Landsat derived snowline variations in Nyainqêntanglha Mountains on the Tibetan plateau

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Abstract

The Nyainqêntanglha Mountains are located on the south-eastern part of the Tibetan Plateau. The Tibetan Plateau and surrounding contains the largest number of glaciers outside the polar region. These glaciers are highly sensitive to climate changes and most recent studies show shrinkage through the last few decades. These studies are mostly based on mass balance measurements or area calculations. In this study, the variations in snowlines are investigated at different locations and orientation of Nyainqêntanglha. Snowlines vary much throughout one year but are more constant over a fixed period in the year. This more constant snowline gives a rough approximation of the Equilibrium Line Altitude (ELA). When the ELA positive, accumulation is greater than ablation and vice-versa. For the classification of snow and ice and for the estimation of snowline heights, QGIS is used with input of available open source available datasets. Classification of snow is done with the Normalized-Difference Snow Index, which uses the high reflectivity of snow in the visible part of the EM spectrum and the highly absorptivity in the near-infrared/short-wave infrared part of the spectrum, to differentiate snow from other land covers.

Snowline variations between different months in the year 2001 only seem to occur between the wet and the dry season. In June the snowline is much lower than in the winter months, November or February. This wet season is caused by the South-East approaching Indian monsoon. The other results seem to indicate that through the years 2001 to 2013 the snowline has risen on the eastern side and has descended on the western side. Also, there's more snow present on a lower elevation in the northern area than in the southern. For these variations, no clear explanation is found. More research has to be done to be able to clarify the found results, for example in albedo differences, the Westerlies monsoon or the effect of precipitation or the sun on different orientations.

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Contents

1. Introduction

The Tibetan Plateau provides water for many major rivers (e.g. Ganges, Mekong, Yangtze, Indus, Huange He, Bramaputra). Glaciers contribute a lot to this water supply. The Tibetan Plateau and surrounding contains the largest number of glaciers outside the polar region (Yao et al, 2012). Glaciers on the Tibetan Plateau are highly sensitive to climate change. Because of the low accessibility of the glaciers on the Tibetan Plateau most research is based on glacier tongue observations or remote sensing techniques (Caidong et al, 2010).

The location of study is the more than 700 kilometer long Nyainqentanglha Mountain range on the Tibetan Plateau, figure 2. The highest peak is Mt Nyainqentanglha, which reaches 7162m. The Nyainqentanglha Mountains contain 7080 glaciers, with a total area of 10700km2, with two thirds of the glacier and five sixths the area lying in the eastern section. The region is interesting because of its position. The eastern section of Nyanqentanglha faces the approaching moist Indian monsoon, see figure 1. The terrain forces the air flow to rise, providing the region with the maximum precipitation and highest moisture on the plateau. This could enhance glacier development (Singh et al, 2011).

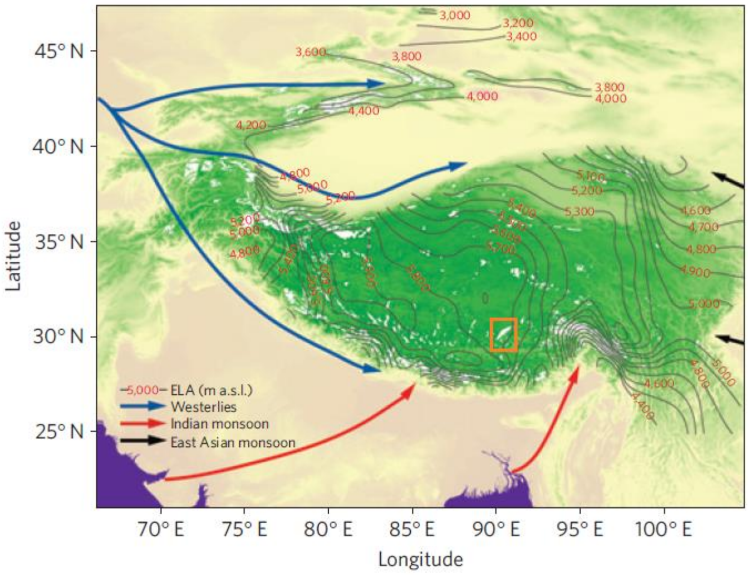


Figure 1: Distribution of glaciers in and around Tibetan Plateau, influenced by mainly the Indian Monsoon and westerlies and less influenced by the East Asian Monsoon. Nyainqentanglha Mountains is within the orange box (Yao et al, 2012).

Throughout the entire Tibetan plateau almost all glaciers receded during the last years, with some exceptions like Karakorum. The current glacier retreat on the Tibetan Plateau is reportedly due to a reduction of precipitation and increase of temperature. The eastern section has more effect of the heat of the sun than the western side of the Mountain range. Between 1976 and 2001 the glacier area decreased by -6,1±3% and the glaciers contintued to shrink during the period 2001-2009 with -0,20%/year. Recently started mass balance measurements on a western glacier of Nyainqêntanglha showed a decrease of -1000mm w.e. (water equivalent = snow depth [mm] x $\frac{\text{snow density}}{\text{water density}}$) per year since 2005. Especially the western section is afflicted to glacier shrinkage (Bolch et al, 2010). On the eastern section, in Gurenhekou, recent mass balances showed a decrease of -2000mm w.e. from 2006 to 2010; -400mm w.e. per year (Yao et al, 2012).

Most conclusions about the state of glaciers are made from mass balances or area calculation. In this study, satellite images from Landsat are used to measure and map old and recent snowlines (snow-ice boundaries, see section 2.1.). Landsat is a data acquisition project which uses satellites with tools that record images from the earth in different spectral bands (electromagnetic spectrum, see section 2.2.). Snowlines mapped during the dry season with minimal snow cover should give an approximation of the Equilibrium Line Altitude (ELA) position (more in section 2.1.). By locating snowlines through different seasons and through different years an estimation of the state of a glacier can be made. Different places on the Nyainqêntanglha Mountains are used to see the influence of different orientation and location. Different orientation are the eastern and western side of the mountain ridge, which have different effect of sun, wind etc. locations may range from North to South.

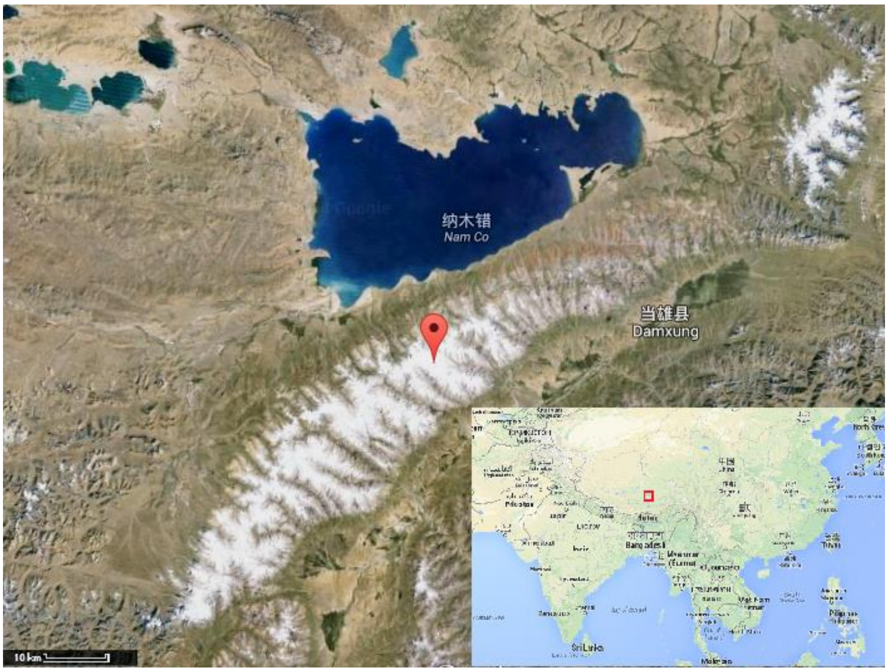


Figure 2: Google Earth images of area of study: the Nyainqentanglha Mountain Range on the Tibetan Plateau.

1.1 Research question

The main question of this study is:
How is the snowline in the Nyainqêntanglha Mountains changing?

To answer this question, several sub-questions are:

- How to detect the snowline on spectral data (like Landsat)?
- How does the snowline elevation change through one year?
- How does the snowline elevation change through the last few years?
- What is the influence of location and orientation on snowlines?
- How are the differences in elevation, location and orientation explained?
- How accurate is the snowline?

2. Study description

2.1. Glaciers and snowlines

A glacier consists of a mass of ice, formed from snow falling and accumulating over the years. Snow falls in ice crystals with a great contact surface. This crystals convert to grains, as showed in figure 3, and eventually to solid glacier ice.

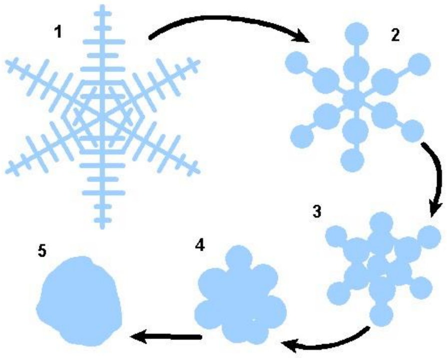


Figure 3: Conversion of snow to glacial ice

When a glacier is covered with snow, the glacier is relatively less influenced by melting of the sun because snow has a higher albedo than ice. Albedo has a value between 0 and 1, where 0 is a perfect absorber and 1 is a perfect reflector. As seen in figure 4, snow is almost a perfect reflector with an albedo of 0.9 and ice is neither of them with an albedo of 0.5. This means that the snow reflects the sun back to the atmosphere and doesn't absorb the heat. Albedo is also being reduced if the snow or ice isn't clean anymore, for example by the presence of little stones (debris) or algae.

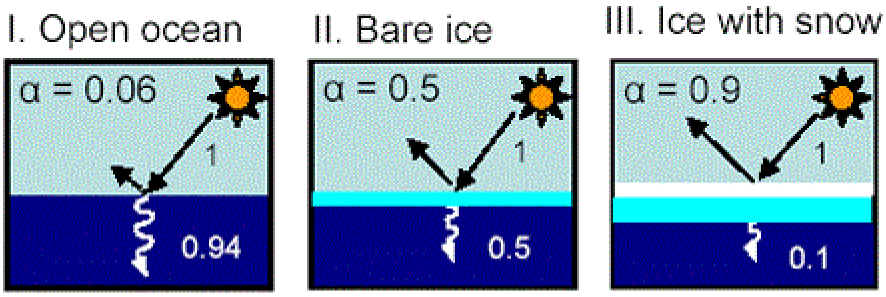


Figure 4: Difference in albedo (National Snow and Ice Data Center, 2014).

The difference between snow and ice is not only important for the albedo but the boundary between this snow and ice is called the snowline. An example of a snowline is showed in figure 5. The difference between snow and ice is clearly visible due to the bright color white of the snow. The snowline varies all the time due to precipitation and melting. In the winter when precipitation is scarce, the snowline is most constant and can give a rough approximation for the Equilibrium Line Altitude (ELA). Below the ELA the glacier surface is ice and above the ELA is the previous remaining winter snow. The ELA lies on the boundary of accumulation and ablation of the glacier. This means that when the amount of accumulation is the same as ablation the value of ELA is 0 and the glacier doesn't shrink of grow. When ELA is positive, accumulation is greater than ablation and the glacier will advance down the valley and when the ELA is negative, the glacier will retreat up the valley.

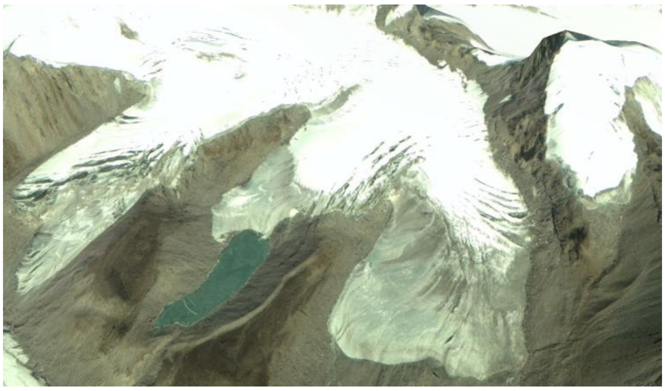


Figure 5: Example of snowlines in Google Earth.

2.2. Remote sensing

Remote sensing means literally viewing something from a distance rather than by direct contact. In this research, when looking at the earth, satellites images are used that detect electromagnetic radiation from the earth's surface or the atmosphere. Every object with a temperature above absolute zero (-273 °C) reflects and emits energy that is called electromagnetic radiation. This radiation is divided into an electromagnetic spectrum to divide different wavelengths. Visible light is a very small part of this spectrum, as seen in figure 6.

