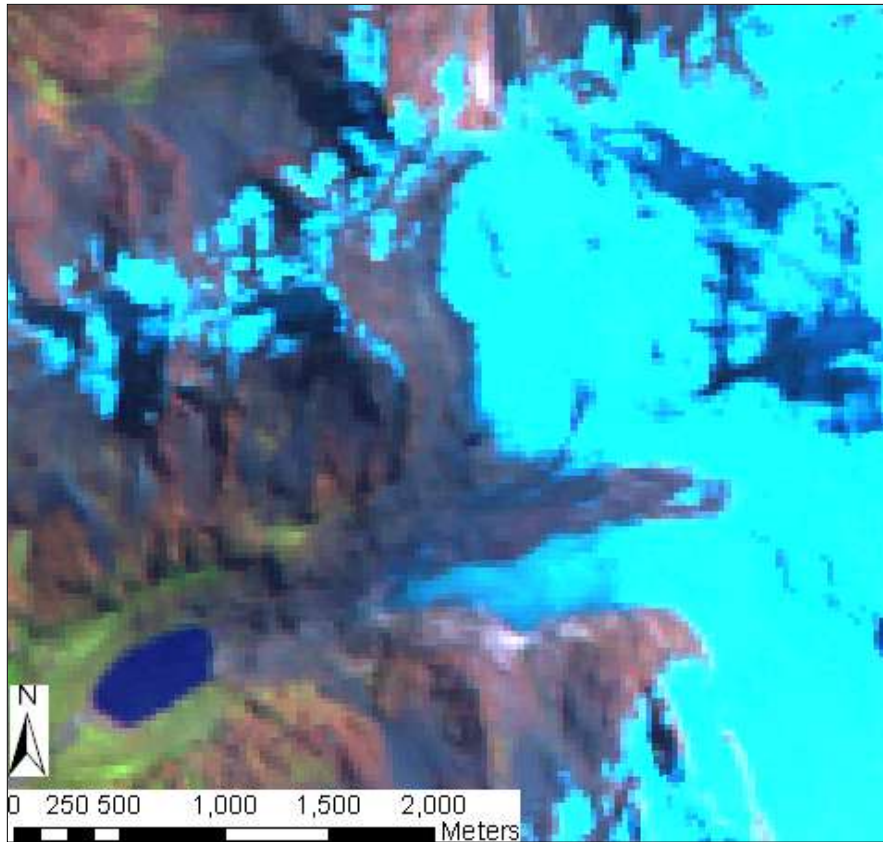

Figure 2: the bright blue glaciated area with the band composite 5, 4 and 2

1.3   To identify the visible snow coverage on the composition of the band, a ratio is used. According to Yavaşli and Ölgen (2008) and Hall et al. (1988), the *TM4/TM5* ratio is used for delineating glaciers and was applied for change detection. Clouds can also be ignored using this technique. The clouds are not very well reflected in the TM 4 band (0.76-0.90 μm) and are therefore distinguished from the snow. By using the 'Single Output Map Algebra', this expression was calculated.

Issue 1.1   Two different Normalized Difference Snow Indices (NDSIs) were calculated before the above mentioned ratio turned out to be correct:

NDSI = [TM4 – TM6] / [TM4 + TM6]   (Lui et al., 2008)

NDSI = [TM2 – TM5] / [TM2 + TM5]   (Silverio and Jaquet, 2005)

The two above mentioned calculations determined the NDSI using ratios of digital numbers of the two TM band. Both indices gave incorrect results. For example, water bodies were also included in the classification of ice. By using the Normalized Difference Vegetation Index (NDVI), water bodies were automatically detected. But using the VI, vegetation was also detected so the results were inconclusive. The formula of Lui et al. (2008) did not work either, since it was created for MODIS data which were not used in this project.

Issue 1.2   The NDSI was applied both in ERDAS and ArcMap. Because of the different resulting values, it can be expected that the output has a stretched value. This was correct when calculating with ERDAS. In ArcMap, the output is and integer with 0, -1 and 1. This has probably to do with the different operation of the programs, whereby ERDAS might calculate with reflectance and ArcMap not. Because the glacier coverage is detected very well (also with ArcMap), it will not be further discussed. This was another reason for not using the NDSI.

