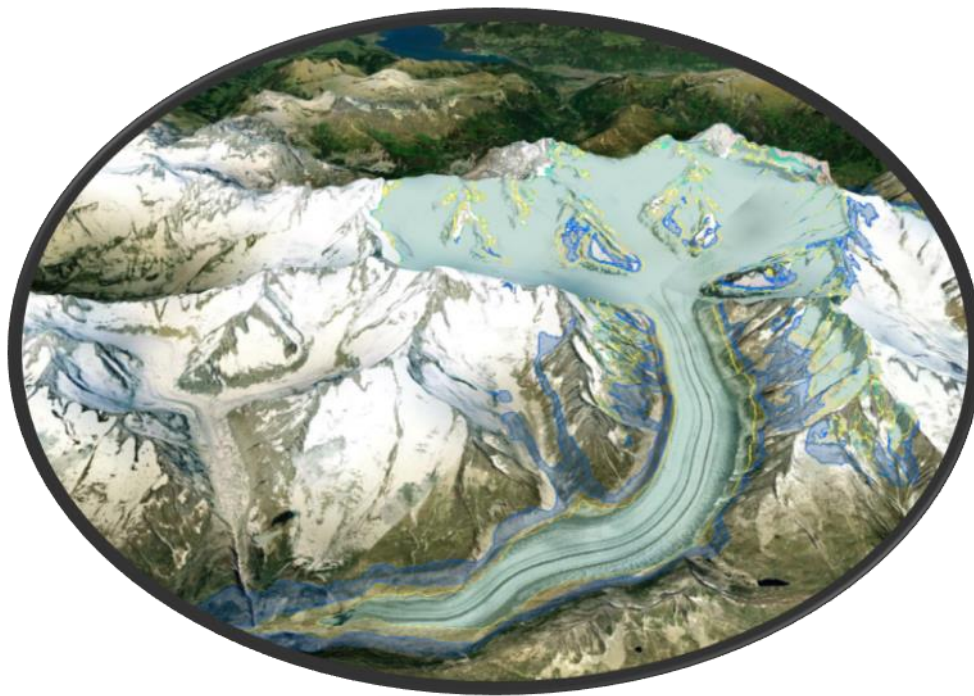


Complementary Certificate in Geomatics

Orientation: Remote sensing and environmental monitoring

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**Study of the recolonisation of glacial fronts by vegetation using
the Swiss Data Cube.**

Under the supervision of:

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RÉSUMÉ

L'observation de l'évolution de la végétation dans les avant-pays des glaciers a jusqu'à présent été faite en se basant essentiellement sur des données de terrain. Par conséquent, profitant de la nouvelle tendance au partage de données ouvertes, ce projet propose une méthode d'analyse d'un jeu de données composé de fichiers raster contenant les valeurs NDVI moyennes annuelles de la Suisse pendant une fenêtre temporelle allant de 1984 à 2018.

Six glaciers ont été choisis pour l'étude : Le glacier d'Arolla, le glacier d'Allalin, le glacier d'Aletsch, le glacier de Grindelwald, le glacier de Morterastch et le glacier du Chablais.

Les profils d'échantillonnage proposés par l'étude ont révélé qu'avec le passage des années, les valeurs NDVI augmentent dans les points d'échantillonnage sur les zones avec végétation, tandis que dans les points avec un sol plus exposé, les valeurs ont tendance à devenir plus négatives.

Trois zones d'intérêt principales ont été définies pour chaque glacier sur la base des contours des glaciers pour les années 1850, 1973 et 2010, couvrant les variations de surface des glaciers de 1850 à 2010. Ainsi, la zone 1 représente la surface du glacier mesurée en 2010, qui est normalement couverte de glace générant des signaux NDVI négatifs ou proches de zéro. La zone 2 représente la zone située entre les contours de 1973 et de 2010, et est généralement composée de sol et de débris exposés, avec peu ou aucune végétation. La zone 3 représente la zone entre les contours de 1850 et 1973 et est composée de sol, de quelques plans d'eau et de végétation temporaire et fixe, nous fournissant des données importantes sur la succession annuelle de la végétation.

Ces zones ont ensuite été utilisées comme limites pour des analyses statistiques et comparées avec les inventaires les plus actuels de changement de longueur des glaciers disponibles en ligne. Les résultats ont mis en évidence un modèle cyclique dans le signal NDVI au sein des zones d'intérêt. Au total, six cycles ont été identifiés (1984 - 1986 ; 1987 - 1986 ; 1990 - 1996 ; 1997 - 2001 ; 2003 - 2004 ; 2004 - 2006), où les changements de NDVI suivent la variation de la longueur des glaciers, révélant ainsi la relation climatique entre les deux ensembles de données. En outre, les glaciers d'Aletsch et de Grindelwald se distinguent comme les glaciers suisses les plus touchés par le réchauffement climatique au cours des dernières décennies, montrant les variations positives de NDVI les plus élevées de l'ensemble de données.

ABSTRACT

Observing vegetation evolution in glacier forelands has until now been made based basically on field data. Therefore, taking advantage of the new trend of sharing open datasets, this project proposes a method to analyse a dataset composed of raster files containing the annual mean NDVI values of Switzerland during a time window spanning from 1984 to 2018.

Six glaciers were chosen for the study: Arolla glacier, Allalin glacier, Aletsch glacier, Grindelwald glacier, Morterastch glacier and Chablais glaciers.

The sampling profiles proposed by the study revealed that with the passing of the years, the NDVI values increased in the sampling points over areas with vegetation, while in the points with more exposed soil the values tend to become more negative.

Three main interest zones were defined for each glacier based on glacier outlines for the years 1850, 1973 and 2010, covering the glacier surface variations from 1850 to 2010. Therefore, the zone 1 represents the glacier area measured in 2010, which is normally covered by ice generating negative or near zero NDVI signals. The zone 2 represents the area between the 1973 and 2010 outlines, and is generally composed of exposed soil and debris, populated by little to no vegetation. Zone 3 represents the area between the 1850 and 1973 outlines and is composed of soil, some water bodies and both temporary and fixed vegetation, providing us with important data on the annual vegetation succession.

These zones were then used as boundaries to statistical analyses and compared with the most actual inventories in glacier length change disponible online. The results have highlighted a cyclical pattern in the NDVI signal within the zones of interest. In total six cycles were identified (1984 - 1986; 1987 - 1986; 1990 - 1996; 1997 - 2001; 2003 - 2004; 2004 - 2006), where the NDVI changes follow the variation in glacier length, revealing the climatic relationship between the two datasets. In addition, the Aletsch and Grindelwald Glaciers stand out as the most affected Swiss glaciers affected by global warming in the last decades, showing the highest positive NDVI variations of the dataset.

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1 INTRODUCTION

1.1 Research objectives

Glaciers are an important indicator of climate change. In the Alps they have been retreating for several years and once the ice has disappeared, a bare area is left that can be recolonised by vegetation. The aim of this internship is to use the Swiss Data Cube and in particular the 35-year time series (annual) of the NDVI vegetation index on a selection of Alpine glaciers in order to study the dynamics of recolonisation of glacier fronts by vegetation.

Objectives:

1. Familiarisation with the Swiss Data Cube and the NDVI time series.
2. Selection of alpine glaciers to be studied.
3. Analysis of data on the dynamics of vegetation recolonisation.

The above objectives will be aborded with extensive bibliographic research followed by a detailed methodology to process the database.

1.2 Climate change and glacier volume loss

The Swiss Alps represents the major natural monument of the country. It is generally divided in Western Alps, Eastern Alps and the northern part, the Bernese Alps to the Appenzell Alps. The southern part is composed by the Mont Blanc massif to the Bernina massif and are shared with other countries such as Italy, Austria, Liechtenstein and France.

The last glaciations greatly transformed Switzerland's landscape which effected many valleys are by glacial erosion. After the Little Ice Age (LIA) maximum, the Alpine glaciers have lost more than 60% of their area (Haeberli et al., 2019). After completely cover the Swiss Plateau, the glaciers started melting in an accelerated rate leaving remnants only in high mountain areas (Nussbaumer et al., 2011)

After the event known as the Little Ice Age, the glacier cover of the Alps began to decrease in a trend that by 1850 (Figure 1) assumed an alarming shift that reveals the increasingly rapid tendency of reduction in glacier length (Nussbaumer et al., 2011). After the last positive mass variation of the Swiss glaciers in the 1980s, the rates of mass change have become increasingly negative(M Fischer et al., 2015).

A recent study from the University of Erlangen-Nuremberg (Sommer et al., 2020). has denounced reduction in the size and volume of most Alpine glaciers. An overall retreat of $\sim 39 \pm 9 \text{ km}^2 \text{ a}^{-1}$, corresponding to an area loss rate of $\sim 1.8\% \text{ a}^{-1}$ was measured by the scientists indicating loss of one-sixth of their total volume in the last fourteen years.

Looking separately at the different Alpine regions of Switzerland, studies (Jouvet et al., 2011; Sommer et al., 2020; Zemp et al., 2015) have demonstrated that the highest mass loss rates are measured in the Western Alps : Bernese and Pennine Alps.

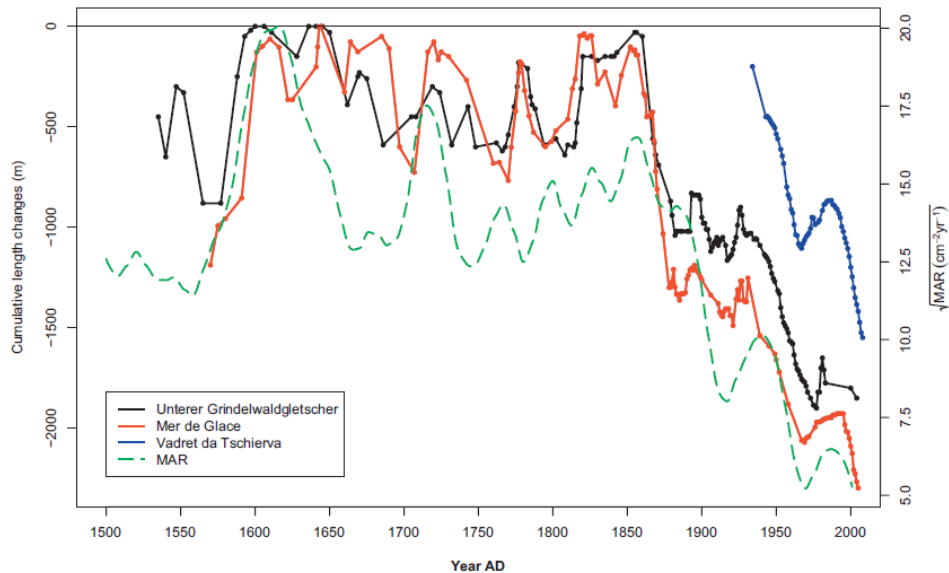


Figure 1 - Comparison of Alpine glacier length changes and mass accumulation rates (MAR) in Lake Silvaplana during the past 500 years (dots: reconstructed/measured values; lines: linear interpolation) adapted from Nussbaumer et al., (2011).