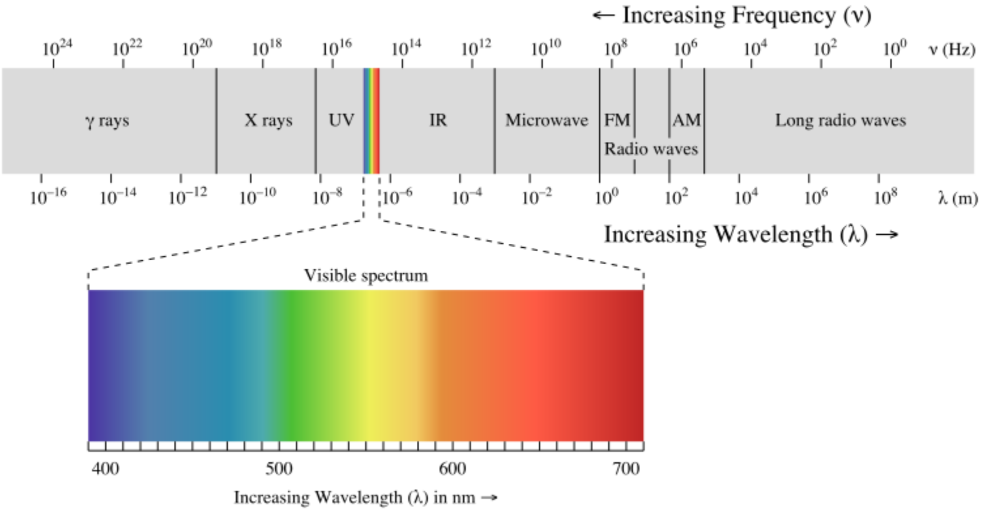


Figure 6: Electromagnetic spectrum

Every kind of surface has its own spectral signature, on which different wavelengths the surface specifically reflects.

Satellites can easily measure ice and snow in the visible and infrared regions of the spectrum. Visible light makes use of the higher albedo of snow and ice and the white colour. With infrared the lower temperature of snow/ice is easily detected.

However, every region also has some disadvantages. For example, when using reflected visible light, data can only be collected during daytime because of the absence of light by night. Also clouds prevent the satellite from viewing the visible light from earth's surface. This same problem with clouds holds for the use of infrared light. Infrared has another problem that melting ice, with a temperature near freezing point, is hardly to distinguish to surrounding water in lakes or ocean.

3. Data

The data on the Tibetan area, used in this research, are open source and freely available on internet. In this research the optical satellite images are used from Landsat and ASTER GDEM whichi are discussed in section 3.1 and 3.2. Also the so-called GLIMS glacier mask is used to find the locations of the present glaciers on the Nyainqêntanglha Mountains and will be discussed in section 3.3.

3.1. Landsat

The Landsat program is the longest running project for acquisition of satellite images of the surface of the Earth and is operated by NASA and USGS (United States Geological Survey). It has started in 1972 and there are 8 satellite launched since then. Only Landsat 7 and 8 are still active, but Landsat 5 was also used till one year ago. These three are also the most used satellites in this research. Landsat scenes are multispectral photographs of a certain region acquired at a certain time. The Landsat 5 TM (Thematic Mapper) data has 7 spectral bands with a resolution of 30 meters. Landsat 7 ETM+ (Enhanced Thematic Mapper+) has 1 extra band with a resolution of 15 meter (figure 7). The newest Landsat 8 has even 11 bands. The difference between the Landsat 7 ETM+ and Landsat 8 are shown in figure 8.

The images have been processed to Standard Terrain Correction Level 1 (L1T). This correction uses ground control points to check for example on faults of sensors, outliers and sensors distortions. A digital elevation model (DEM) is used to check the accuracy of the topography.

The approximated scene size of one Landsat image is 170 km north-south by 183 km east-west.

Enhanced Thematic Mapper Plus (ETM+)	**Landsat 7**	**Name**	**Wavelength [µm]**	**Resolution [m]**
	Band 1	Blue	0.45-0.52	30
	Band 2	Green	0.52-0.60	30
	Band 3	Red	0.63-0.69	30
	Band 4	Near Infrared	0.77-0.90	30
	Band 5	Shortwave Infrared-1	1.55-1.75	30
	Band 6	Thermal Infrared	10.40-12.50	60 (resampled to 30)
	Band 7	Shortwave Infrared-2	2.09-2.35	30
	Band 8	Panchromatic	.52-.90	15

Figure 7: Bands and wavelengths in Landsat 7. The first 7 bands are also included in Landsat 5. *[landsat.usgs.gov]*

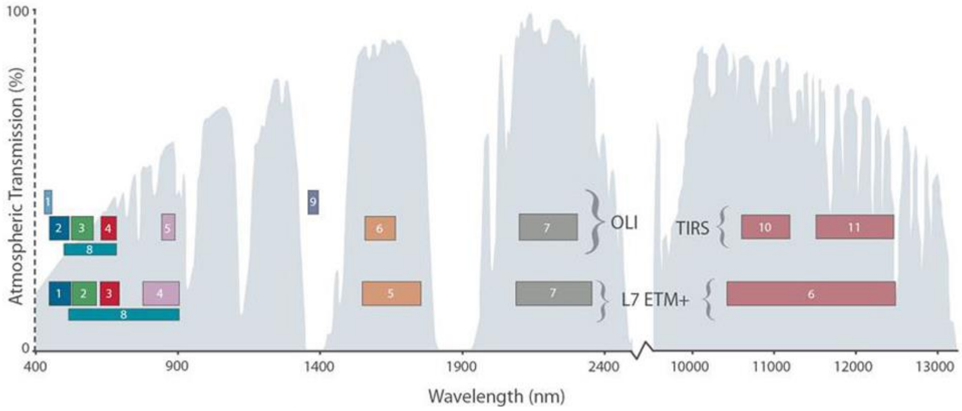


Figure 8: Band pass wavelengths for Landsat 8 OLI and TIRS sensor, compared to Landsat 7 ETM+ sensor. *[landsat.usgs.gov]*

Landsat data is available on the website of the United States Geological Survey (USGS). USGS is the geological agency of the United States government (USGS, 2014). Examples of different Landsat bands are showed in figure 9.

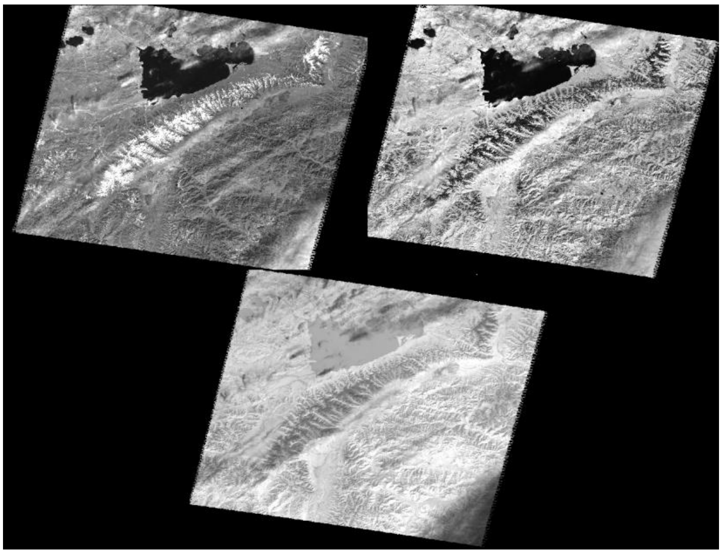


Figure 9: Landsat 5 November 2009, bands 3, 5 and 6 raw data.

3.2. ASTER GDEM

ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) is a sensor on the TERRA satellite launched in 1999. With the use of infrared cameras stereo pairs have been used to produce global digital elevation models (GDEM) with a scene-size of approximately 60x60km, as explained in figure 10.

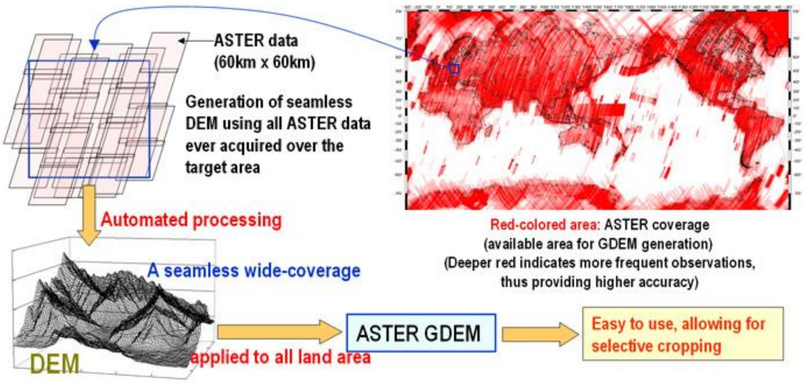


Figure 10: Development of ASTER data tot ASTER GDEM

On 29 June 2009, the Global Digital Elevation Model (GDEM) was released to the public. It was compiled using automated photogrammetry applied to the complete ASTER scene archive, containing more than 1.65 million scenes acquired between 2000 and 2007 (METI, 2009). It covers 99% of land's surface, which is a lot more than the previous Global Digital Terrain Model of the Earth: Shuttle Radar Topography Mission (SRTM), which covers 80% of land's surface. Since version 2 of ASTER GDEM also the resolution is better than SRTM: 30 meters. Both SRTM and ASTER GDEM are suitable for compilation of topographic parameters in glacier inventories. When parameters are averaged over a greater area (e.g. mean elevation) the variability is a lot smaller than parameters that depend on a single DEM value (e.g. minimum or maximum elevation) (Frey, Paul, 2011). The elevation accuracy of ASTER GDEM over a larger area in Tibet is around ±11.14m (Billemont, 2010). Data is available on the website of the USGS, but also on the website of NASA (NASA, 2014). Raw data is showed in figure 11.

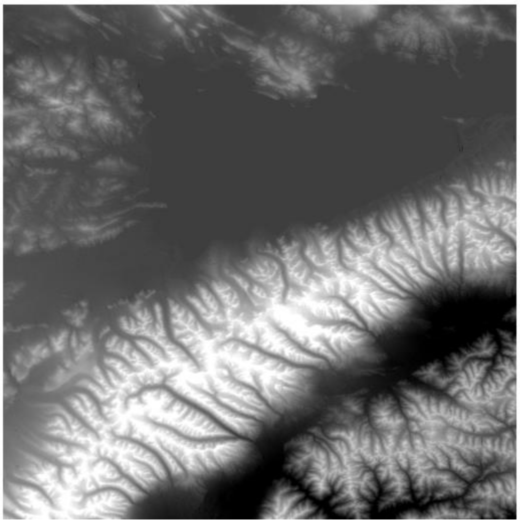


Figure 11: ASTER GDEM raw data

3.3. GLIMS glacier mask

Global Land Ice Measurements from Space (GLIMS) is a project to monitor the world's estimated 160,000 glaciers, using data from optical satellite instruments. Mostly used data is collected by the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) instrument aboard the Terra satellite and the LANDSAT Enhanced Thematic Mapper Plus (ETM+), along with historical observations. The glaciers are distributed into GIS-compatible formats, for example ESRI shapefiles, used in this research. The quality is strongly varying due to different sources and analysis methods used.

The product of Tibet was submitted by Li (2003), Chinese Academy of Sciences. The GLIMs glacier mask is a copy of original data from the Cold and Arid Regions Environmental and Engineering Research Institute (CAREERI) but it is referenced to the WGS84 Geographic Coordinate System. The CAREERI glacier mask is developed and distributed by the World Data Center for Glaciology and Geocryology, Lanzhou China. This glacier inventory was based on topographic maps, aerial photography, optical remote sensing and in situ measurements from 1978 to 2002 (Phan, V.H., 2014).

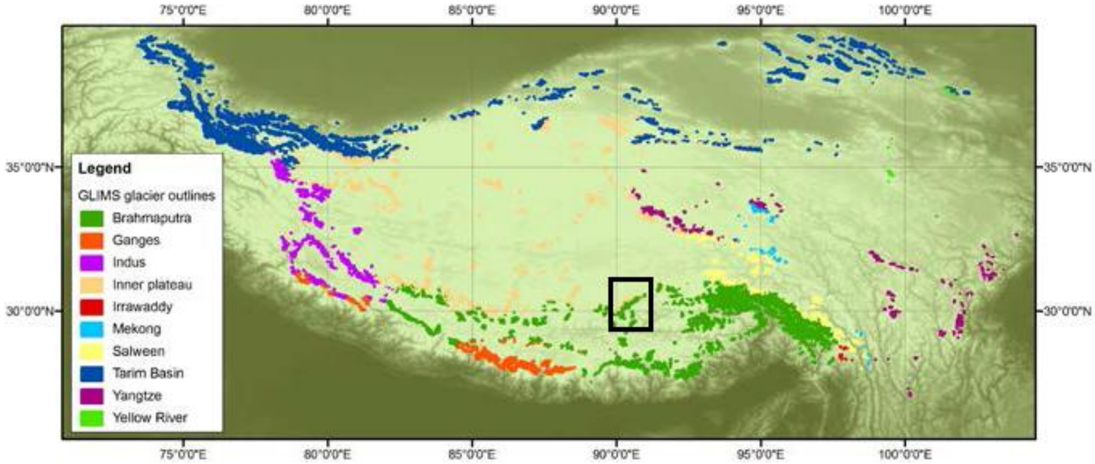


Figure 12: GLIMS glacier outlines coloured per basin on the Tibetan plateau. Nyainqêntanglha Mountains are marked with the black box.