Issue 1.3   As a result of the steep slopes angles, several patches appear very dark on the Landsat. These dark patches are caused by the shadow of the steep patches and also the moraine covered ice in the glaciers. Therefore the ratio does not classify these patches as glacier. This point will be discussed hereafter.

2. Classifying the snow coverage (figure 4a)

2.1   The output of the 'Single Output Map Algebra' had different values. Only two values are necessary: glaciated or non-glaciated area. Therefore the ratio values have been reclassified.

2.2   Different images had a different range of ratio values. Therefore different break values were necessary for correct glacier detection. The non-glaciated areas are 0 and the glaciated areas 1. With a break value class break and class ranges can be manually defines in the classification tool. The break values can vary each image since the ratio values differs. The glaciated area started with the break value in table 4:

Table 4: Break values for each image

Acquisition Date	Break Value
30-12-1989	>3
15-09-1991	>2
18-12-1999	>4
22-05-2007	>3

2.3   Calculating, adapting and visualizing areas works better with a polygon shapefile, the raster is converted to polygon. It is important to uncheck the 'simplify polygon' box otherwise the output is inaccurate.

2.4   Hereafter a 'mask' shapefile 'Study Field' (9°27'50''S - 9°30'0''S to 77°21'50''W - 77°19'30''W) has been created. The 'Clip' tool was used to reduce the polygon and the Landsat to approximately 16 km^2.

Issue 2.1   It is important to use the appropriate clip function in ArcMap. The tool is available as a Data Management Tool and Analysis Tool. The clip function in Data Management Tool is used for raster data while the clip function of the Analysis Tool is also used for shapefiles. Therefore the clip function of the Analysis Tool has been used.

Issue 2.2   The steep dark glaciated patches were not classified as glaciated area (figure 3). It is difficult to implement this error into the expression of the ratio; therefore another method has been used to get around this problem and will be discussed later.
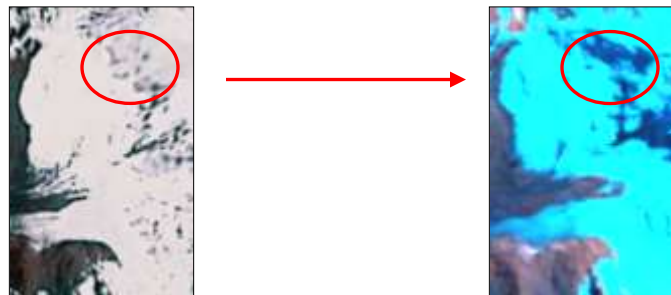

Figure 3: incorrect classification of steep dark patches (left: GoogleEarth, 2009, right ArcMap)

3. Changing steep dark patches into glaciated area (figure 4b)

3.1   The dark patches will be merged with neighboring polygons (the glaciated area) with the 'Eliminate' tool, if they have the largest shared border or the largest shared area. As a result the glaciated polygon is much bigger than the incorrectly classified area (except for the image of 1999), this tool works perfectly.

3.2   Before using the 'Eliminate' tool, a selection of polygons has to be made, otherwise the tool does not work. This can be solved by using 'Select layer by Attribute'. The Query Builder within this tool is for selecting the correct values (here: the steep dark patches). In this case the 'Gridcode 0' stands for non-glaciated area. The 'ID' is used for selecting the correct polygon. The ID of the right polygon is extracted from the 'Get Unique Value' button out of the Query Table (within the tool).

3.3   The polygons of the steep dark patches are adjusted from value 0 to value 1 (glaciated area). To create one polygon out of different polygons with the same value, 'dissolve' can be used. It is important to check the field 'GRIDCODE', which contains the 0 and 1 values.

3.4   The tool 'Append' is used combine all the separate shapefiles with the polygons of different years (the pink part in figure 4b). This is very useful for projecting the output into an ArcScene project. The 'Polygon to Raster' was used because a raster can be better displayed in ArcScene since the shapefile contains a few indefinable errors which affected the 3D visualization.

Issue 3.1   The 'Eliminate' tool did not work on the shapefile of 1999 because the polygons of the black patches were bigger than the polygons of the glaciated area. Therefore step 3.3 and 3.4 were used for the small polygons (here: the small steep patches), but a shapefile 'Bypass Polygon' was used for elimination of the large part (figure 5b,). The 'Bypass Polygon' is a shapefile with a manually created polygon of the black area which has to be glaciated. With the 'Merge' tool the polygon was implemented and again 'Dissolve' was used for creating one polygon (the red part in figure 5b).