1.3 study area

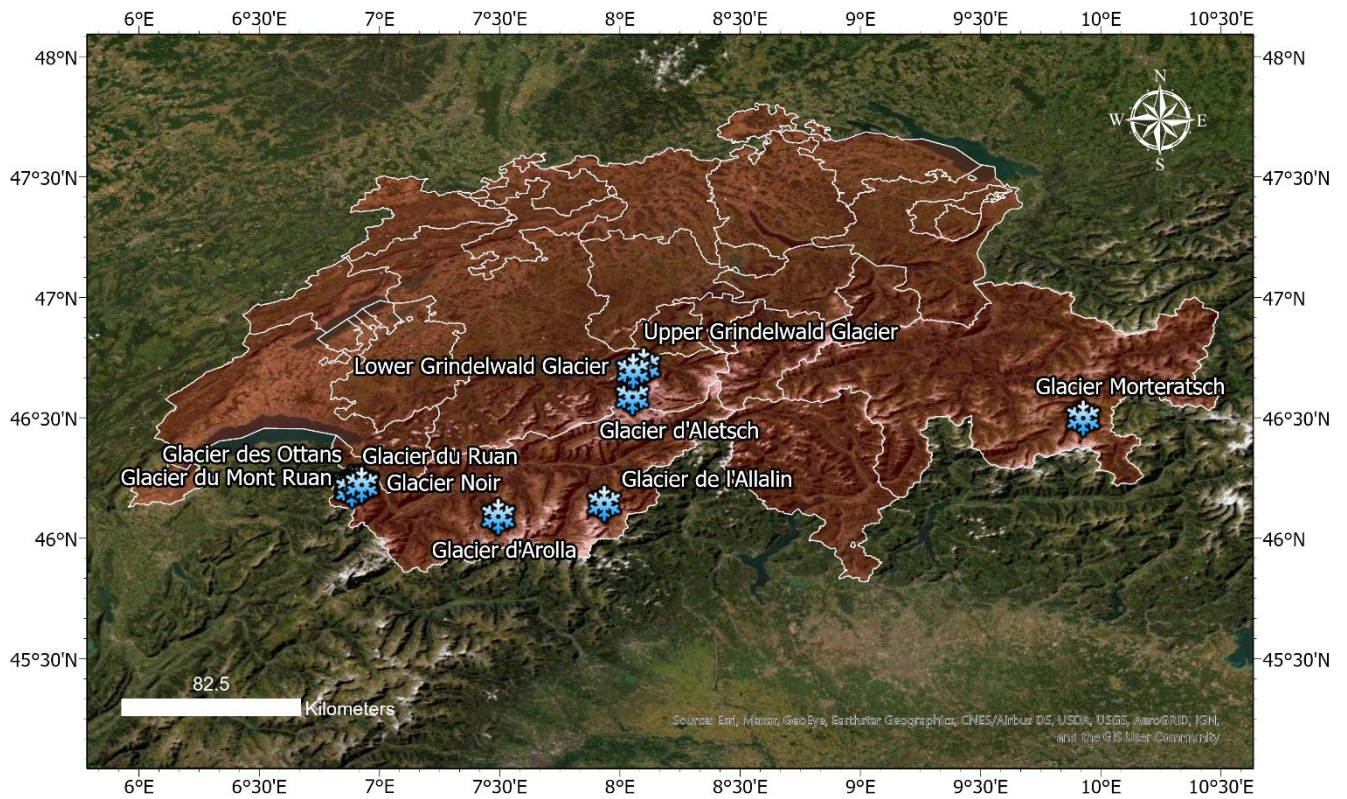


Figure 2 - Location of the glaciers to be studied in the Swiss Alps.

For the present study, 6 glaciers distributed over the Swiss Alps have been chosen to get a general idea of each region (Figure 2). The Aletsch and Gindelwald glaciers represent the northern Berne Alps. The Allalin and Arolla glaciers represent the southern alps (Penine Alps) while the Monterastch and Chablais glaciers represent the eastern and western Alps, respectively.

1.3.1 Geography and Climate

The Swiss Alps can be divided into three different zones which are delimited according to altitude and climate. (Heinz Staffelbach, 2010). The climatic changes we have experienced in the last decades have influenced the limits of these zones, thus having direct consequences on the migration of vegetation along the Swiss Alps (Holzinger et al., 2008; Theurillat & Guisan, 2001).

1.3.1.1 Subalpine zone

The Subalpine zone is the region that lies below the tree line. It is the largest and most important region. The vegetation is composed by conifers forests above 1,200–1,400 meters. The upper limit of the Subalpine zone differs in some regions but is about 1,800 meters on the north side of the Alps and about 2,000 meters on the south side.

1.3.1.2 Alpine zone

The higher altitudes (2,800 and 3,200 meters) and the low average temperatures in the Alpine zone keeps it clear of trees. Therefore, this zone contains mostly grass and small plants along with mountain flowers. The extent of the Alpine zone is limited by the first permanent snow, its altitude greatly varies depending on the location.

1.3.1.3 Glacial zone

The glacial zone is the area of permanent snow and ice (over 3,200 metres). In this area the snow accumulates and after compaction transforms in ice, which flows down the valleys. The present study will be carried out mainly in this area, where the glaciers are concentrated.

1.3.2 Bernese Alps:

1.3.2.1 Aletsch glacier:

The Grosser Aletsch glacier is the largest mass of ice in the Swiss Alps (Figure 3).



Figure 3 - 3D view of the Aletsch glacier in the Bernese Alps. Image from Google Earth Pro.

The length of the Grosser Aletschgletscher has been measured since 1870. In 1918, the first pile was installed at an altitude of 3350 metres on the Jungfrau and the snow accumulation and the annual mass balance have been measured almost continuously up to the present day (Jürg & Hambrey, 2020). Also, between the 1940s and 1980s, the spatial distribution of the glacier mass balance was recorded by means of an intensive measurement network. So, all this monitoring can be extremely useful for this study.

1.3.2.2 Upper and Lower Grindelwald glaciers:

The Grindelwald glacier is located in the canton of Bern and actually it is divided into upper and lower part (Figure 4).

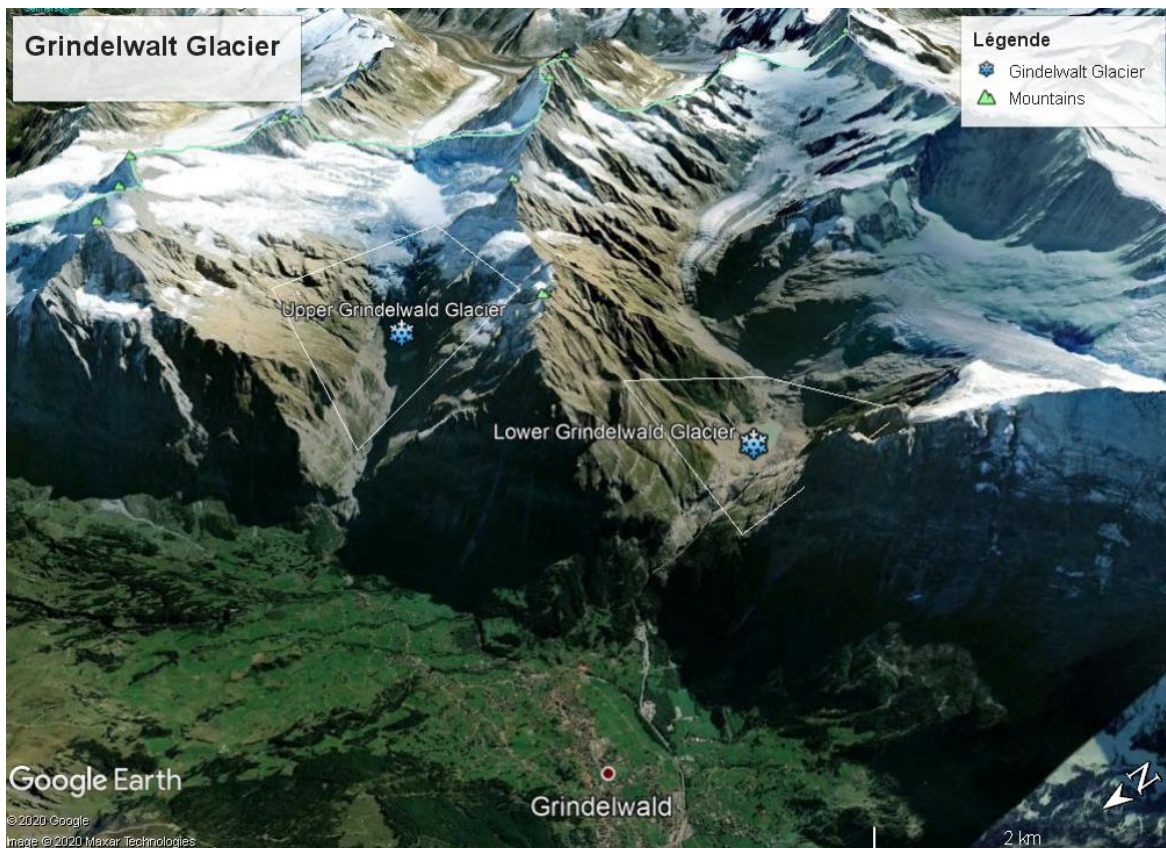


Figure 4 - 3D view of the upper and lower Grindelwald glacier in the Bernese Alps. Image from Google Earth Pro.

The upper part, Oberer Grindelwaldgletscher, has an area of 8.42 km² and a length of 6.22 km (data from 2009). In 1973, the glacier had an area of 9.42 km². The relative change in area is equivalent to -10.65 % (Jürg & Hambrey, 2017b).

During the Little Ice Age (LIA), the lower part, Unterer Grindelwaldgletscher, ended either in the rock terraces above the glacier gorge or at least six times further down the valley floor. The formation of a fan-shaped tongue during these advances had a direct impact on the local population and agriculture (Tagliabue, 2013).

Over the last 160 years, the two Grindelwald glaciers have receded considerably. Nevertheless, the Unterer Grindelwaldgletscher is still one of the largest glaciers in Switzerland today. In the upper Ischmeer area, near the Schreckhorn hut, the glacier has a maximum ice thickness of around 230 m (GLAMOS - Glacier Monitoring Switzerland, 2019).