4. Methodology

There are different methodologies used in this research. First we need to select our satellite image, which is done in section 4.1. Then we explain the different classification methods in sections 4.2 and 4.3 and we select the best one in section 4.4. We explain different methods for representing ASTER GDEM elevation data in section 4.5 and select the best method in section 4.6.

4.1. Satellite image selection

Different Landsat satellite images are used for snowline detection. They are showed in figure 13. From the Introduction it is known that monsoon in South East Asia is from June to September. In this period a lot of snow covers the glaciers on Nyainqêntanglha Mountain range. Therefore, images were selected during the dry season, October to April, to minimize the amount of snow cover to have the highest probability of extracting a good snowline that is comparable between multiple years. To compare snowlines in winter and summer, multiple dataset are chosen within one year.
Also the absence of cloud cover was considered because clouds can hide the snowlines and create shadows that complicate the classification process. For that reason only one dataset in the wet season, 13 June 2001, was suitable. All other dataset in the summer have too much cloud cover to perform a snowline classification.

Date		**Sensor**	**Resolution [m]**	**Source**
Multiple years, dry season	7 February 2001	Landsat 7 ETM+	30	USGS
	16 January 2008	Landsat 5 TM	30	USGS
	31 December 2013	Landsat 8	30	USGS
One year, multiple seasons	17 November 2000	Landsat 7 ETM+	30	USGS
	25 March 2001	Landsat 7 ETM+	30	USGS
	13 June 2001	Landsat 7 ETM+	30	USGS
	4 November 2001	Landsat 7 ETM+	30	USGS

Figure 13: table of used satellite data.

4.2. Manual classification

First we try to find the snowline by just looking at color differences between snow and ice in clear datasets. This method is simple and we can always use it, because we don't need complicated calculations or computer programmes to do this.
We can see difference in color for snow and ice and mark this boundary. When we overlay these snowlines for different years we have a rough indication of how the snowlines moves, like is done in figure 14.

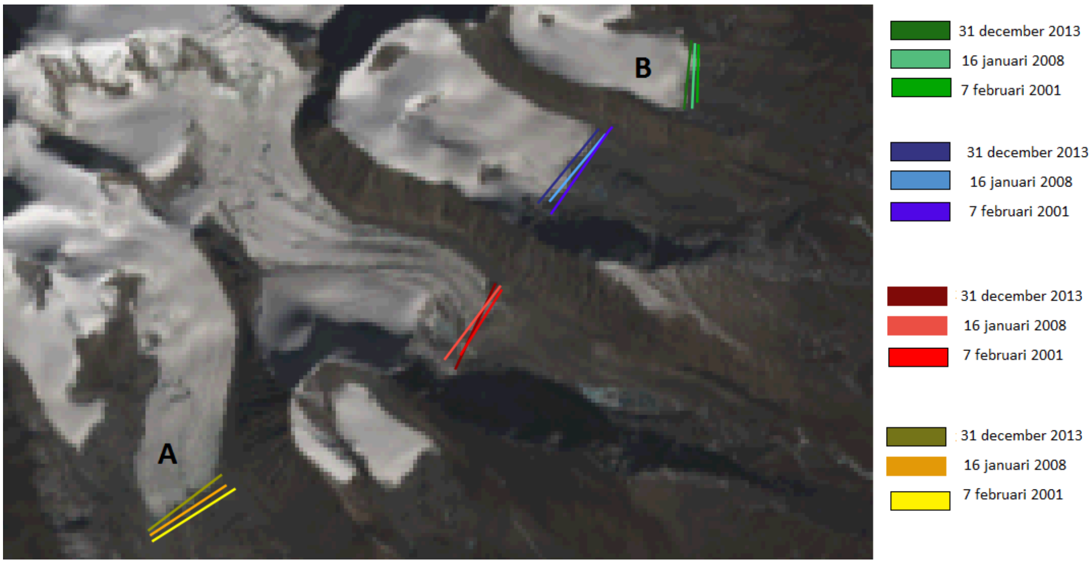


Figure 14: Snowlines from 3 different years, displayed on Landsat 8, 31 December 2013.

4.3. Classification in QGIS

QGIS is a free programme to create, edit, visualise and analyse geospatial information. GIS stands for Geographic Information System. GIS software, like QGIS, allows users to create maps with many layers using different map projections, for example Landsat bands to create different color images. The two newest versions of QGIS, 2.0.1 Dufour and 2.4.0 Chugiak, are used in this research (QGIS, 2014). There are different ways to find snowlines using QGIS. They are explained in sections 4.3.1. and 4.3.2.

4.3.1. Semi-automatic classification plugin

There are two different kinds of classification possible when using GIS programmes: supervised and unsupervised classification. An unsupervised classification uses pixel properties to classify the pixels automatically without user interference. The user needs to interpret the classes after classification and do some quality checks on the results. Supervised classification uses the spectral signatures of training data, made by the user, to classify an image. Training data is easily created to represent the classes you want to extract.

For automatic supervised classification in the QGIS programme a plugin was used called: the semi-automatic classification plugin. This plugin provides pre-processing tools like Landsat conversion to reflectance, the land cover classification process and postprocesing tools like accuracy assessments. All Landsat data used in this research is first pre-processed with Landsat conversion and atmospheric correction. Landsat DN (Digital Numbers) are conversed to Top of Atmosphere reflectance (TOA). Atmospheric correction is applied using the DOS 1 method (Dark Object Subtraction 1). Dark objects, like deep water, have a reflectance of zero but are recorded with a value resulting from atmospheric scattering. This value is subtracted from the spectral bands to avoid this atmospheric scattering. Regions of Interest (ROI) are created to distinguish different land cover types. With these training data QGIS makes a classification for the whole image. There are three available classification algorithms in the plugin: the maximum likelihood, minimum distance and spectral angle mapping. The first two assigns the ROI with the respectively highest probability or minimum distance to the mean value of the training pixels. The spectral angle mapping method calculates the angle between the reflectance of the pixel and the reference training spectra. The different classification algorithms are compared and the best result is chosen.

4.3.1.1. Different classification algorithms

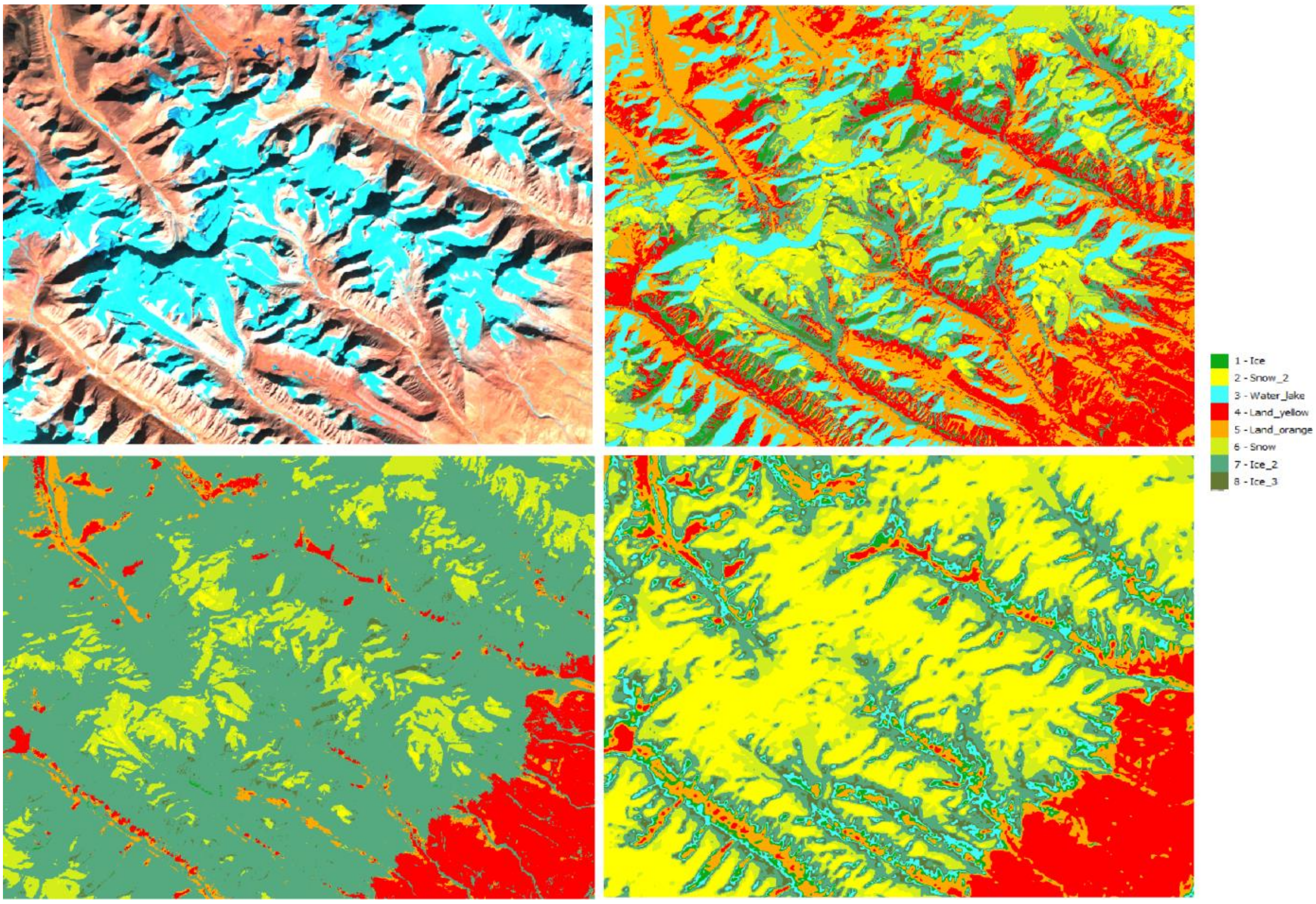


Figure 15: Different classification algorithms for Landsat 5 January 2008, clockwise: false colour image (not same colours as in legend), spectral angle mapping algorithm, minimum distance algorithm, maximum likelihood algorithm.

If we look at the figure 15 we see that the maximum likelihood algorithm is the worst classification because it doesn't cover all the snow. The spectral angle mapping algorithm has a misclassification for shadows as classified as lake water. The minimum distance algorithm has classified more snow and less misclassified lake water When we compare it to the false color image, this snow is not present on the corner of the mountains. Although the spectral angle mapping has misclassified shadows, it still has the best classification between snow and ice.
This misclassification is easy to explain. For the semi-automatic classification plugin we have classified each spectral signature (explained in 2.2.) as a specific land cover. When we make a spectral signature plot we can see the wavelengths of these different properties. There occurs a problem if two wavelengths of a totally different land cover are very near each other. Figure 16 gives an example: Ice has almost the same wavelength as lake water. Therefore, the classification has a lot of lake water color in the middle of the mountain, which should be ice.

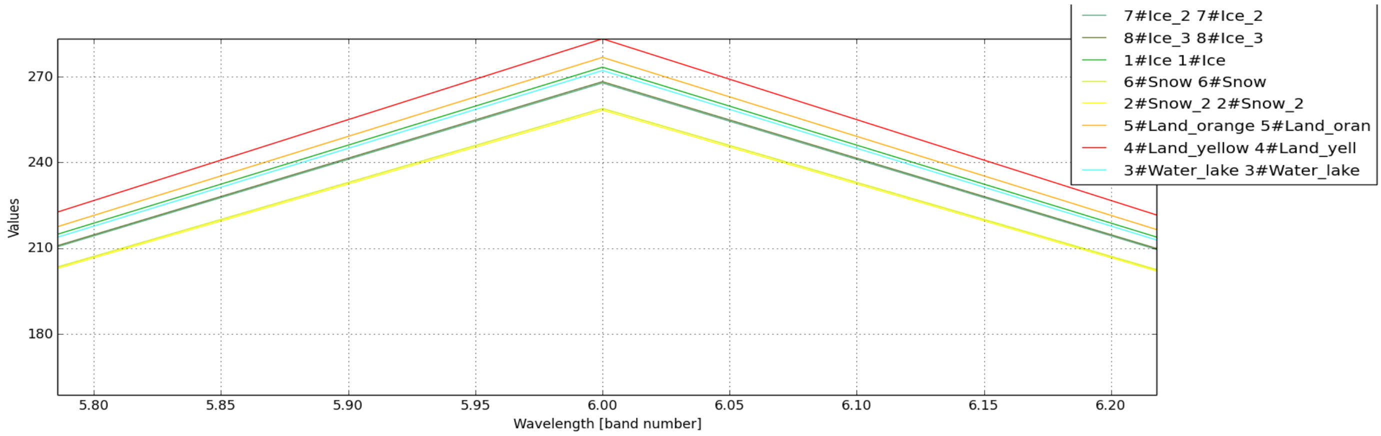
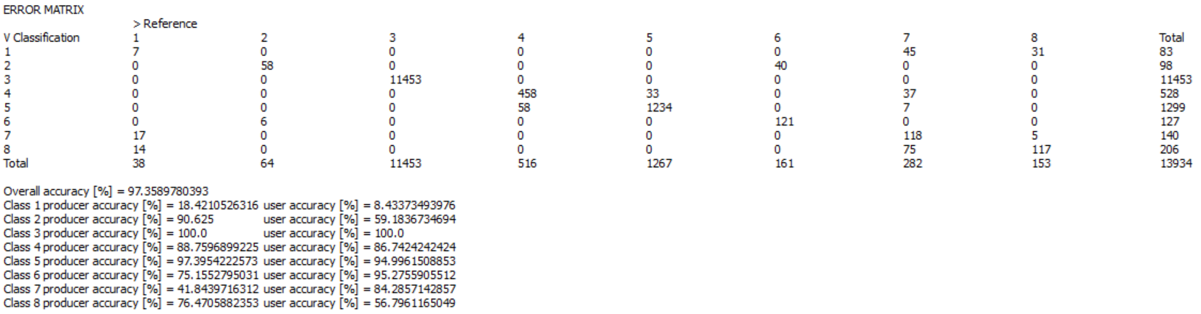


Figure 16: Spectral signature plot of classification for Landsat5 January 2008.