4. Projecting into ArcScene (figure 5c)

4.1   The best available DEM were downloaded from the NASA website. One DEM was assembled using the 'Mosaic' tool since several DEM were tiles. After mosaicing, the 'Study Field' was selected with the 'Clip' tool.

4.2   The base height was set to the DEM layer, as well for the raster-file with all the year of the glacier reconstructions. This resulted into a 3D visualization of the glacier reconstructions of all years (figure 5).

Issue 4.1   The DEM of the NASA-website was not fully filled with data. The sea area had a value of 0. Therefore the height of the sea compared with the mountain range was not correct. When the base-height was set, a great difference in values between sea and land appeared so the true relief was not visible. The difference between the high values of land and low values of the sea were not in proportion. To avoid

this error, the DEM was clipped on 'Study-Field'. The clipped DEM had no voids (zero values) and therefore a good base height could be formed in ArcScene.

Issue 4.2   One of the objectives of this project was to calculate the areal loss (m^2) of ice. This part of the project was not successful, because area calculation could not be accurately applied in this high mountain area. A different solution for calculating the area was not implemented in the time available.

Issue 4.3   It is necessary to convert the DEM of the study area and the rasterfile to the projected coordinate system WGS_1984_UTM_Zone_18N. The height is than in meters instead of degrees.

Issue 4.4   It was not possible to project lines into ArcScene because they did not fit perfectly on the DEM. As a result some parts of the position of the glacier has fallen out.
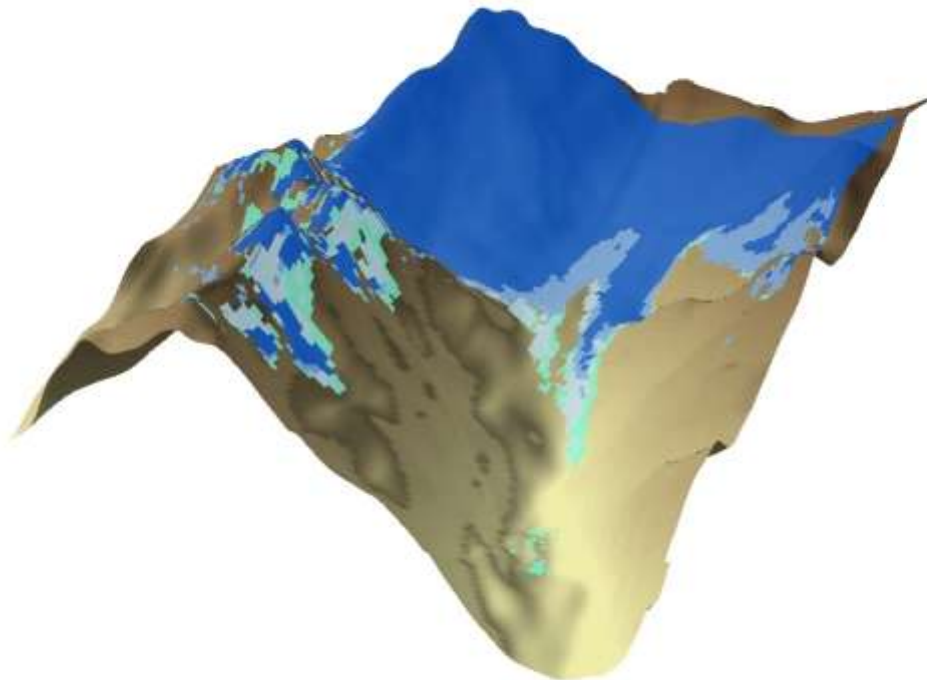

Figure 4: 3D visualization of the glacier reconstruction with ArcScene

Explanation on figure 5a, b and c

Figure 5a is represents a workflow for a model to calculate satellite image ratios and converting of the ratser output to vector output. The output of the model in figure 5a (for example Polygon_1989_Clip) is the input for the model in figure 5b (for example Polygon_1989).