1.3.3 Pennine Alps

1.3.3.1 Allalin Glacier:

The Allalin glacier is located in the canton of Valais and borders the Allalinhorn, Rimpfischhorn and Strahlhorn to the west (Figure 5). It has an area of 9.17 km² and a length of 6.77 km (Alean & Hambrey, 2017).

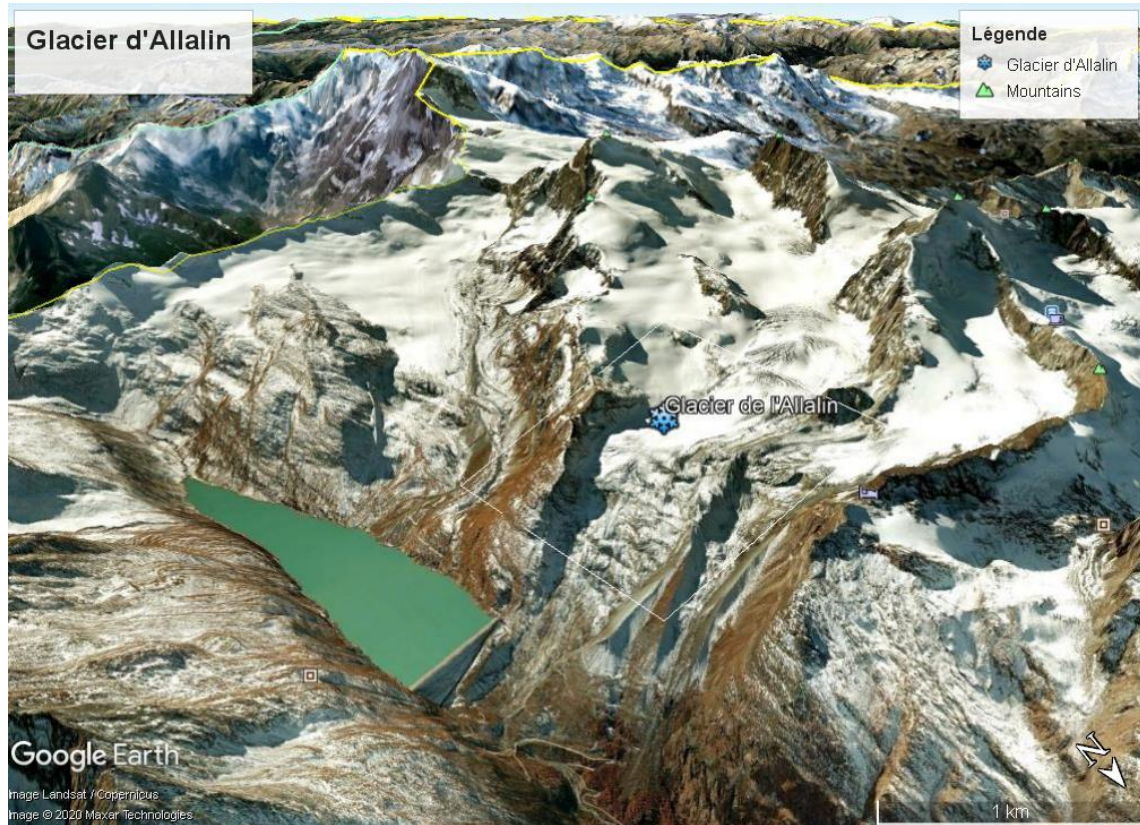


Figure 5 - 3D view of the Allain glacier in the Pennine Alps. The Mattmark dam is located in the bottom middle of the picture. Image from Google Earth Pro

In 1973, the glacier had a surface of 9,98 km² and the relative change in area is equivalent to -8.11%. On August 30, 1965, an ice avalanche devastated the Mattmark dam construction site and 88 people died in this tragedy (RTS, 2015).

After the ice avalanche of 1965, the glacier regained in five years the 400 m it had lost, to extend almost to the bottom of the valley in the mid-eighties. Since then, it has been retreating and its volume has decreased by an average of 1.8 million m³ per year since then (Huss et al., 2015).

The local hydropower company managing the energy production in the Mattmark area promotes a glaciological monitoring program to recognizing potentially dangerous glacier behaviour at an early stage. The evolution of the glacier fronts and volume changes is measured annually.

1.3.3.2 Arolla Glacier:

The Arolla Glacier is situated in the Pennine Alps in the canton of Valais in Switzerland (Figure 6). In 1973 it had an area of 13.17 km² (Glacier Monitoring Switzerland, 2019).

The Arolla glacier is in fact composed of two glaciers: The Mont Collon glacier (Lower part) and the

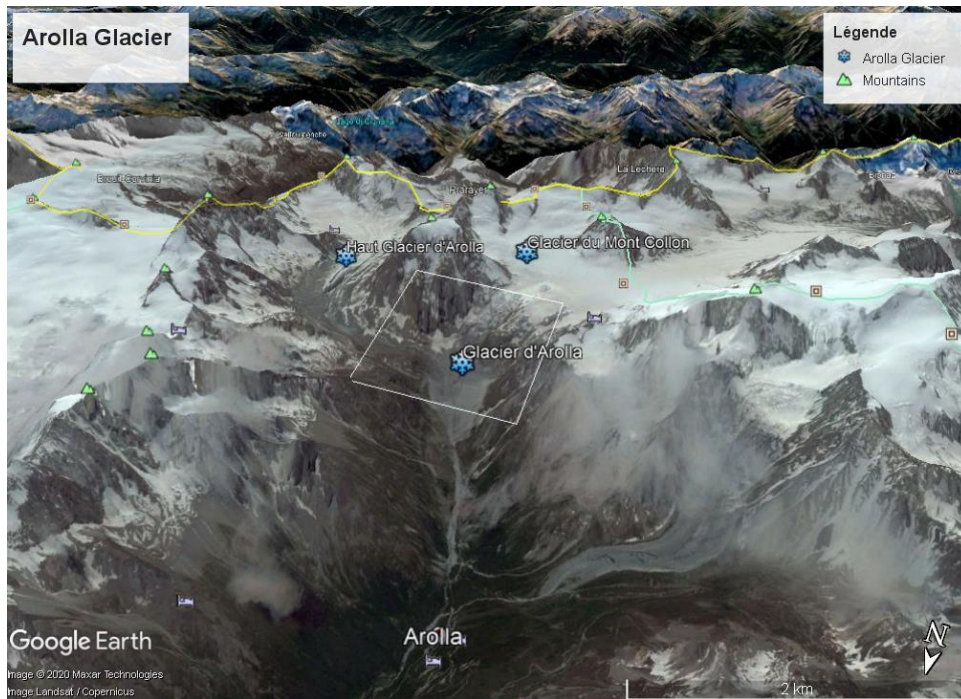


Figure 6 - 3D view of the Upper (*Haut Glacier D'Arolla*) and lower (*Glacier du Mont Collon*) parts of Arolla glacier in the Pennine Alps. Image from Google Earth Pro.

Haut Glacier d'Arolla (Upper part).

The Lower part (*Glacier du Mont Collon*) follows this steep descent called "Bas Arolla glacier." It continues for about 1 kilometer to the north and the ice tongue stops at an altitude of 2160 meters (2007). The glacier emerges from the Borgne d'Arolla which then joins the Borgne Ferpècle then flows into the Val d'Herens before reach the Rhone plain. (Valais Wallis, 2021)

The upper part (*Haut Glacier d'Arolla*) is located east of Mount Collon measuring 4 km of length and a 1 km of width covering an area of 5 km². (Jürg & Hambrey, 2017a) It originates from the snowfields hanging north of Mount Brulé (3585 m) and then descends with a slope of 12 to 15% towards the northwest and then north. The glacier tongue ends at an altitude of 2550 m in 2007 (Glaciers Monitoring Switzerland, 2019)

1.3.4 Chablais

1.3.4.1 Group of Grand Ruan glaciers:

The “Grand Mont Ruan”, in the swiss canton of Valais (Figure 7), is a summit of the Giffre Massif on the french border and culminates at 3,056 m, slightly exceeding the average altitude of permanent snow formation called "eternal" (about 2,900 m in the Northern Alps). This summit has the peculiarity of sheltering on its slopes several rather imposing glaciers: “Glacier du Ruan”, “Glacier des Fonds”, “Glaciers de Prazon” and “Glacier de la Tour Sallière”. These glaciers are probably the current vestiges of the last period of glaciation and now are threatened by the global warming of the last thirty years probably disappearing during the 21st century (Haeberli et al., 2019).

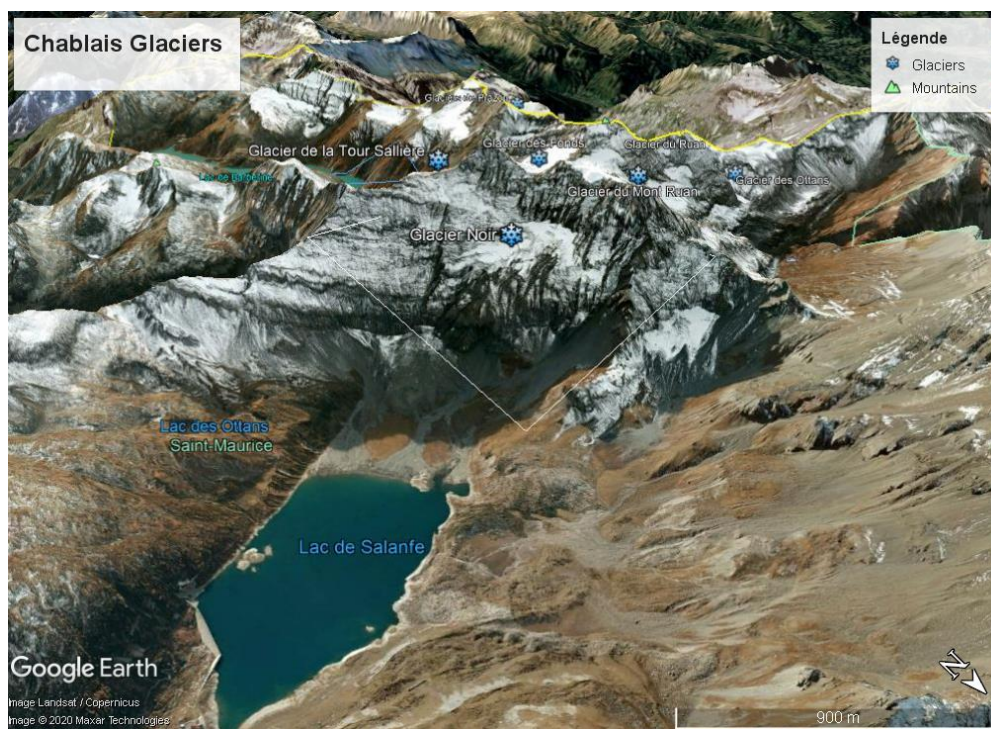


Figure 7 - 3D view of the Mont Ruan in the Chablais Region. The Salanfe lake is fed by the melting of the multiple glaciers that cover Mount Ruan. Image from Google Earth Pro.