When we continue using the semi-automatic classification plugin we therefore only use the spectral angle mapping.

After this classification an accuracy assessment can measure how accurate the classification actually is. This is showed in figure 17. The example of the chosen spectral angle mapping classification has an accuracy of 97,36%.



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ERROR MATRIX
                > Reference
V Classification  1       2       3       4       5       6       7       8       Total
1                 7       0       0       0       0       0       45      31      83
2                 0       58      0       0       0       40      0       0       98
3                 0       0       11453   0       0       0       0       0       11453
4                 0       0       0       458     33      0       37      0       528
5                 0       0       0       58      1234    0       7       0       1299
6                 0       6       0       0       0       121     0       0       127
7                 17      0       0       0       0       0       118     5       140
8                 14      0       0       0       0       0       75      117     206
Total             38      64      11453   516     1267    161     282     153     13934

Overall accuracy [%] = 97.3589780393
Class 1 producer accuracy [%] = 18.4210526316 user accuracy [%] = 8.43373493976
Class 2 producer accuracy [%] = 90.625        user accuracy [%] = 59.1836734694
Class 3 producer accuracy [%] = 100.0         user accuracy [%] = 100.0
Class 4 producer accuracy [%] = 88.7596899225 user accuracy [%] = 86.7424242424
Class 5 producer accuracy [%] = 97.3954222573 user accuracy [%] = 94.9961508853
Class 6 producer accuracy [%] = 75.1552795031 user accuracy [%] = 95.2755905512
Class 7 producer accuracy [%] = 41.8439716312 user accuracy [%] = 84.2857142857
Class 8 producer accuracy [%] = 76.4705882353 user accuracy [%] = 56.7961165049
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Figure 17: Example error matrix of spectral angle mapping classification in figure 14.

4.3.2. Normalized-Difference Snow Index

Another way to detect snow on glaciers is by using the Normalized-Difference Snow Index, NDSI. Snow is highly reflective in the visible part of the EM spectrum and highly absorptive in the near-infrared/short-wave infrared part of the spectrum. Bands 2 and 5 (of Landsat 5 and 7) are used to calculate the NDSI:

$$NDSI = \frac{band\ 2 - band\ 5}{band\ 2 + band\ 5}$$

We can use QGIS to perform this calculation and give a minimum threshold from which it’s classified as snow. When snow is scarce, in the winter months, we see that we have to put the threshold very low and in the summer months, when there is plenty of snow, the threshold should be very high. This can be due to the fact that in summer the reflectivity is higher than in winter because of the reflection from the sun. The thresholds are shown in figure 18.

Date		**Direction**		***NDSI threshold***
Multiple years, dry season	7 February 2001	North and South		*>-0,35*
		Mid		*>-0,4*
	16 January 2008	North and South		*>0*
		Mid	East	*>-0,2*
			West	*>0*
	31 December 2013	North, Mid and South		*>-0,3*
One year, multiple seasons	17 November 2000	North, Mid and South		*>0,4*
	25 March 2001	Mid and South		*>0,45*
		North	East	*>0,5*
			West	*>0,45*
	13 June 2001	North, Mid and South		*>0,4*
	4 November 2001	North, Mid and South		*>0,4*

Figure 18: Different thresholds for different glaciers on different satellite images.

Snow is best visible in QGIS with a combination of bands of 5 as red, 4 as green and 3 as blue. When we have performed the NDSI calculation, this creates a black and white map for which snow is classified as 1 and everything else as 0. This is extracted to lines and overlaid on the 5,4,3 combination. This way the right threshold is checked for the particular glacier. When it fits, the polygon is made for snow-cover of that glacier. These polygons can de compared between years. An example of such glaciers is shown in figure 19.

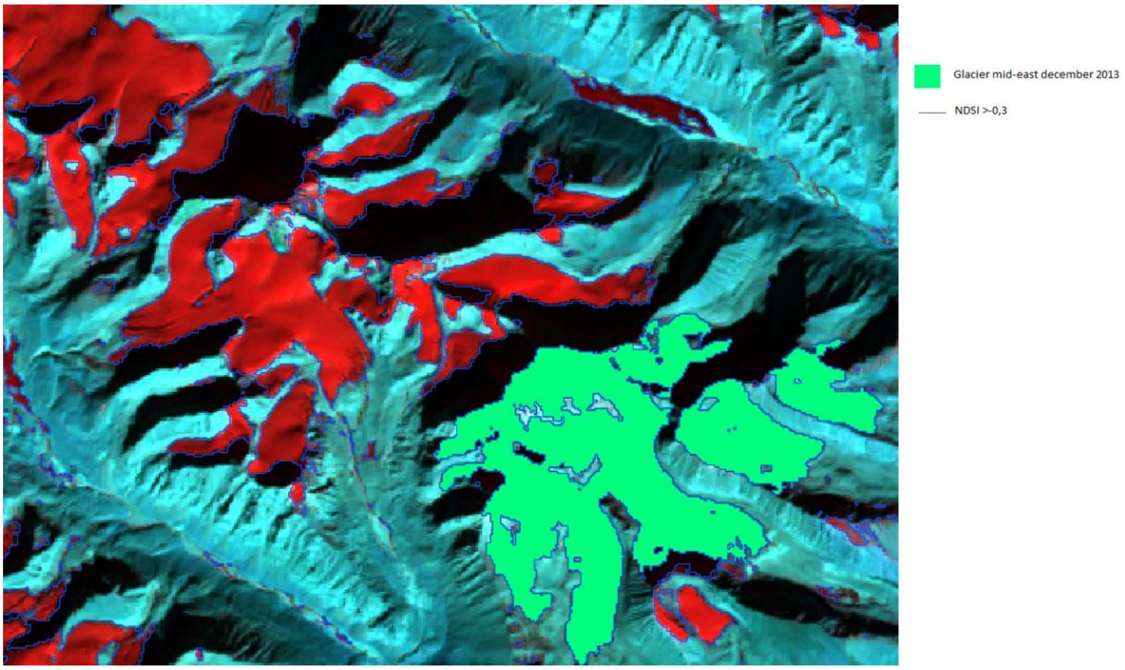


Figure 19: Example of classification with use of NDSI, displayed on band combination 5,4,3 where snow is bright pink.

4.4. Classification method selection

When the different classification methods described in 4.2, 4.3.1 and 4.3.2. are compared, the best one can be selected. The results are showed in figure 20.

	Advantages	Disadvantages
Manual classification (4.2)	○ Fast ○ Simple ○ Polygons extractable to compare with other years	○ Hardly reproducible by different views ○ Not so accurate; only straight snowlines ○ Much work for greater area; Time consuming
Semi-Automatic Classification plugin (4.3.1.)	○ Classification of greater area ○ After optimizing all input parameters, it gives an accurate image	○ Hardly reproducible by different training data and classification algorithms ○ Making training data can be time consuming ○ Good computer needed, otherwise time consuming processes and it often get stuck ○ Hard to compare different datasets
Normalized Difference Snow Index (4.3.2.)	○ Classification of greater area ○ Fast ○ Accurate snow cover/snowlines ○ Polygons extractable to compare with other years	○ Clouds can interrupt the classification ○ Different thresholds makes it less reproducible

Figure 20: Table of different classification methods

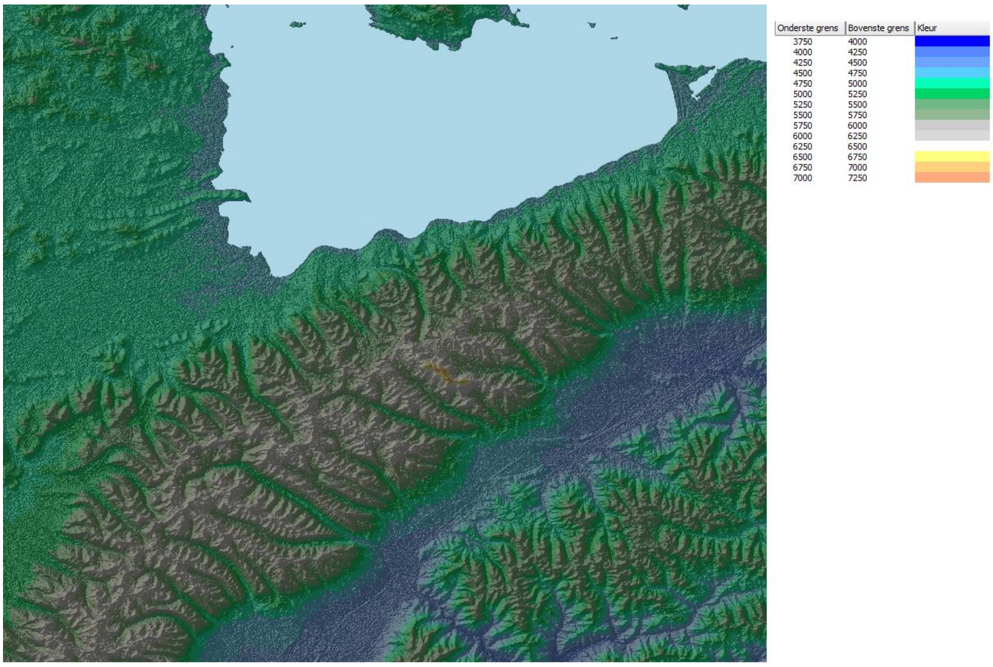
In this research the Normalized Difference Snow Index is likely to be the best option. Although different thresholds make it less reproducible, it is the most reproducible of all. It also one of the fastest methods and it gives accurate results.

4.5. Using ASTER GDEM for elevations variations

To make useful conclusions of snowline variations, the elevation is needed. the Global Digital Elevation Model (GDEM) of ASTER is used, as described in 3.2. There are different ways to visualize this data in GIS programmes to extract elevation of the snowlines.

4.5.1. Relief

We can make a relief of ASTER GDEM with a self-scaled colour bar, like figure 21. In this relief, the shape of the Nyainqêntanglha Mountain is well visible. We can use it to estimate the elevation of the snowlines of glaciers, but the difference in colour at 250m is not exact enough.



Onderste grens	Bovenste grens	Kleur
3750	4000	🟦
4000	4250	🟦
4250	4500	🟦
4500	4750	🟦
4750	5000	🟩
5000	5250	🟩
5250	5500	🟩
5500	5750	🟩
5750	6000	⬜
6000	6250	⬜
6250	6500	
6500	6750	🟨
6750	7000	🟧
7000	7250	🟧

Figure 21: Relief of ASTER GDEM data.

4.5.2. Profile Tool

QGIS has a plugin which is called the Profile Tool. With these plugin a line can be drawn and the plugin shows the profile of the line sketched. This is a time consuming process, because the profile line has to be drawn manually. An example of the drawn line and the corresponding profile are shown in figures 22 and 23.