Figure 5b shows part 3 of the method. The pink and red components of the model in the figure 5b are the files which have been adjusted since model misses some steps to a fully automated classification and has been made manually. Figure 5c shows part 5 of the method which is created in ArcScene.
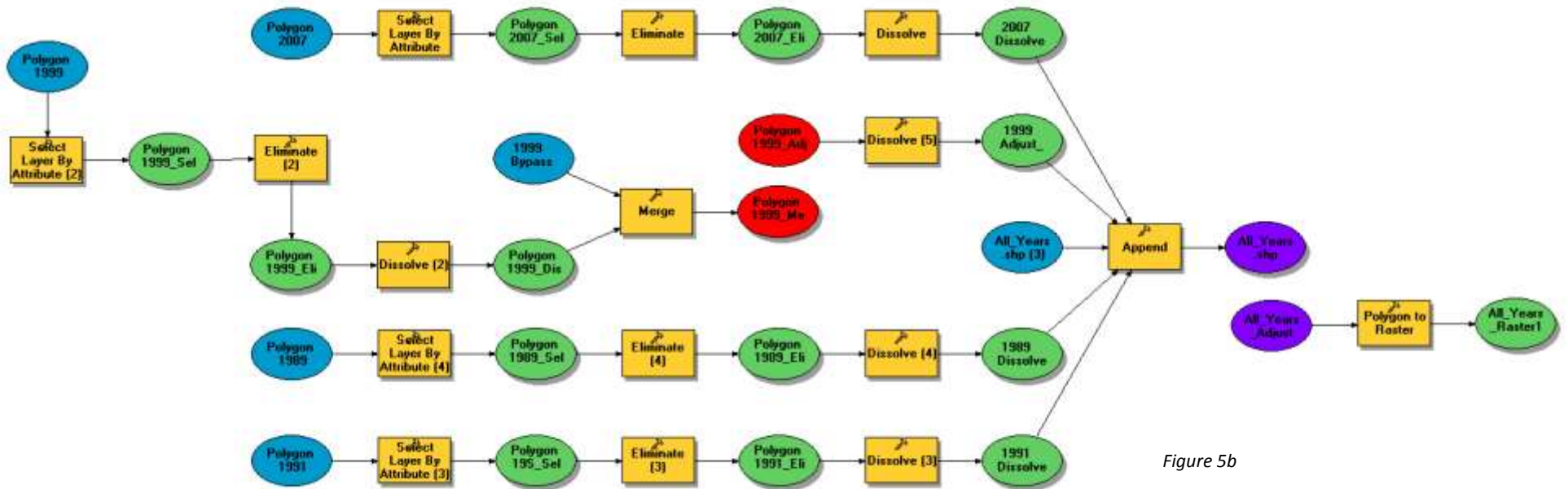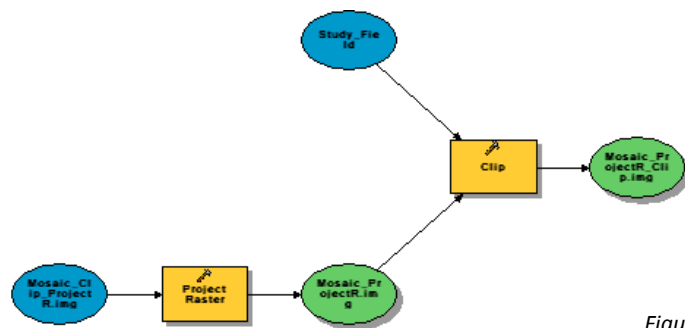
Figure 5a
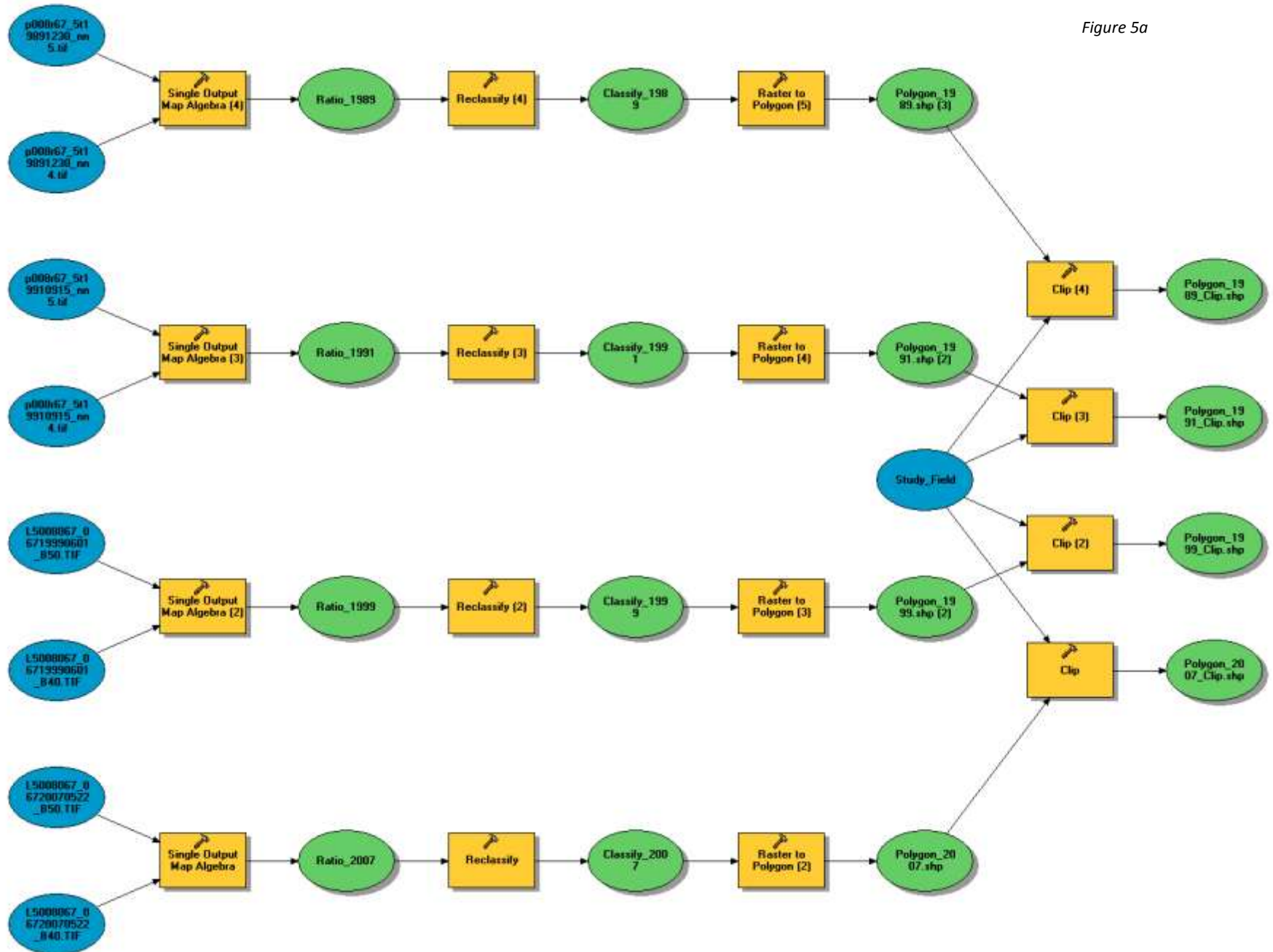
Figure 5b