1.3.5 Western Alps

1.3.5.1 Morteratsch Glacier:

The Morteratsch glacier (Vadret da Morteratsch) is located in the canton of Graubünden and it's considered the third largest and the most massive glacier (by volume) in the south-eastern alps (Figure 8). It has an area of 14.87 km² and a length of 7.43 km (Glacier Monitoring Switzerland,

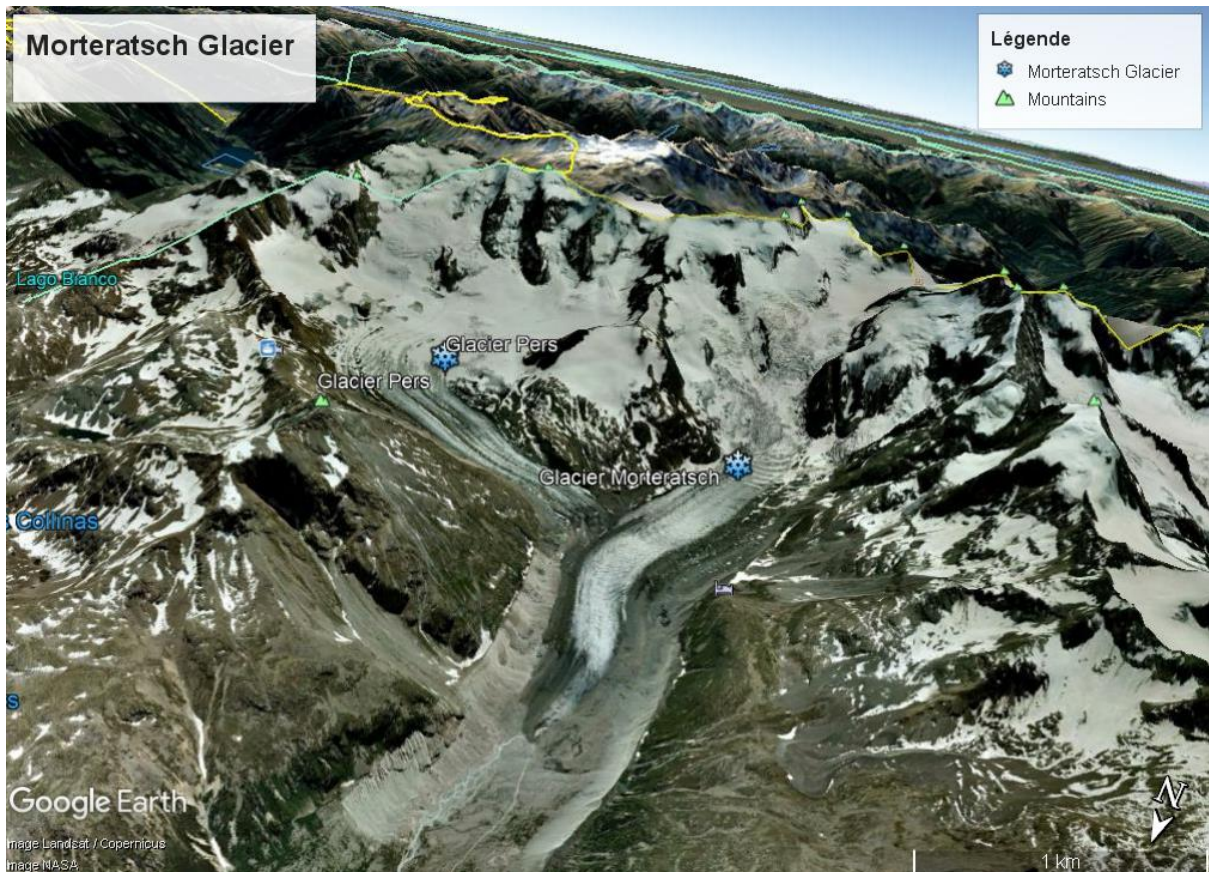


Figure 8 - 3D view of the Pers Glacier that joins the Morteratsch Glacier in the Rhaetian Alps. Image from Google Earth Pro.

2019).

Together with the Pers Glacier, originating at Piz Palü, which joins the Morteratsch just below a rock formation. per year. This long-term average has markedly increased in recent years, reaching 30 meters per year from 1999–2005. During the last ten years, it lost another 1 kilometre (Glacier Monitoring Switzerland, 2019).

2 DATA AND METHODS

2.1 DATA

In order to carry out the desired analyses on the Swiss glaciers a compilation was proposed using data provided by national and international glacier monitoring sites plus data from NDVI (Normalized Difference Vegetation Index) “Annual Mean – Switzerland” provided by the Swiss Data Cube.

2.1.1 GLAMOS

The project GLAMOS (Glacier Monitoring in Switzerland) systematically documents and monitors long-term glacier changes in the Swiss Alps. The project is operated jointly by the ETH Zurich and the Universities of Fribourg and Zurich and is in cooperation with the Cryospheric Commission (CC). The Federal Office for the Environment (FOEN), MeteoSwiss within the framework of GCOS Switzerland, the Swiss Academy of Sciences (SCNAT), and the Federal Office of Topography Swisstopo are the financial sponsors, and the data are freely available and could be used for scientific and non-commercial propose under the requirement of correct indication of the source. The data can be downloaded directly from the GLAMOS web site.

Dataset:

The Swiss Glacier Inventory 2010 provides areas and outlines of all glaciers in Switzerland referring to the years 2008-2011 (Mauro Fischer et al., 2014).

The Swiss Glacier Inventory 1973 provides areas and outlines of all glaciers in Switzerland referring to the year 1973 (Müller et al., 1976; Wipf et al., 2000 and Paul, 2004).

The Swiss Glacier Inventory 1850 is based on historical maps and geomorphological evidence and are delivered as a shapefile providing areas and outlines of all glaciers in Switzerland referring to the year 1850 (Maisch et al., 2000; Paul, 2003)

2.1.2 NDVI

NDVI is often used around the world to monitor drought, forecast agricultural production, assist in forecasting fire zones, and desert offensive maps. Farmers are using NDVI to facilitate crop scouting and give precision to fertilizer application and irrigation. NDVI is preferable for global vegetation monitoring since it helps to compensate for changes in lighting conditions, surface slope, exposure, and other external factors.

Put simply, NDVI is a measure of the state of plant health based on how the plant reflects light at certain frequencies (near-infrared light and red light).

Chlorophyll (a health indicator) strongly absorbs visible light, and the cellular structure of the leaves strongly reflect near-infrared light. When the plant becomes dehydrated, sick, afflicted with disease, etc., the spongy layer deteriorates, and the plant absorbs more of the near-infrared light, rather than reflecting it. Thus, observing how NIR changes compared to red light provides an accurate indication of the presence of chlorophyll, which correlates with plant health.

This study proposes to use the NDVI to investigate the development of vegetation on the areas that has been exposed by the retreatment of the glaciers among time. With this approach, we can use the vegetation to observe the variation of the front of the glaciers and consequently, changes in climate, environment, and stability of the ground (alluvial fans, riverbed, unstable moraines).

The dataset used for the project was provided by the Swiss Data Cube (SDC) in GeoTiff files that composes an annual time-series of Landsat Analysis Ready Data (ARD)-derived Normalized Difference Vegetation Index (NDVI) computed from Landsat 5 Thematic Mapper (TM) and Landsat 8 Operational Land Imager (OLI).

NDVI is calculated in accordance with the formula:

$$\frac{(NIR-R)}{NIR+R}$$

For Landsat sensors, this corresponds to the following bands:

$$\text{Landsat 5, } NDVI = \frac{\text{Band 4} - \text{Band 3}}{(\text{Band 4} + \text{Band 3})}$$

$$\text{Landsat 8, } NDVI = \frac{(\text{Band 5} - \text{Band 4})}{(\text{Band 5} + \text{Band 4})}$$

By design, the NDVI itself thus varies between -1.0 and +1.0. Free standing water which has a rather low reflectance in both spectral bands (at least away from shores) and thus result in very low positive or even slightly negative NDVI values. Soils which generally exhibit a near-infrared spectral reflectance somewhat larger than the red, and thus tend to also generate rather small positive NDVI values (say 0.1 to 0.2). Large values (from 0.6 to 0.8) indicate vegetation and its density.

2.2 METHODS

The global methodology for this research includes determining trends vegetation using NDVI in glaciers fronts. As this is a chronological analysis, the process of change detection will involve the pixel values of 33 images (1984 – 2018) to compose a solid dataset. This is done by sampling the values of images with two methods.

The first method involves the creation of sampling profiles that pass through the centre of the front of the studied glaciers. The profiles are bounded by the 1850 and 2010 outlines, sampling the annual NDVI change data within the area of interest. Studies as Fischer et al., (2019) use sampling points within the areas of interest, obtaining good results. This study proposes the use of profile lines that sample the pixels of NDVI values, providing well localized results for each year of the chronosequence.

The second component is determining the statistics for the landscape vegetation changes inside of three areas of interest. The NDVI values for each image (Year) will be analysed using the ArcGIS Pro tool “zonal statistics as a table”. As we use the same areas to calculate the statistics, The results thus will provide the chronological evolution of the vegetation within each zone separately.

The third component will be identifying different features on the study area based on NDVI threshold values. These threshold values will identify 5 different features within the study area, providing the spatial evolution of the glacial environments.

2.2.1 OGC Web Feature Service (WFS)

The Open Geospatial Consortium (OGC) Web Feature Service (WFS) was used to add geospatial information to our project about the fluctuation of glaciers. This service provides complete and reliable fluctuation features of each glacier around the world (Figure 9). By adding these points of interest to the map we can have access to all this content in a fast and practical way.