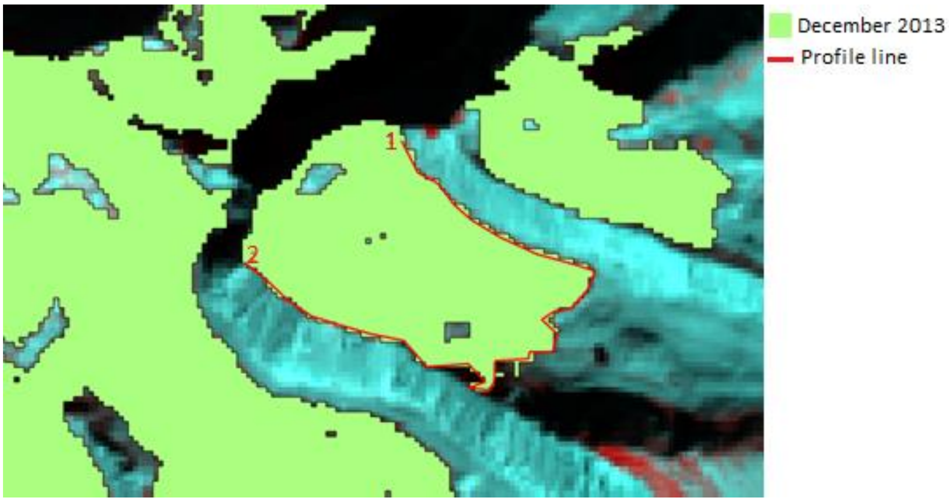


Figure 22: Used line in polygon of snow cover of December 2013 to show profile

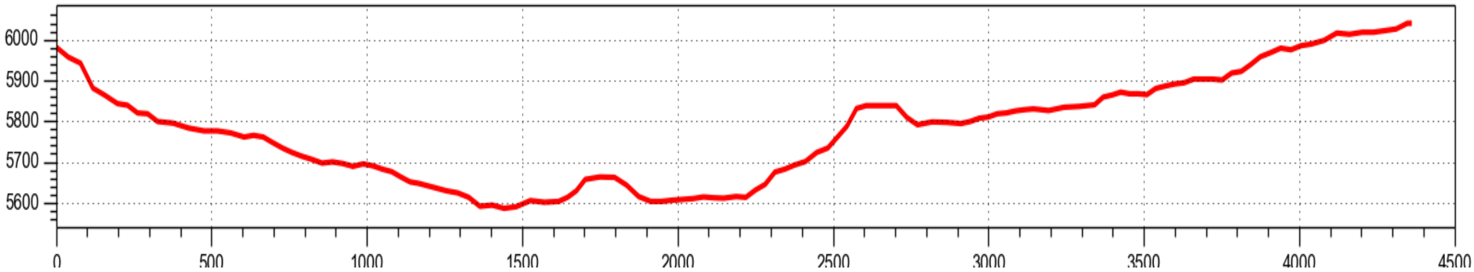


Fig 23: Profile line of line showed in figure 21. Left side is at 1, right side is at 2.

4.5.3. Contour Lines

Another method to make the Global Digital Elevation Model visible is using contour lines. Depending on how many contour lines are made, the process can be very fast. Also depending on how many contour lines are made, the process can be very messy or very clear. The 10 meter contour line is a clear example where the contour lines are not too messy but you can see still the shape of the mountain. This example of the 10 meter contour line is shown in figure 24.

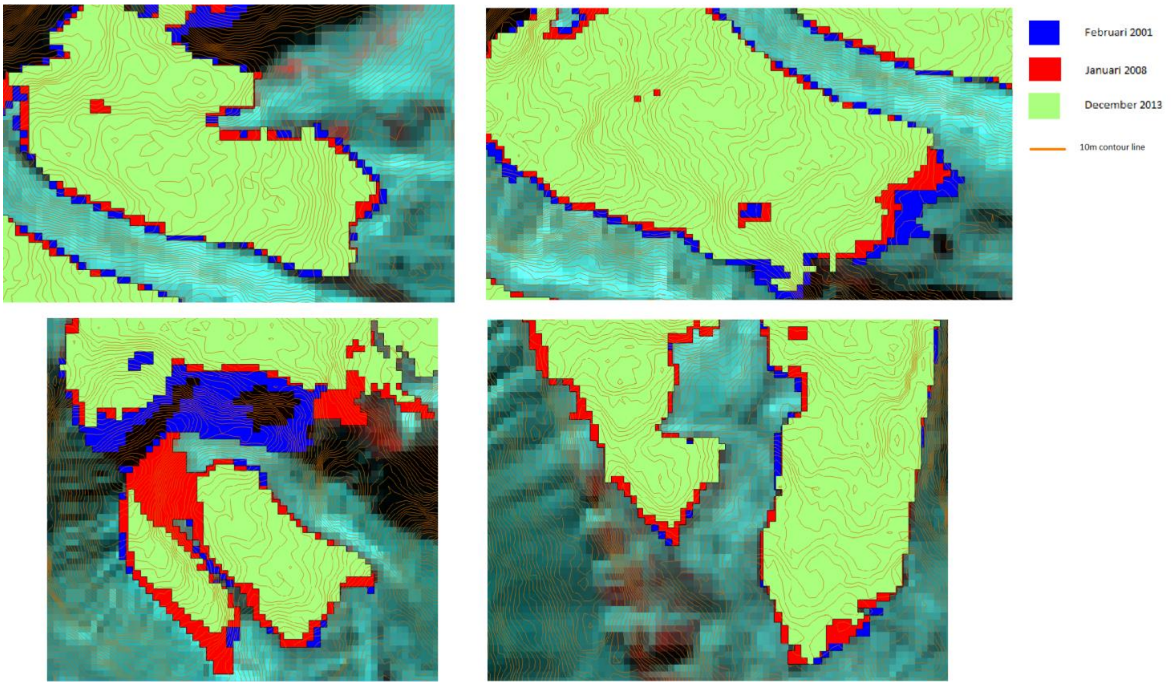


Figure 24: Glacier tongues zoomed in with elevation contour lines of 10 meter.

4.5.4. Regular point grid

The last method starts with making a grid of regular points with a certain distance from each other. When the distance is very small, the program needs some time, when the distance is very big, the results are less accurate. We again need a plugin, called the Point Sampling Tool. This plugin can sample values from raster layers, like ASTER GDEM, to specified sampling points. The result is a grid of regular points with each point having its value from ASTER GDEM. An example is shown in figure 25.

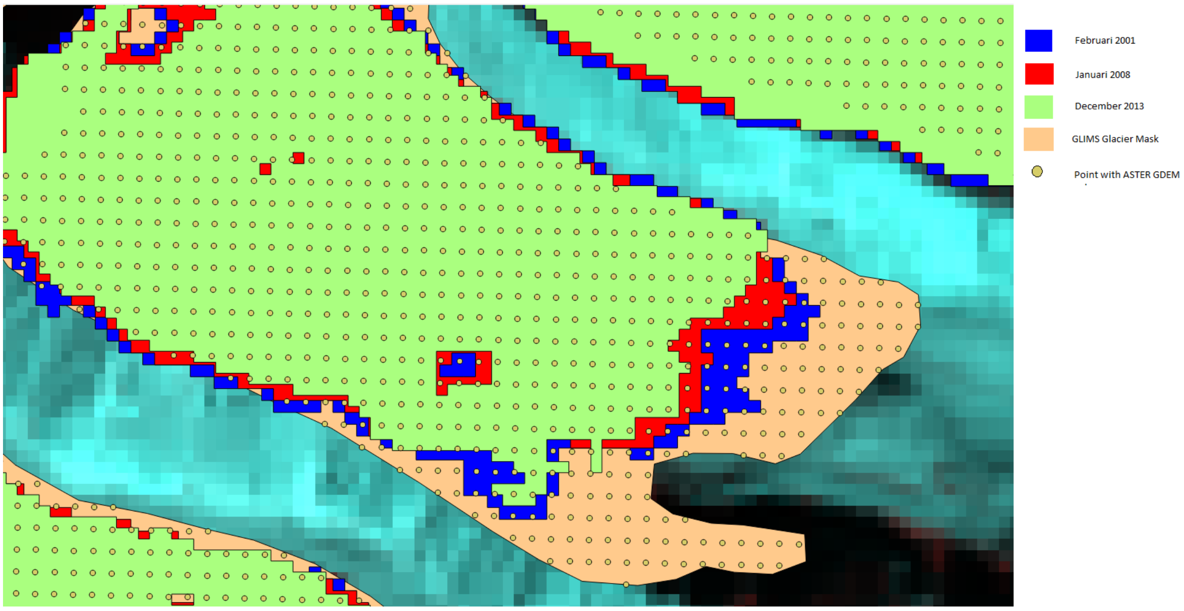


Figure 25: Grid of regular points, with values from ASTER GDEM.

To use these points for snowline research, different points are selected near the edges of the polygon of the different glaciers. For this selection of points the maximum, minimum and average height are available. This data is used to compare different glaciers in different datasets. An example of a selection of points is showed in figure 26.

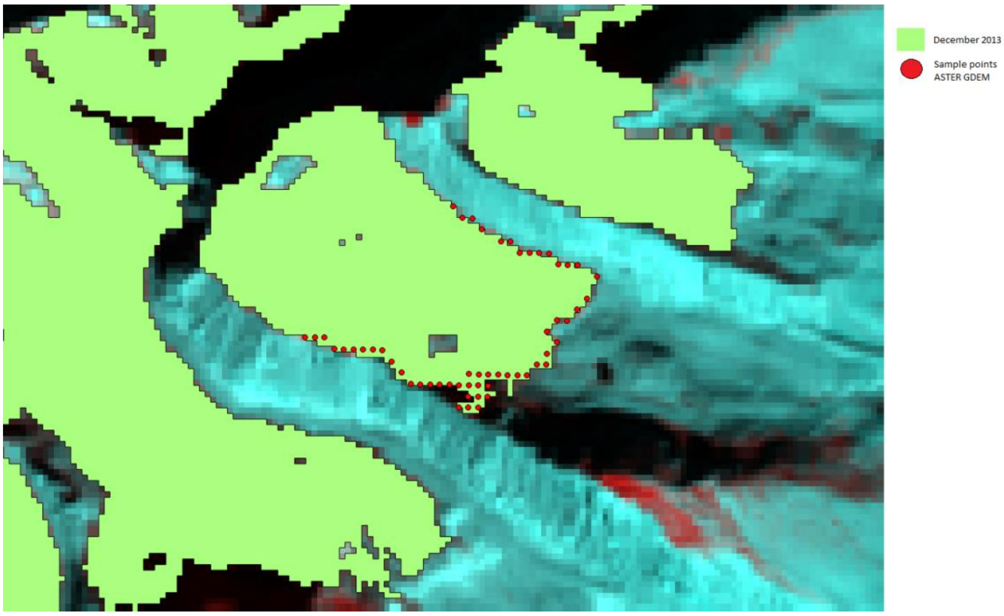


Figure 26: Selection of sample points for glacier mid-east.

4.6. Elevation method selection

When the different elevation methods described in 4.5.1. till 4.5.4 are compared, the best one can be selected. The results are showed in figure 27.

	Advantages	Disadvantages
Relief	○ Simple & simple ○ Good overall image	○ Too big scale for snowline variations ○ Badly visible when overlying a polygon

Profile Tool	○ Very accurate ○ Profile gives a good image of snowline	○ Time consuming process to define profile line ○ Hardly reproducible by clicking the same profile line
Contour	○ Fast & simple ○ Shape of mountain is good visible	○ No exact height on contour lines ○ Hard to compare with different images
Regular point grid	○ Very accurate ○ Average, minimum and maximum snowline elevation for whole glacier ○ When points are generated, process is simple	○ When making too many dots, the program will be slow ○ When making too less dots, the method won't be accurate ○ For snowline elevation, different dots must be merged. This is a time consuming process and also not completely reproducible

Figure 27: Table of different elevation methods

In this research the Regular point grid and the Profile tool are the two best options. However, the profile tool is a very time consuming process and hard to compare between different years. Therefore, the Regular point grid will be used mostly and the Profile Tool only when more exact measurements are needed.

4.7. GLIMS

When we look at the GLIMS glacier mask superimposed on the Landsat data, we see a shift in the glacier mask. In the middle of the mountain ridge we see that there's clearly snow on top, which is obvious because it's the highest part of the mountain, but the GLIMS glacier mask doesn't cover it. In figure 28 the snow is coloured blue and it is easy to see the shift in the glacier mask with the red arrows.

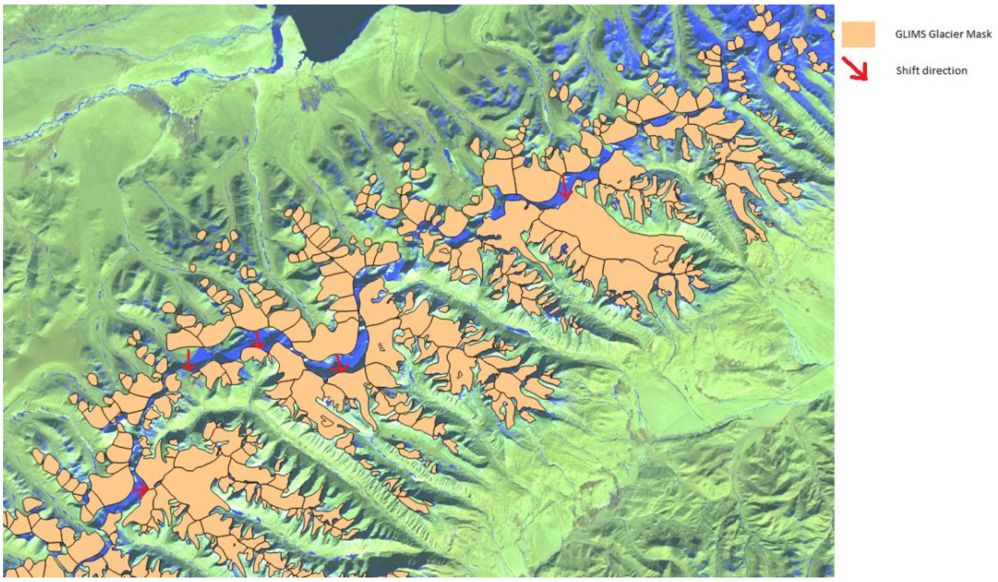


Figure 28: GLIMS glacier mask and its shift marked in red.