Figure 5c

Conclusion

Which methods and tool have been used for identifying the glaciated area?
Firstly ArcMap was used instead of ERDAS for it was not compatible since the whole process had to be made with one program for the automated classification.
The tools 'Layer Stack' and 'composite bands' were used for combined the different TM-bands. The formula TM4/TM5 was very usable for delineating glaciers and exclude the clouds. Break values had to be set since the ratio must converted into two values: glaciated and non-glaciated area. Consequently not every image had the same border value for glaciated area since not every TM-image is the same. Therefore different break values in the 'Reclassify' tool were set. This was verify with the position of the glacier on the images. Thereafter 'Eliminate' classified the dark patches into glacier. At last the tool 'Append' was used for put together all the separate shapefiles.

What is the best way to project the glacier in 3D with ArcScene?
A DEM was downloaded from the NASA site and thereafter the Study Field was clipped out of the DEM. By setting the base height at one or two, a clear images was created from the glaciers in the Cordillera Blanca.

Which problems occur during the project and what were the solutions?
Other classification indices did not work since water bodies were classified as glacier too. The 'Eliminate' tool did not work on the shapefile of 1999 because the polygons of the black patches were bigger than the polygons of the glaciated area. Therefore a shapefile 'Bypass Polygon' was used for elimination of the large part. The 'Bypass Polygon' is a shapefile with a manually created polygon of the black area which has to be glaciated.

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