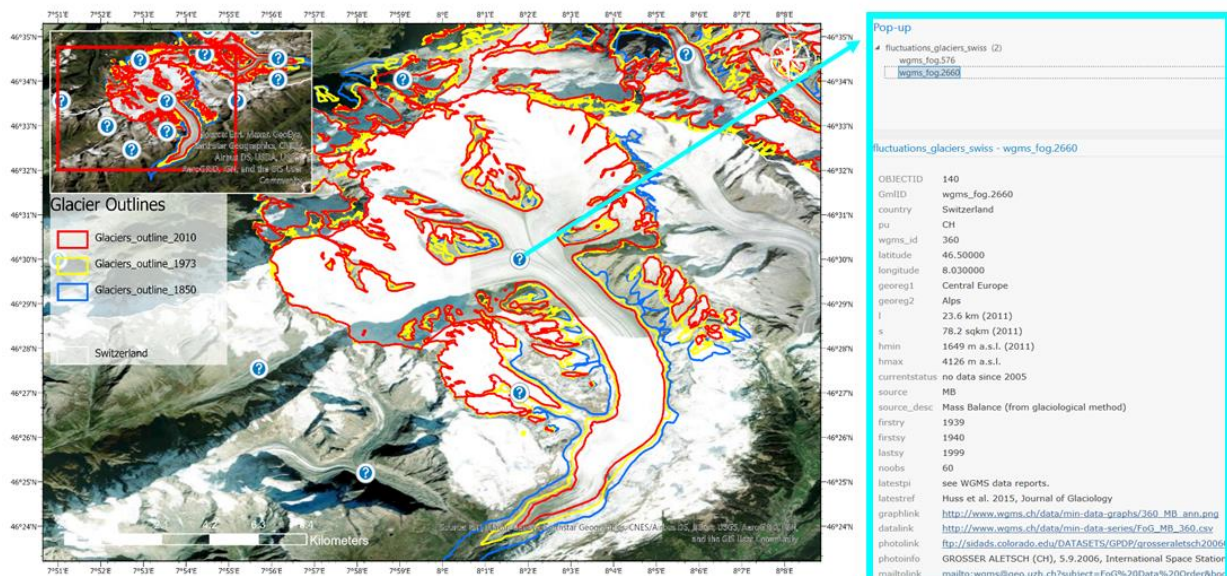


Figure 9 - Map with the points of interest that contains the information about the glacier's fluctuation (The data was downloaded from the “World glacier monitoring service”). In detail, there is an example (Aletsch glacier) of the information that could be access.

2.2.2 Glaciers transects

After preparing the data and defining the areas of interest, a method was proposed to allow the spatial analysis of the variation of NDVI values within the surfaces exposed by the melting and retreating of glaciers. To do this, we built central profiles (Figure 10) on the areas of interest to sample the NDVI values.

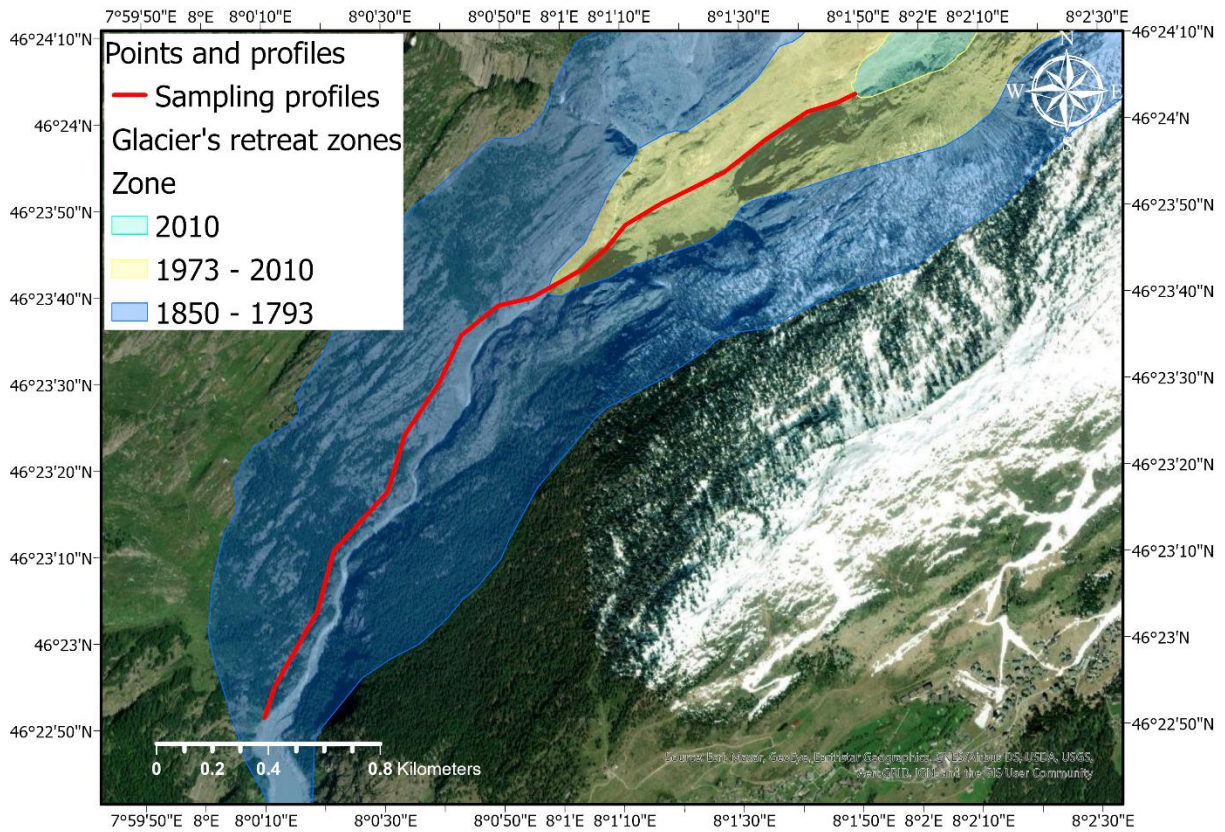


Figure 10 - Map illustrating the sampling profile of Aletsch Glacier. Note that the transect passes through the centre of the three areas of interest in the study.

From the polyline shapefile (profile) we can extract the NDVI values contained in the GeoTiff file using the geoprocessing tool "Extract by Mask". The result of this process gives us a Geotiff file containing only the pixels crossed by the profile line (Figure 11).

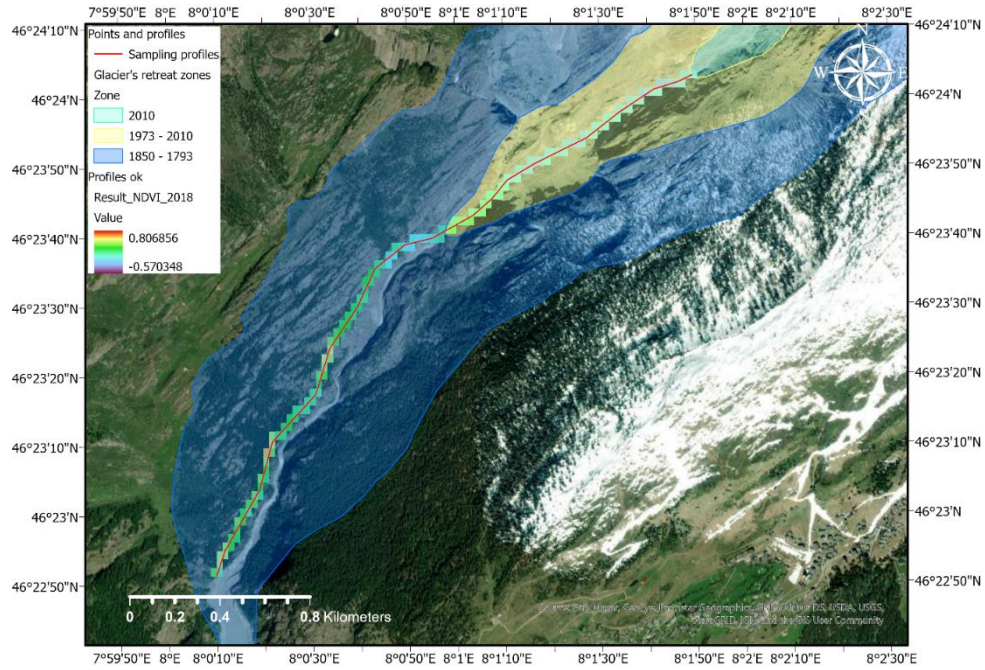


Figure 11 - Map illustrating the pixels sampled by the profile in the Aletsch's glacier front

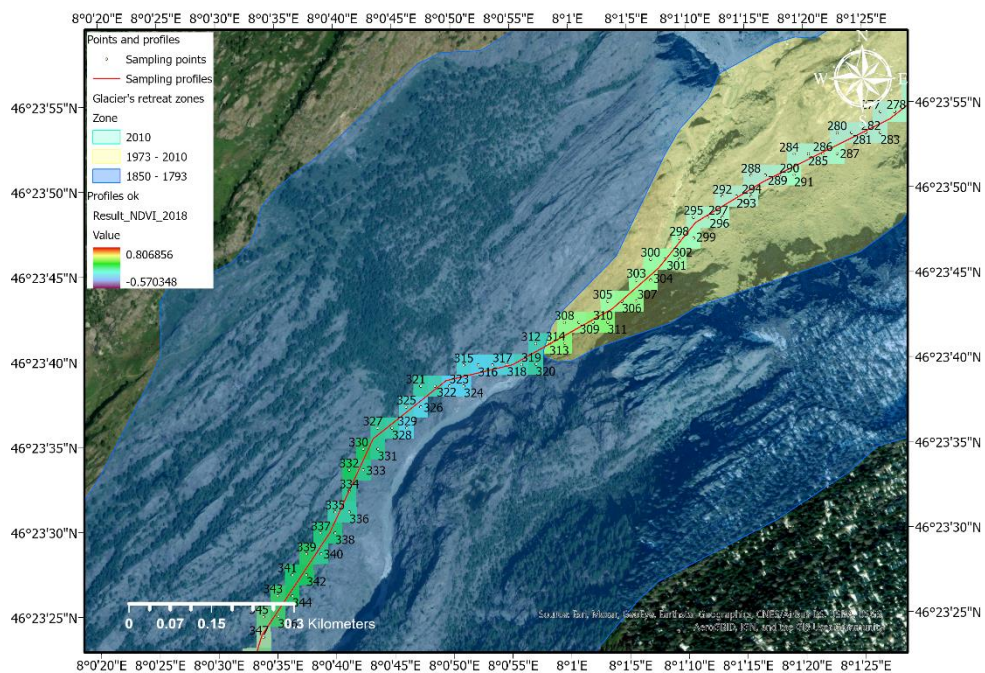


Figure 12 - Map illustrating the pixels converted in points and their respective number.

In order to analyse the values more clearly and compare the NDVI in different years, the resulting Geotiff file has been transformed into points. In fact, each pixel has been transformed into a point that has the NDVI values (Figure 12). By inserting the values of the generated points, it was possible to produce graphics that allowed the visualization of the results.