Another way we can see the shift is by adding the NDSI snow covers. When we overlay them with the GLIMS glacier mask, figure 29, we see that on the eastern section the GLIMS glacier mask is reasonable but on the western side it really extends the NDSI snow cover too much.

For this reason the GLIMS glacier mask is useful because we know that our snow cover is on a glacier and we are really extracting snowlines, not just loose snow. On the eastern side we also have an indication of how much glacier isn't covered with snow but on the western this isn't reliable. For that reason GLIMS is not included in the results and conclusion of this research.

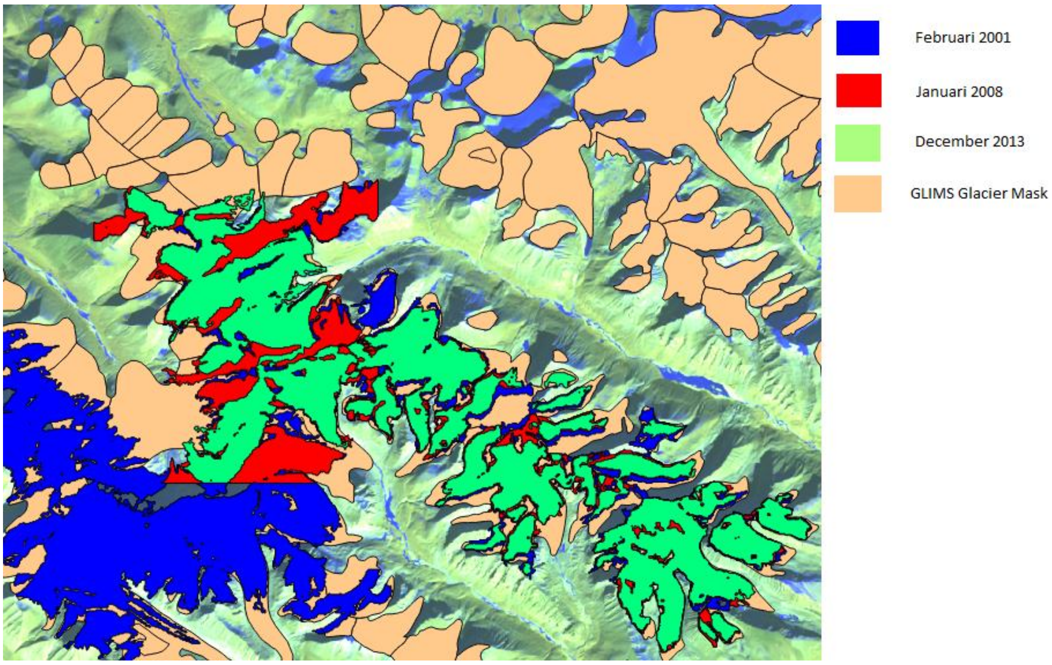


Figure 29: GLIMS glacier with polygons of snow cover made by NDSI method

5. Results

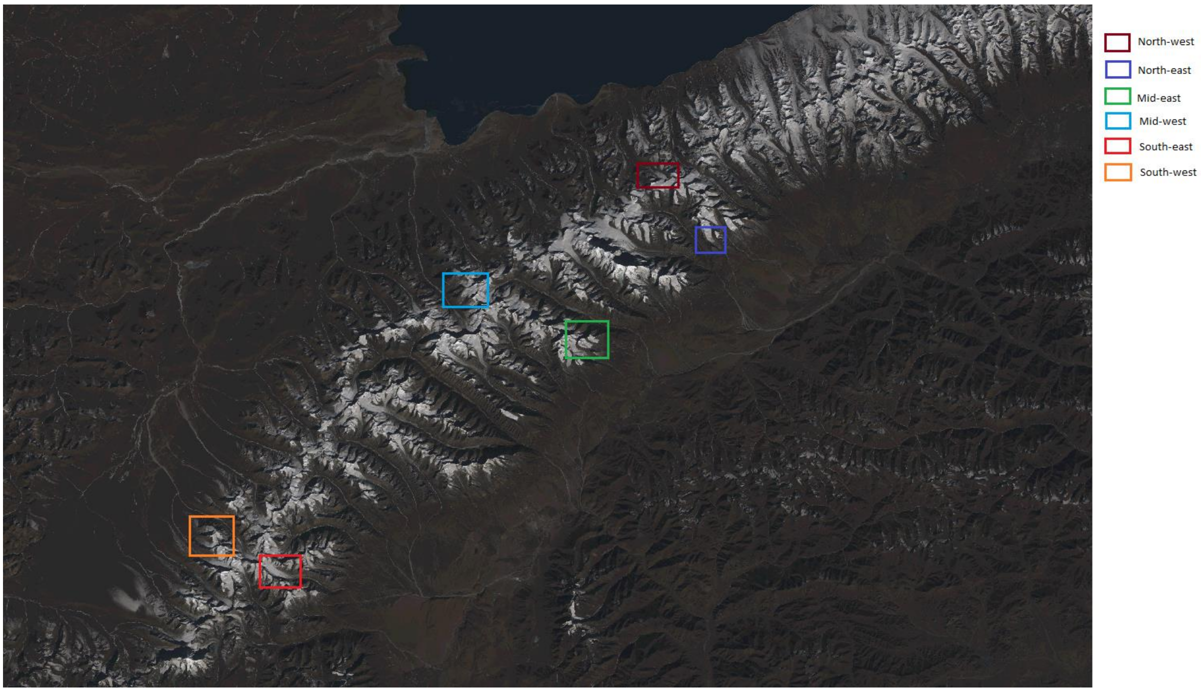


Figure 30: 6 different glacier used in this research.

From the method, explained in chapter 4, we obtained many snowline elevation data of six different glaciers from 7 different dataset on the Nyainqêntanglha Mountain Range. The six different glaciers are showed in figure 30 and are named according to their location, from northwest to southeast. To make a good comparison between all this data, it is subdivided in different parts. In section 5.1. snowline variation for almost 13 years on these 6 different locations is studied. In section 5.2. snowline variation for 1 year in different seasons but also on these 6 locations is studied.

5.1. Variation through seasons

To compare the differences in snowline elevation for different months in the year November 2000 till November 2001, we use three different subsets. First, we compare the 3 glaciers on the eastern side of Nyainqêntanglha. Then, we compare the 3 glaciers on the western side. At last, we look at the absolute difference between these eastern and western glaciers.

5.1.1. Eastern variation

Figure 31 shows the results for the eastern glaciers from November 2000 till November 2001. The average values are easiest to compare. Maximum and minimum values show the range of the different snowlines. The most notable difference is in June. Here the snowline elevation is significant much lower than the rest of the months. Also, the end of March is a little bit lower than the beginning of February, especially in the middle area of Nyainqêntanglha. The difference between November 2000, February 2001 and November 2001 is very constant. Therefore we use the winter months to compare variation through different years. The summer months, like June 2001, differ about 120-150 meters with the winter months.

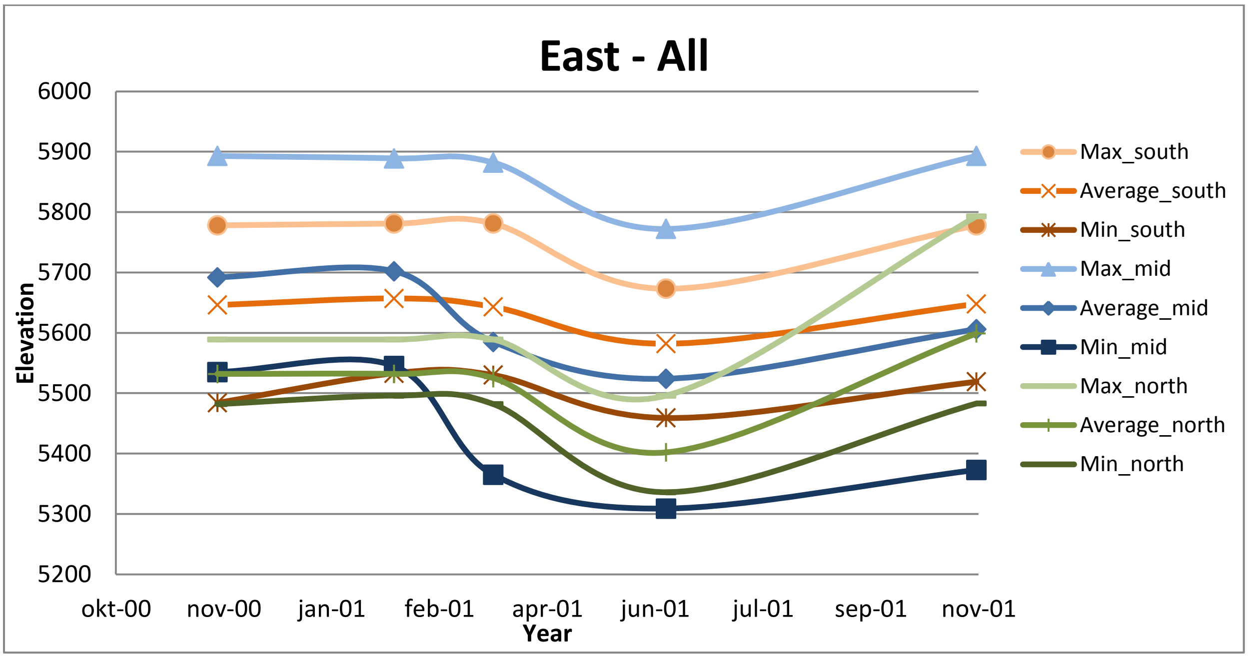


Figure 31: Snowline elevations of eastern section from November 2000 to November 2001.

5.1.2. Western variation

Figure 32 shows the results for the western glaciers in one year. In general it seems to be the same as figure 31. When we look in more detail we see more differences. We see an increasing elevation from north to south in winter months. In the north-west the elevation is lowest; in the south-west the elevation is highest. But , in the summer month, June, the southwest is almost the lowest. This southwestern part has a very wide range between summer and winter (about 450 meter), which is much smaller for the northwestern part (about 200 meter).

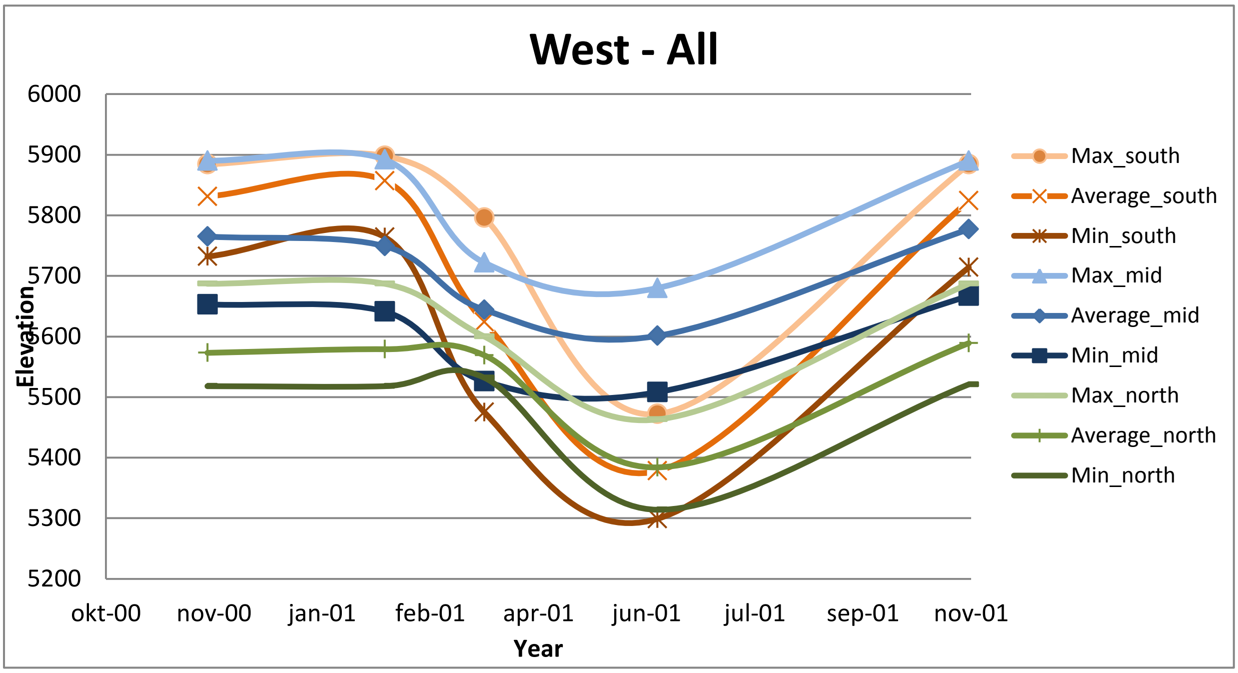


Figure 32: Snowline elevations of western section from November 2000 to November 2001.