2.2.3 NDVI thresholding

NDVI values are currently processed in different ways depending on the objectives of each project (A. Fischer et al., 2019; Gamon et al., 2013; Gandhi et al., 2015). In an attempt to estimate the vegetation evolution in the newly exposed areas by the glaciers retreat, a NDVI thresholding has been proposed. The processing consists in creating categories of NDVI values representing known elements like vegetation and ice. For this, five classes of values have been proposed, water bodies/debris, glacier, glacier variation, young grass vegetation and fixed vegetation.

As this study is focused on glaciers changes since 1850, the NDVI values have been clipped using the corresponding glacier outline polygon for that year. In this way we can access the NDVI data from 1984 to 2018 within the glacier variation area from 1850 to 2010.

The raster file containing the clipped NDVI values were reclassified using five predefined classes where, simply put, lower (negative) values represent the glacier or instable areas with debris movements, while higher values (positive) represent 2 different types of vegetation (Table 1).

New classes	NDVI values	Features
1	< - 0.15	Water bodies/Debris
2	< - 0.02	Glacier
3	< + 0.15	Glacier variation
4	< + 0.4	Grass
5	< + 0.9	Fixed vegetation

Table 1 - Classes of NDVI values used in the reclassification and their respective features.

From the new raster file with the proposed classes, we can observe a spatial distribution of each desired feature. In order to estimate the position of the glacier's fronts, the raster file was converted into a vector file and the proposed classes transformed into polygons that represent the limits of each feature.

2.2.4 Zonal statistics analysis

Summarizes the values of a raster within the zones of another dataset and reports the results as a table (Figure 13). In other words, the functions are computed on the cell values from the input value

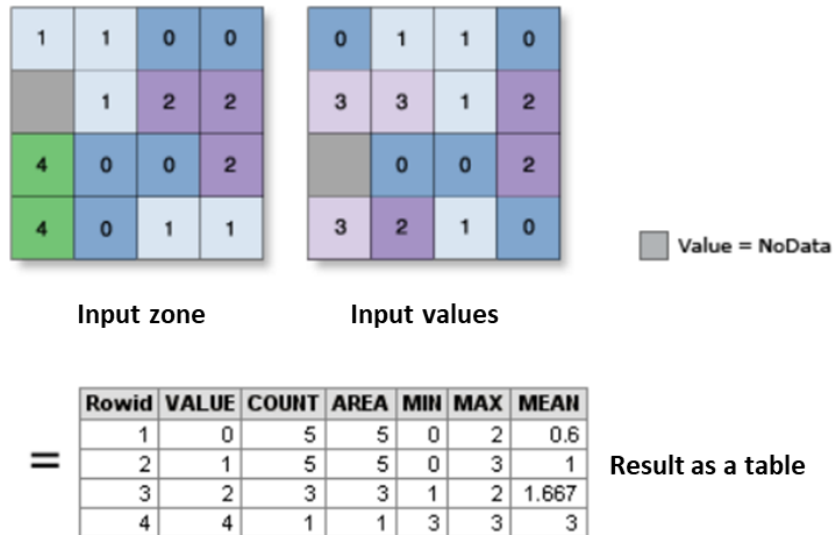


Figure 13 - Sketch showing the inputs (zones and values) for the statistical analyses and the table provided with the results.

raster intersecting or falling within each zone of a specified input zone dataset (ESRI, 2020).

An input zone can be a vector file or an integer raster file. All kinds of areas of interests with defined boundaries are good examples of an input zone, for example, administrative or political boundary, buffer zones, slope or elevation values or classes. An input value raster includes any raster file that contains values that can be analyzed visually and statistically, as well as erosion potential maps, land suitability maps, among others.

3 RESULTS

3.1 Glaciers transects

All procedures preceding the analysis (DATA AND METHODS) were followed to obtain reliable and accurate results. Therefore, this care allowed good quality analysis, which generated a large dataset for each glacier. This dataset is basically composed of the annual mean of NDVI values (from 1984 to 2017) in sampling points along glaciers transects.

The result of these analyses generates large datasets, which, due to their size, represent a great challenge for their organization and synthesis. In order to observe the variations in large datasets over time in a clear and visible way, the study proposes graphical resources that illustrate simply and intuitively the annual evolution of NDVI values along the proposed profiles.

The values sampled using Arcgis Pro software were exported as tables, loaded in excel and then processed. A general table was organized conveniently for the study, and later the data for each glacier were analyzed separately (all the tables are available in the annex).

3.1.1 Stacked line charts

A line chart emphasizes the amount of change over a period or compares multiple items. Data points are plotted in series using evenly spaced intervals and connected with a line to emphasize the relationships between the points. A stacked line chart is a line chart in which lines do not intersect, because they are cumulative at each point. This kind of graphic harmonises the display of large datasets and facilitates the observation of their variation over a time window.

The graphics are the same for all the glaciers, the only difference is that some glaciers have more than one profile. The y-axis represents the cumulative NDVI values while the x-axis the number of each point in the profile. Therefore, each line represents a sampling year which is marked by a blue sequential colour scale that facilitates observing their annual evolution.

3.1.2 Arolla Glacier

As the Arolla glacier presents two main fronts it was decided to create two sampling profiles that pass through the central part of the glaciers giving a more realistic representation of the NDVI values (Figure 14). The first profile, Arolla - 1, has a total of 76 points ranging from point 710 to 786 (Figure 15), while the second profile, Arolla - 2, has a total of 72 points starting at point 787 and ending at point 859 (Figure 16).

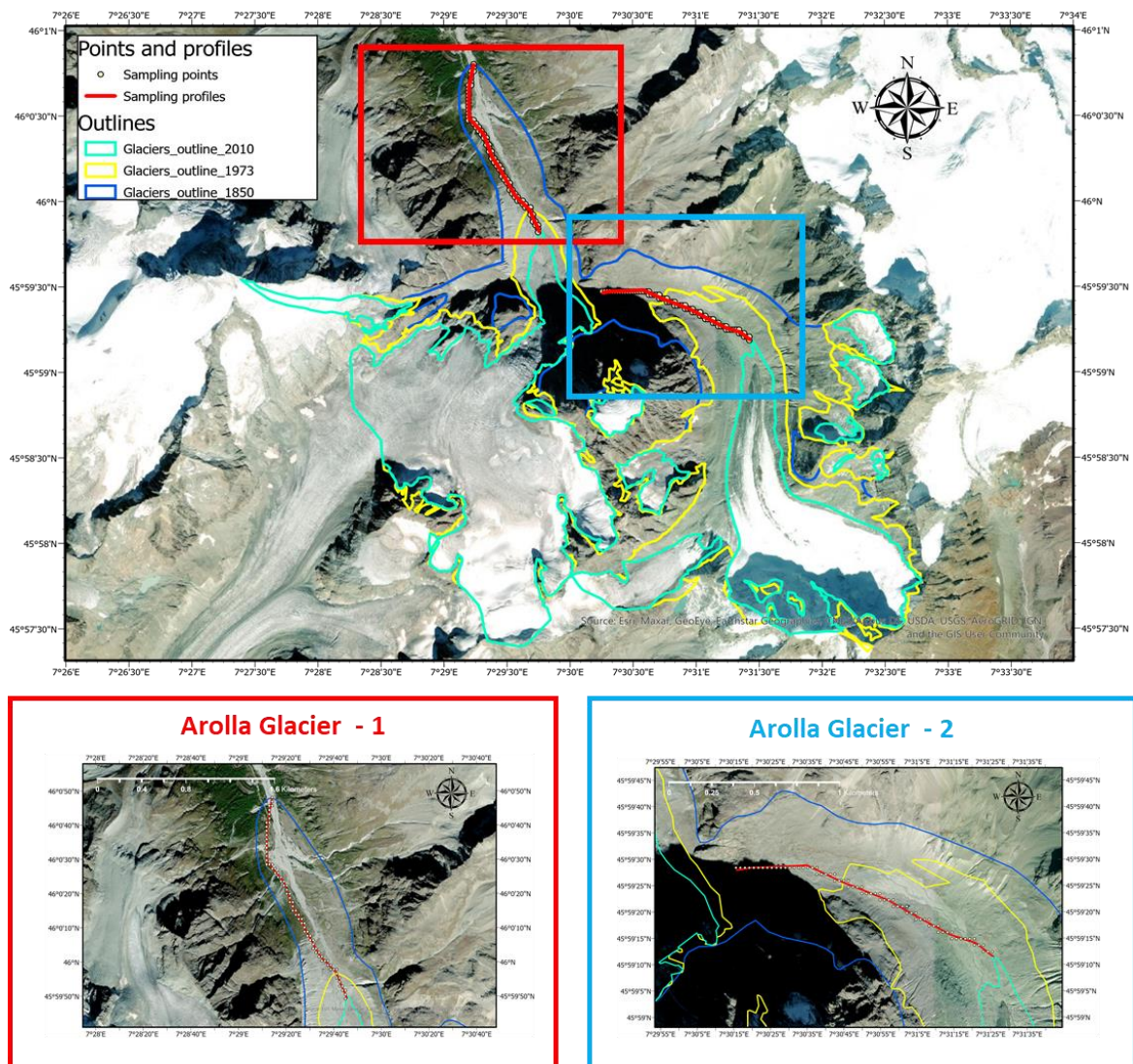


Figure 14 - Overview of Arolla Glacier illustrating in detail the two transects (Arolla Glacier 1 and 2) on the two glacier fronts and the respective sampling points. Note that the transects cross the glacier fronts in the middle going from 1850 up to 2010 giving us data from the exposed area after glacier retreat.