5.1.3. East-West variation

For the difference in east-west variation all 3 options, North, Mid and South, are shown in figure 33. We see that in the North the differences between East and West are much smaller than in the South.

Also, the eastern part lies in general a little bit lower than the western part. We already saw in 5.1.2. that the range between summer and winter in the south-western part is the widest.

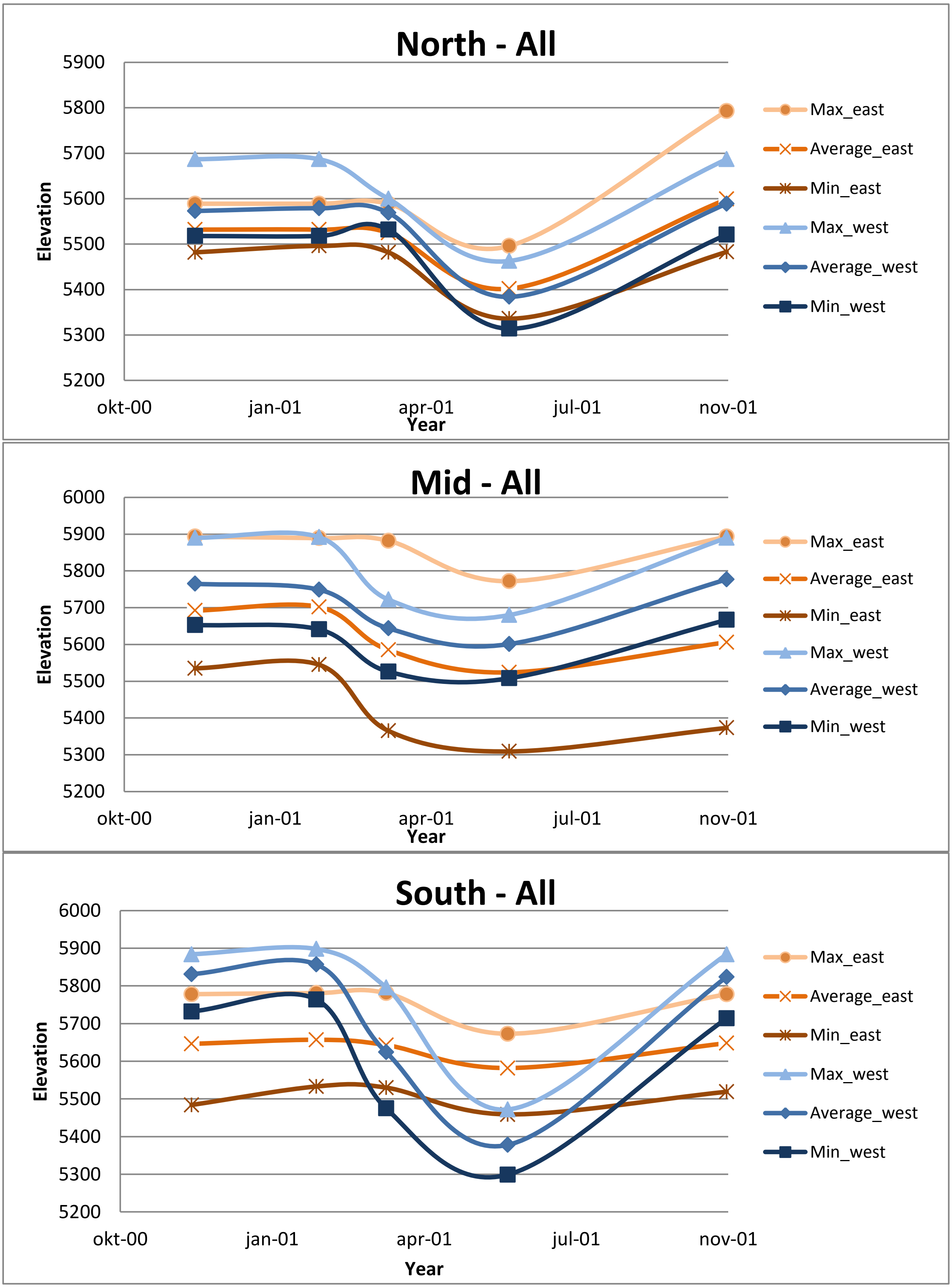


Figure 33: Snowline elevations of north, mid and south glaciers from November 2000 to November 2001

5.2. Variation through years

As said in 5.1.1. the winter months are used to compare difference in snowline elevation for different years because these are more constant. Again, we use three different subsets to compare differences in location and orientation. First, we compare the 3 glaciers on the eastern side of Nyainqêntanglha. Then, we compare the 3 glaciers on the western side. At last, we look at the absolute difference between these eastern and western glaciers.

5.2.1. Eastern variation

Figure 34 shows the results of the eastern glaciers snowline variation. It is clearly visible that the snowlines are much more constant than in figures 31, 32 and 33. However, we see a slight increase of the snowlines through the year. In the North this increase is less than in the South and the middle, which are almost equally steep. The increase is also higher between 2008 and 2013 than from 2001 to 2008. Another difference is shown in absolute elevation. We see that the snowline elevation in the mid-east is slightly higher than the south-east and much higher than the north-east. Also, the variation between maximum and minimum value is for the mid-east much bigger than for south-east and also for north-east.

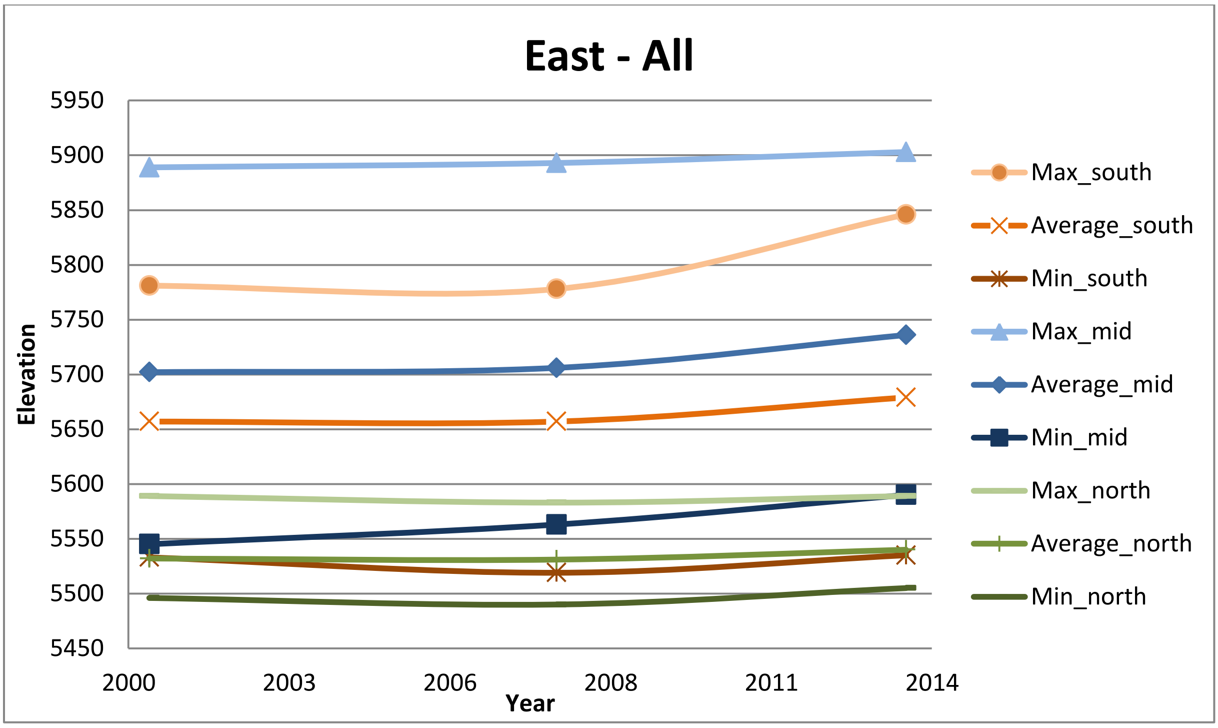


Figure 34: Snowline elevations of eastern section from February 2001 to December 2013.

5.2.2. Western variation

Figure 35 shows the results of the western glaciers snowline variation. It is clearly visible that every snowline is now decreasing through the years. In the north this decrease is more than in the south and much more than the middle, which is almost a straight line. The decrease takes place almost entirely between 2001 and 2008. From 2008 to 2013 the decrease is minimal, except for the maximum of north-west, which has a completely different shape than the rest. Another difference is, again, shown in absolute elevation. We now see an increasing elevation from north to south. In the north-west the elevation is lowest; in the south-west the elevation is highest. The variation between maximum and minimum value is almost the same for north, mid and south.

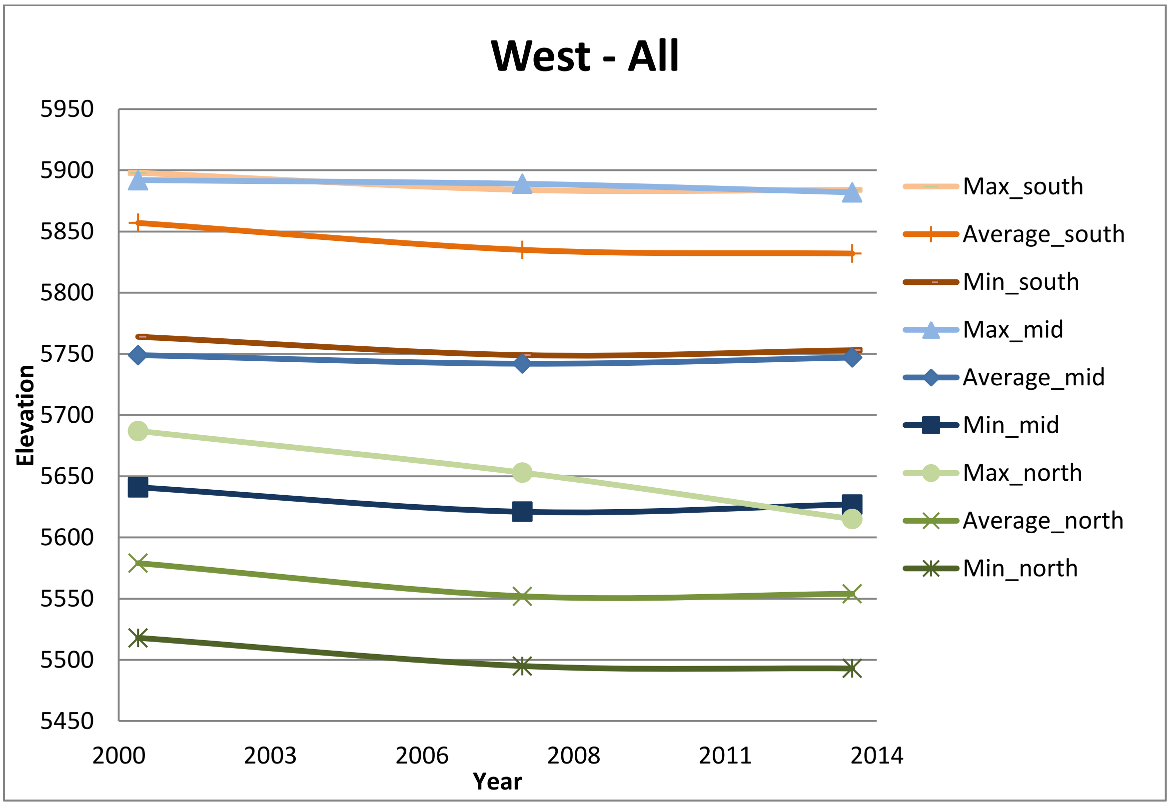


Figure 35: Snowline elevations of western section from February 2001 to December 2013.

5.2.3. East-West variation

For the difference in east-west variation all 3 options, North, Mid and South, are shown in figure 36. In 5.1.1. and 5.1.2. was showed that the eastern lines are increasing and the western lines are decreasing. We also see the North-west outlier that has a completely different shape. Except for that outlier, the difference in absolute elevation in the northern glaciers is very small. We see that the difference from the decreasing West and increasing East is much smaller in 2013 than in 2001. The western snowlines now still have a higher absolute elevation than the eastern snowlines, but this difference will be levelled out if it continues like this. The same holds for the middle glaciers. This is different for the southern glaciers. There the maximum value of the East is almost the same as the minimum value for the West. The western snowlines are much higher than the eastern snowlines.