In a general way the Arolla - 1 profile showed two different classes of values, one that becomes more and more positive along the years, and other that becomes more and more negative (Figure 18). The sampling points which are present in vegetated areas (716 to 732, and 744 to 754) show values, which with the passing of the years become more and more positive while the points which sample areas of exposed soil or glacier front variation (710 to 714, 736 to 742 and 760 to 786) show

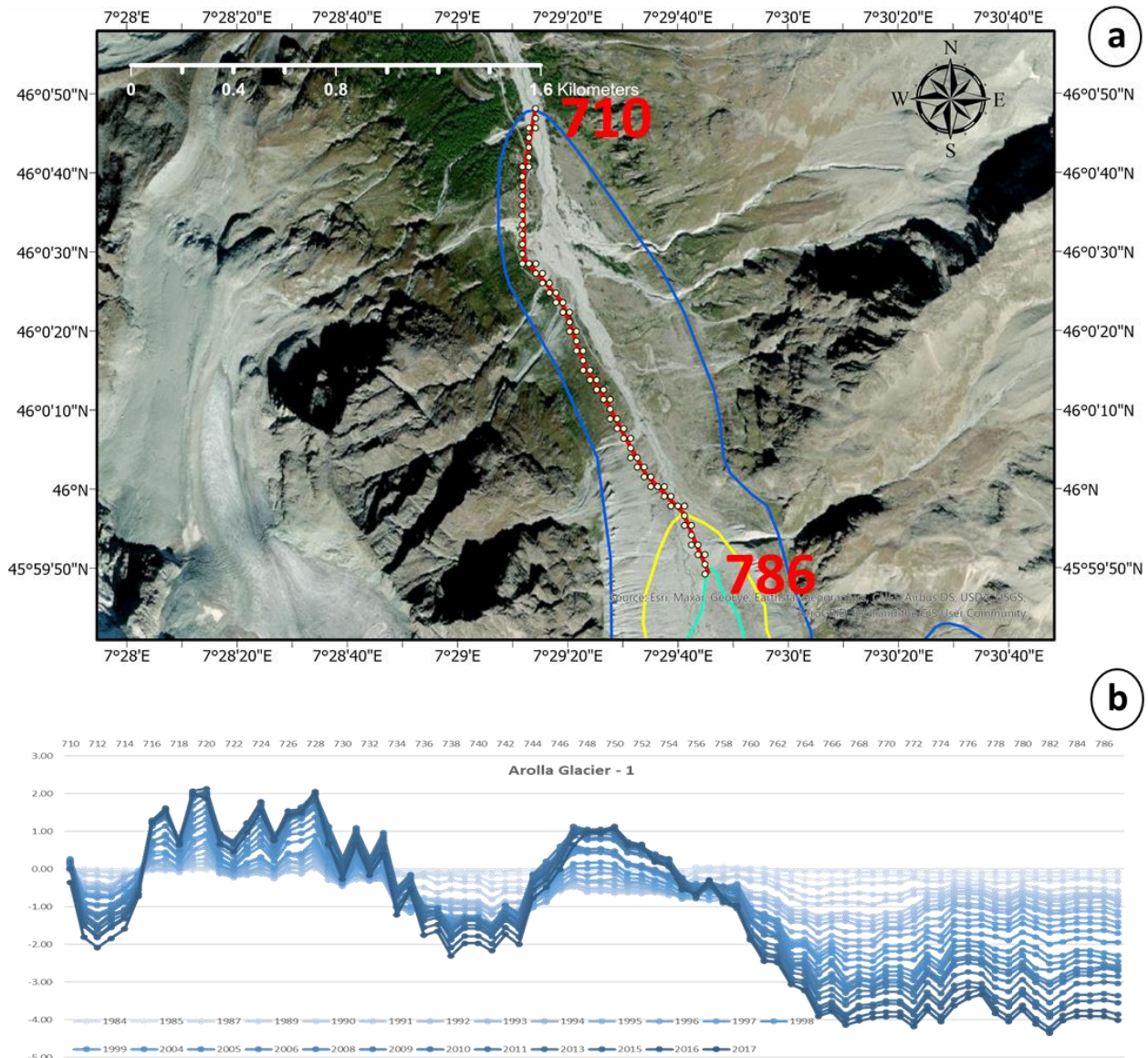


Figure 15 – a: Map illustrating in detail the Arolla glacier – 1 transect and the respective sampling points. b: Stacked line chart where the y-axis represents the cumulative NDVI values while the x-axis the number of each point in the profile. Therefore, each line represents a sampling year which are represented by a blue sequential colour scale going from light blue, 1984, to dark blue 2017.

more and more negative values.

The Arolla - 2 profile showed values that becomes more and more negative along the years (Figure 16), and despite the overall negative trend, we can observe two different value classes. The first (787 to 816) is observed in the samples of exposed soil where the glacier was present in 1850, which along the years, became more negative. In the other hand, the points which sample areas of exposed soil and glacier front variation between 1973 and 2010 (818 to 858) show relatively fewer negative values.

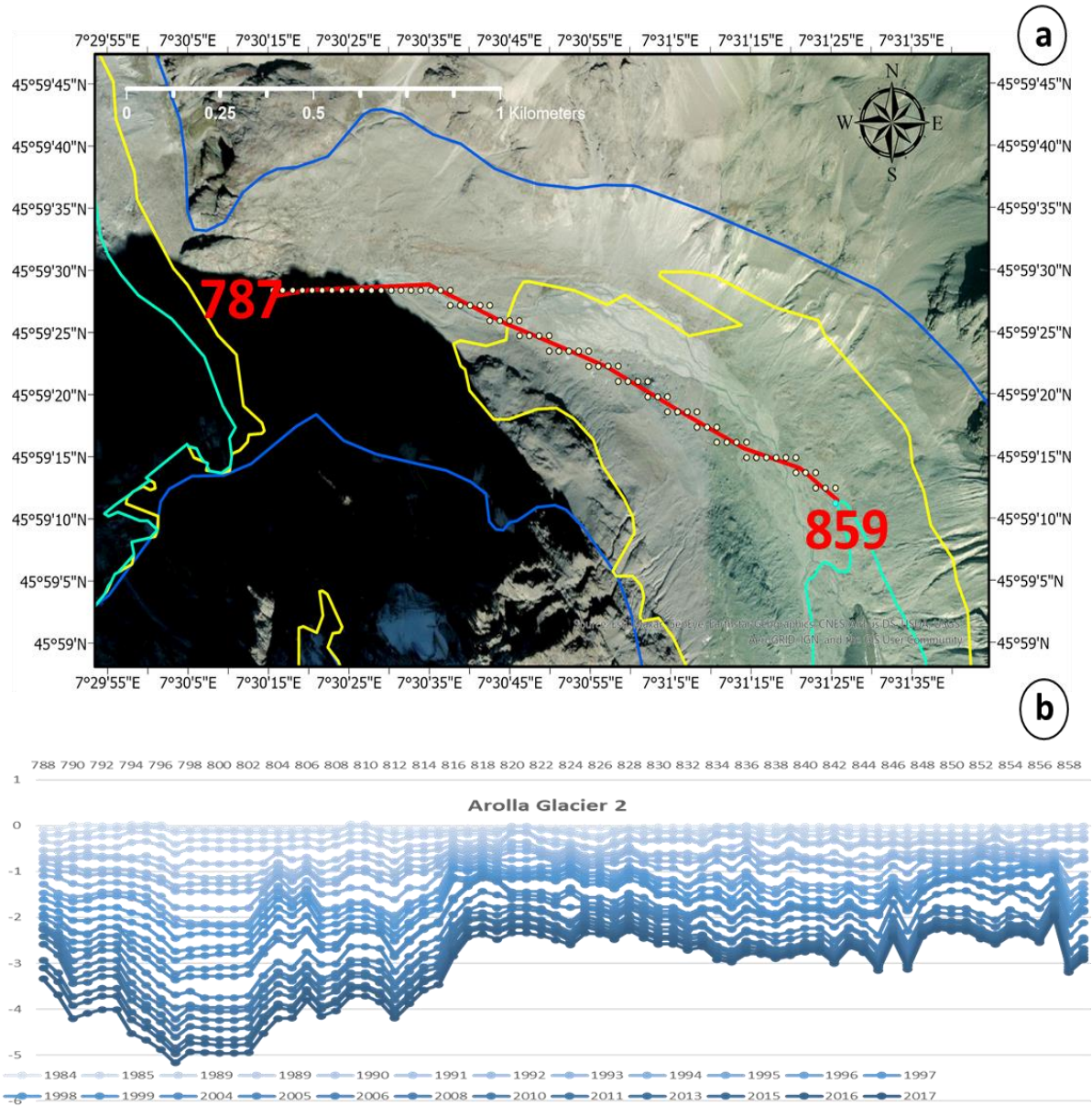


Figure 16 - Map of Arolla Glacier – 2 profiles illustrating in detail the transect and the respective sampling points. b: Stacked line chart where the y-axis represents the cumulative NDVI values while the x-axis the number of each point in the profile. Therefore, each line represents a sampling year which are represented by a blue sequential colour scale going from light blue, 1984, to dark blue 2017.