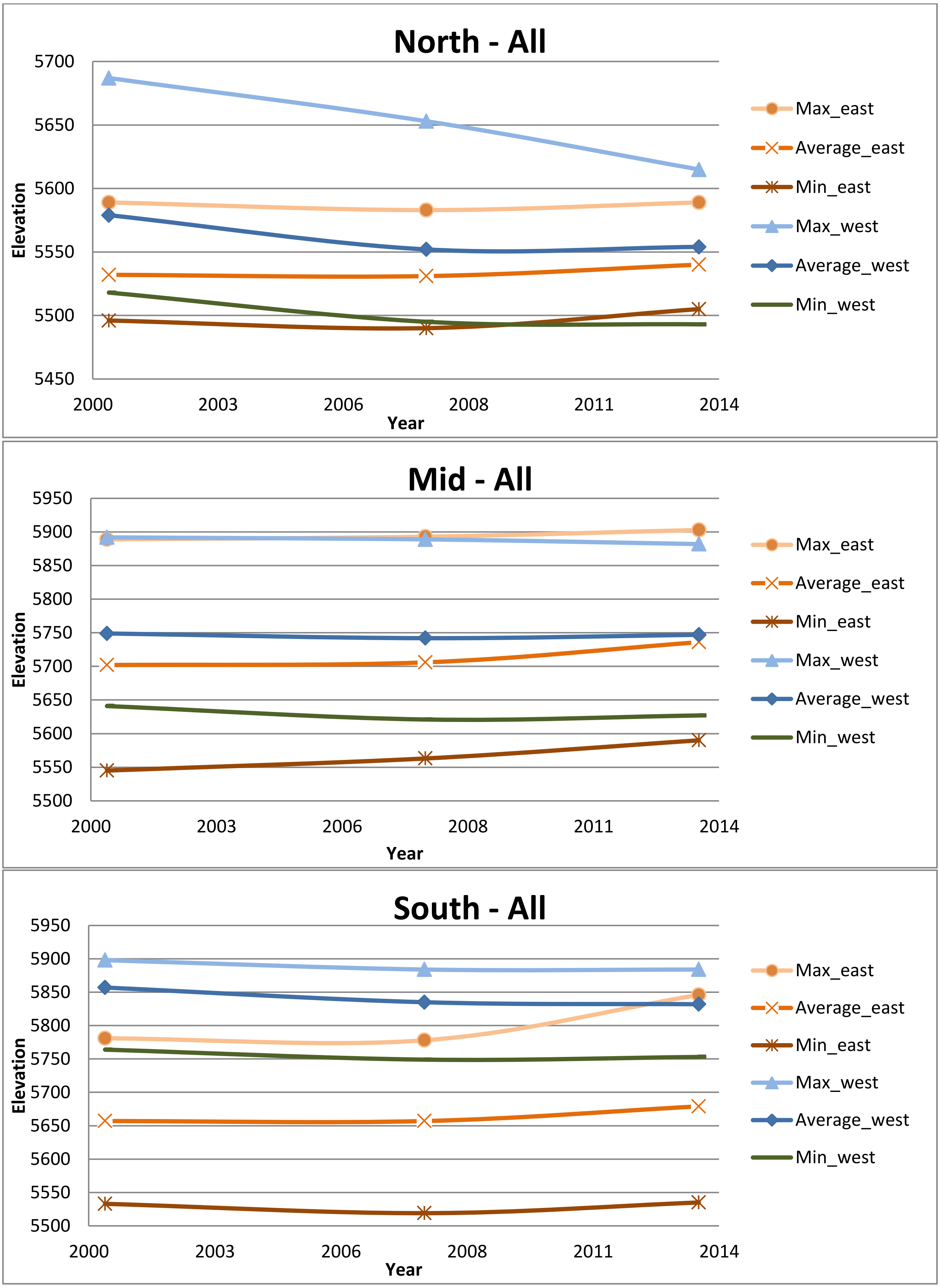


Figure 36: Snowline elevations of north, mid and south glaciers from February 2001 to December 2013

6. Conclusions and recommendations

6.1. Conclusions

As from section 1.1. we have set the following research questions, that will be answered in mostly chronological order:

- How to detect the snowline on spectral data (like Landsat)?
- How does the snowline elevation change through one year?
- How does the snowline elevation change through the last few years?
- What is the influence of location and orientation on snowlines?
- How are the differences in elevation, location and orientation explained?
- How accurate is the snowline?

There are many ways to detect snowlines on spectral data like Landsat. The main requirement for detecting the snowline is a good classification for snow. Manual classification isn't precise enough to give an accurate snowline. The semi-automatic classification plugin in QGIS can give a rough classification for snow but when spectral signatures of other land covers are much alike the classification loses its accuracy. Also the classification of snow is not extractable to compare different data. GLIMS glacier mask doesn't separate ice and snow and also shows a shift on the ridge of Nyainqêntanglha. GLIMS is therefore only useful to make sure we deal with snow that is lying on a glacier. For classifying snow the best method is using the Normalized-Difference Snow Index. This method uses the high reflectivity of snow in the visible part of the EM spectrum and the highly absorptivity in the near-infrared/short-wave infrared part of the spectrum. Polygons of the snow cover are made to extract and compare different datasets.
The second part for detecting snowline is the elevation. Different ways to extract the values of Global Digital Elevation Model (GDEM) of ASTER to the snowlines are compared. Making a relief or contour lines gives a good image of the mountains shape but not exact values of the snowlines. The Profile Tool in QGIS gives exact values but the process takes a lot of time to make for each glacier and it's hard to compare all these separate profiles. When making a grid of points with values of ASTER GDEM, a selection can be picked for every snowline. For this selection an average, maximum and minimum height is extracted. These values are very useful to compare and give an estimation of the movement of snowlines through different seasons or different years.

The snowline elevation through one year resulted in what we expected from literature studies: a much lower snowline in the summer months than in the winter. This is because of the wet season in summer, May till September, and the dry season in winter, October till April. Although we only had data for the month June, this snowline is much lower than all the other months on every location of the mountain. The difference between November 20000 and February 20001 are negligible and also March is almost the same, sometimes a bit lower, probably due to the first snowfall in the Mid and Southern parts of Nyainqêntanglha. In the south-western part the difference between dry and wet season is about 450 meters, while in the north- and southeast it is about 150meters. Furthermore, some other things are noticed: the absolute elevation of the North is lower than the South and the differences between East and West are greater in the South than in the North. From 3.2. and Billemont, 2010 we adopted that the accuracy of ASTER GDEM in Tibet was about 11 meter. With values of around 100 to 450 meters, we can say this gives an accurate estimation of the movement of the snowlines.

Although former mass balance studies showed most of the times a shrinkage of the glaciers on the Nyainqêntanglha Mountains from the 70's till now, this is not the same for the snowlines in the last 13 years. The snowlines much differ in the eastern side and the western side of Nyainqêntanglha. The western snowlines are much higher than the eastern, so there's more snow on the eastern side of the mountain. But, on the eastern side the snowline is increasing. From 2.1. we have seen that in the winter months the snowline may be an approximation of the Equilibrium Line Altitude (ELA). This means the ELA on the eastern side is a negative value, which means there is more ablation than accumulation and this could indicate the glacier is shrinking. On the other hand shows the western side an decrease of the snowline. This means a positive value for the ELA, more accumulation than ablation, an indication of a growing glacier. The increase of the snowline the eastern section is about 40 meter, where the decrease of the snowline in the western section is about 30 meter. So although the western section now has a higher absolute elevation for the snowline than the eastern section, this difference is going to be flattened. One other remarkable thing is that the absolute elevation of the snowlines is lower in the North than in the South, whereas the differences in absolute elevation between East and West in the Southern parts are greater than in the Northern.
With the same accuracy of ASTER GDEM in Tibet of Billemont (2010) of 11 meter, we can say that 30/40 meters given a proper assumption about the snowlines movements.

All these differences between North-South, East-West, positive-negative ELA need an explanation. The simplest explanation for most of them is the monsoons, told in the Introduction and figure 1. There are different opinions about the influence of precipitation on glacier behaviour. Some say it's the most important factor (Zhang et al, 2013), some say it's a negligible factor (Zhou et al, 2010). For snowlines we don't know the influence of precipitation. The Indian Monsoon comes from the South/South-East direction and therefore should give more precipitation on the South/South-East parts of Nyainqêntanglha. If we look at our results this doesn't match. In the North is more snow than in the South and in the West is a positive ELA, where it is negative on the East. The direction of the Westerlies is able to lead to the results found. It is a possible explanation that the influence of Westerlies is greater than the Indian Monsoon on the Nyainqêntanglha Mountains. It is also a possible explanation that precipitation is indeed not a great factor in snowline variations. The lower snowline in the North than in the South can be maybe influenced by the temperature. The North has a more land inward location and therefore can have a lower temperature which could lead to more snow in the Northern part of Nyainqêntanglha. Melting by the sun or a different albedo on different locations are some other factors. Albedo is decreasing in the Western parts of the Nyainqêntanglha (Qu et al, 2014), but on the Eastern parts is no comparable information available. The albedo in the eastern parts must be even less to explain the results of this research. The melting of the sun can affect the eastern side of Nyainqêntanglha more than the western side, but there's no scientific evidence for this phenomenon.

6.2. Recommendations

Several problems occurred during this study. Also many suggestions to improve the results and conclusions about the subject are proposed.

6.2.1. NDSI threshold calibration

For the classification with use of the semi-automatic classification plugin an automatic atmospheric correction was applied to reduce the effect of clouds, smoke or haze. For the NDSI method this correction was not applied. Research from Burns and Nolin, 2014 showed a noticeable difference in

NDSI threshold with and without atmospheric and topographic correction, especially on debris-free glacier area. A debris-free glacier area with an uncorrected NDSI image may be underestimating debris-free glacier area if the same threshold is used. Small differences in the choice of threshold associated with a particular NDSI scene can have significant effects on the estimation of debris-free glacier area. For this research, the threshold was always checked with the data, but nevertheless a good improvement would be to do first atmospheric and topographic correction on the used data.

6.2.2. SRTM vs. ASTER GDEM

From 3.2 and Frey, Paul, 2011 we assumed that ASTER GDEM and SRTM would both be suitable for compilation of topographic parameters in glacier inventories, especially when parameters are averaged over a greater area, instead of parameters that depend on a single DEM value. For the snowline elevation we used a subset of some different DEM values of ASTER GDEM but not a really great area. It would be a good suggestion to investigate if using SRTM in the same method would give different values for the elevation.
When we make a difference plot of ASTER GDEM and SRTM we see that especially in the mountainous areas there's a difference. For figure 37, white color is for a difference >30 or <-30 meters between ASTER GDEM and SRTM. This strikes quite a great area of Nyainqêntanglha.

Figure 37: Difference plot between ASTER GDEM and SRTM, white color is for a difference >30 or <-30 meters

6.2.3. MODIS snow cover

In this research the usage of GLIMS glacier mask was tried. This glacier mask didn't separate snow and ice and also was shifted in the area of Nyainqêntanglha and was not usable for the classification of snowlines. The MODIS snow cover product would be suggested to try. Moderate Resolution Imaging Spectroradiometer (MODIS) is a passive imaging spectroradiometer, arranged in 36 spectral bands. This snow cover product is used before in research in Tibet, also with the use of NDSI (Tang, B-H. et al, 2013). The resolution of MODIS is only 250 meters but it would be interesting to investigate if the MODIS snow cover product is useful for snowline detection.

6.2.4. Albedo research

To come to a better explanation of the results of this research, more knowledge about the Nyainqêntanglha Mountains is needed. For example about the effect of different albedo and the different values of albedo at different locations of the Mountain Range. If the albedo on the western side is much higher than on the eastern side of Nyainqêntanglha, this would be a good explanation why on the eastern side there ELA is negative although there's much precipitation from the Indian Monsoon. With a low albedo this snow would disappear faster because the heat of the sun is adsorbed.

6.2.5. Advanced software

From 4.6. we know that the semi-automatic classification plugin is quite an exact process but very time consuming and it often gets stuck on a regular computer. QGIS is open source software and is therefore perfect for most regular applications but with more advanced software, like ENVI, these sorts of automatic classification programs may work better.

6.2.6. Outliers in yearly variation

For the variation through years 3 dataset were used from 2001 till 2013. The conclusions were drawn from only this 3 results. The results will be more reliable if more different datasets are processed to avoid outliers. There is a possibility than in one year the monsoon became sooner or later and this influenced the precipitation. Or an accidental snowstorm in winter, causing a lower snowline, just some days before the data was taken can have a great influence on the conclusions.

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