3.1.3 Allalin Glacier

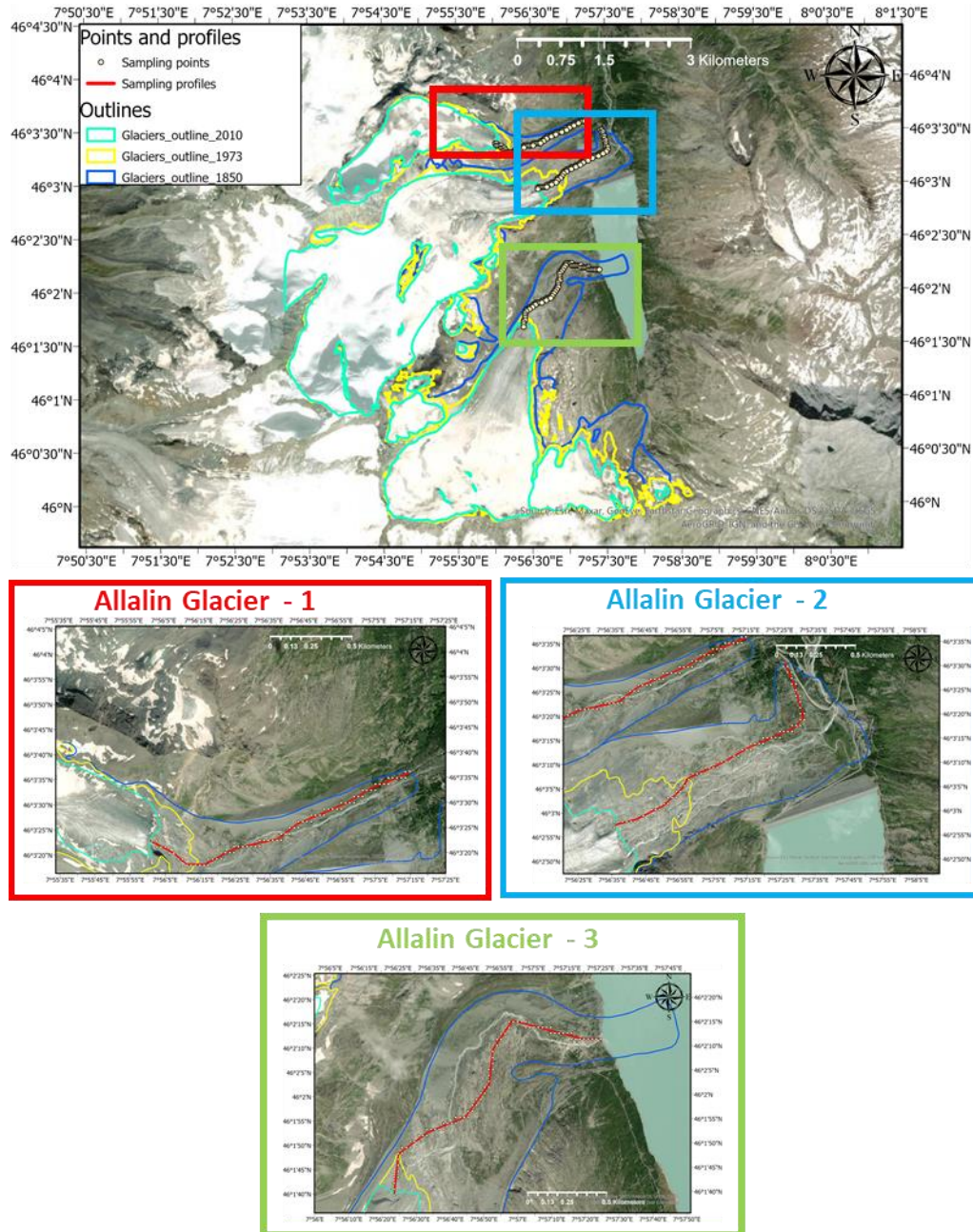
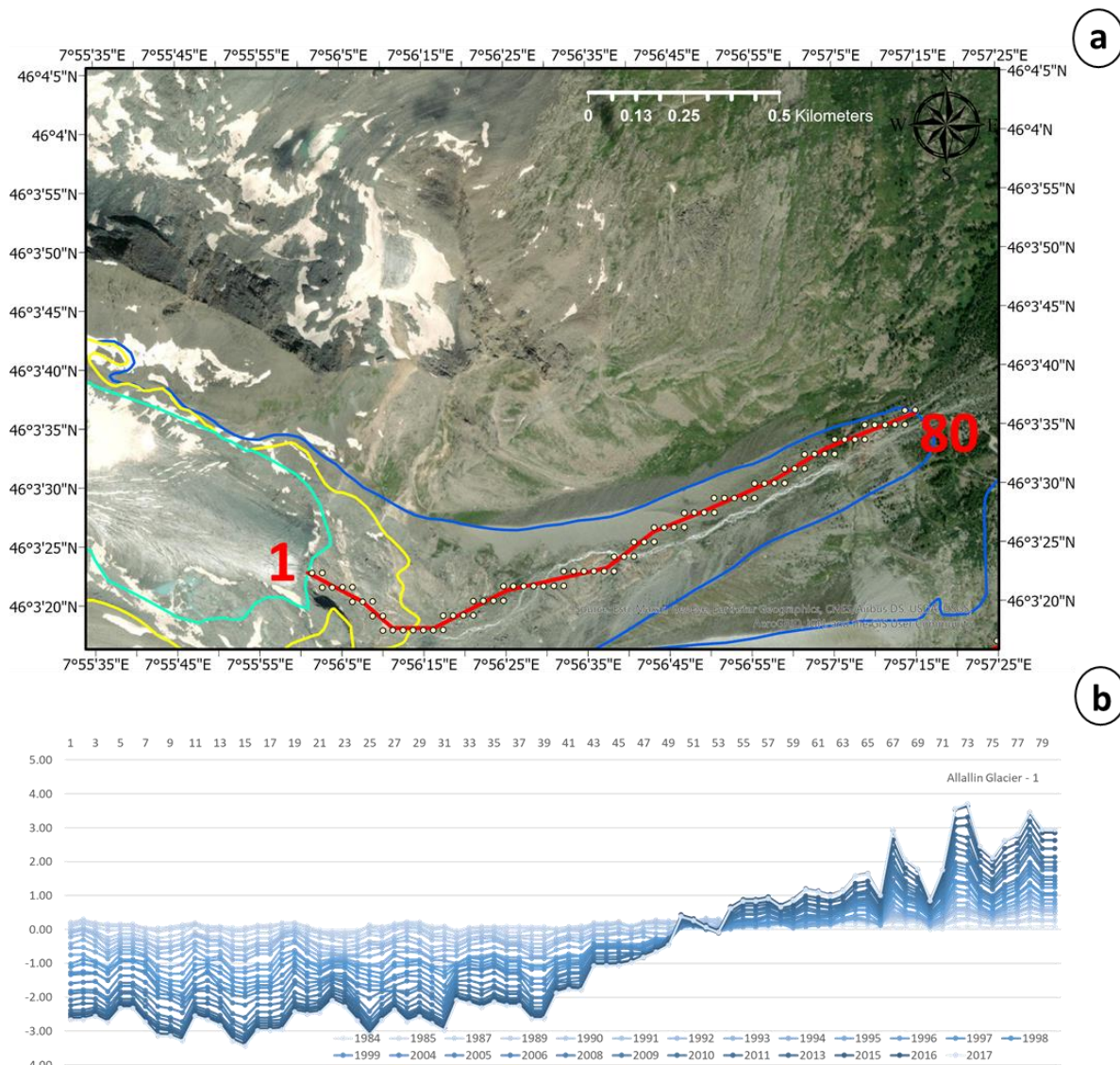


Figure 17 - Overview of Allalin Glacier illustrating in detail the three transects (Allalin Glacier, 1, 2 and 3) on the three glacier fronts and the respective sampling points.

The Arolla glacier presents three main fronts, so three sampling profiles were created passing through the central part of the glaciers sampling more realistic NDVI values (Figure 17). The Allalin – 1 profile ranges from point 1 to 80 (Figure 18), the second one, Allalin - 2, starts at point 81 and ends at point 159 (Figure 19) and the third one samples from point 160 to 242 (Figure 20).

The Allalin - 1 profile showed two different classes of values, one that becomes more and more positive along the years, and other that becomes more and more negative (Figure 18). The sampling points which are present in vegetated areas (51 to 80) show values, which become more and more positive while the points which sample areas of exposed soil or glacier front variation (1 to 50) show more and more negative values.



The Allalin - 2 profile is located on the main glacier front. We can also observe two different classes of values, one that becomes more negative along time and another one that becomes more positive (Figure 19). The sampling points which are closer to the glacier front in 1850 (51 to 80) show a positive trend while the points which sample areas of exposed soil or glacier front variation (81 to 117) show values with a negative trend.

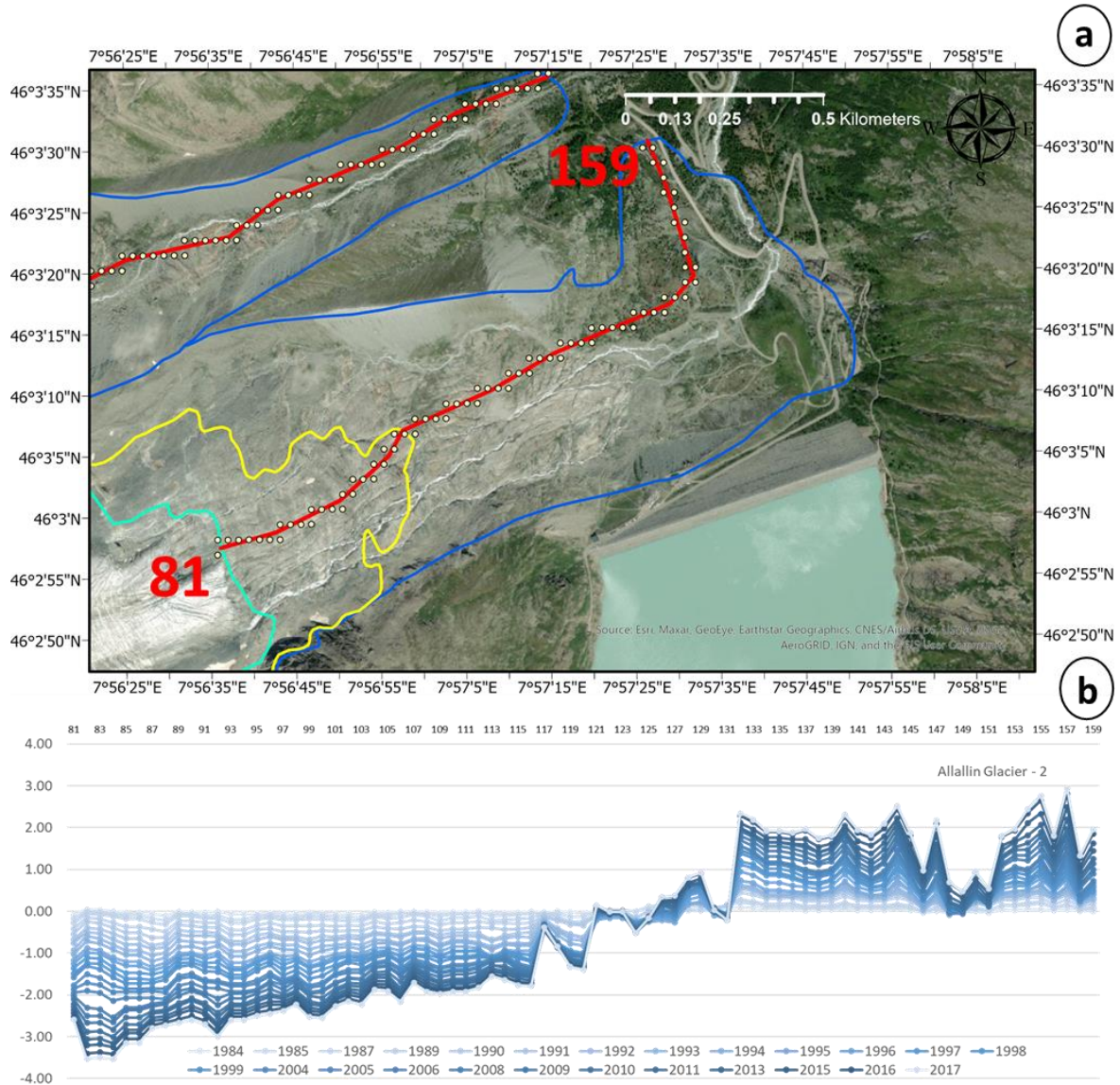


Figure 19 - a: Detail of Allalin Glacier – 2 profile illustrating the transect and the respective sampling points. b: Stacked line chart where the y-axis represents the cumulative NDVI values while the x-axis the number of each point in the profile. Therefore, each line represents a sampling year which are represented by a blue sequential colour scale going from light blue, to dark blue.

The Allalin - 3 profile cross more than 1 kilometers within the area exposed by the glacier retreating between 1850 and 1973 (Figure 20). Inside this area, the sampling points that touch the vegetation (217 to 242) show values that become, in general, more and more positive despite few points close to the water bodies that show negative values. Going in direction of the actual glacier front the points show more and more negative values (220 to 160), close to exposed soil or glacier front variation.

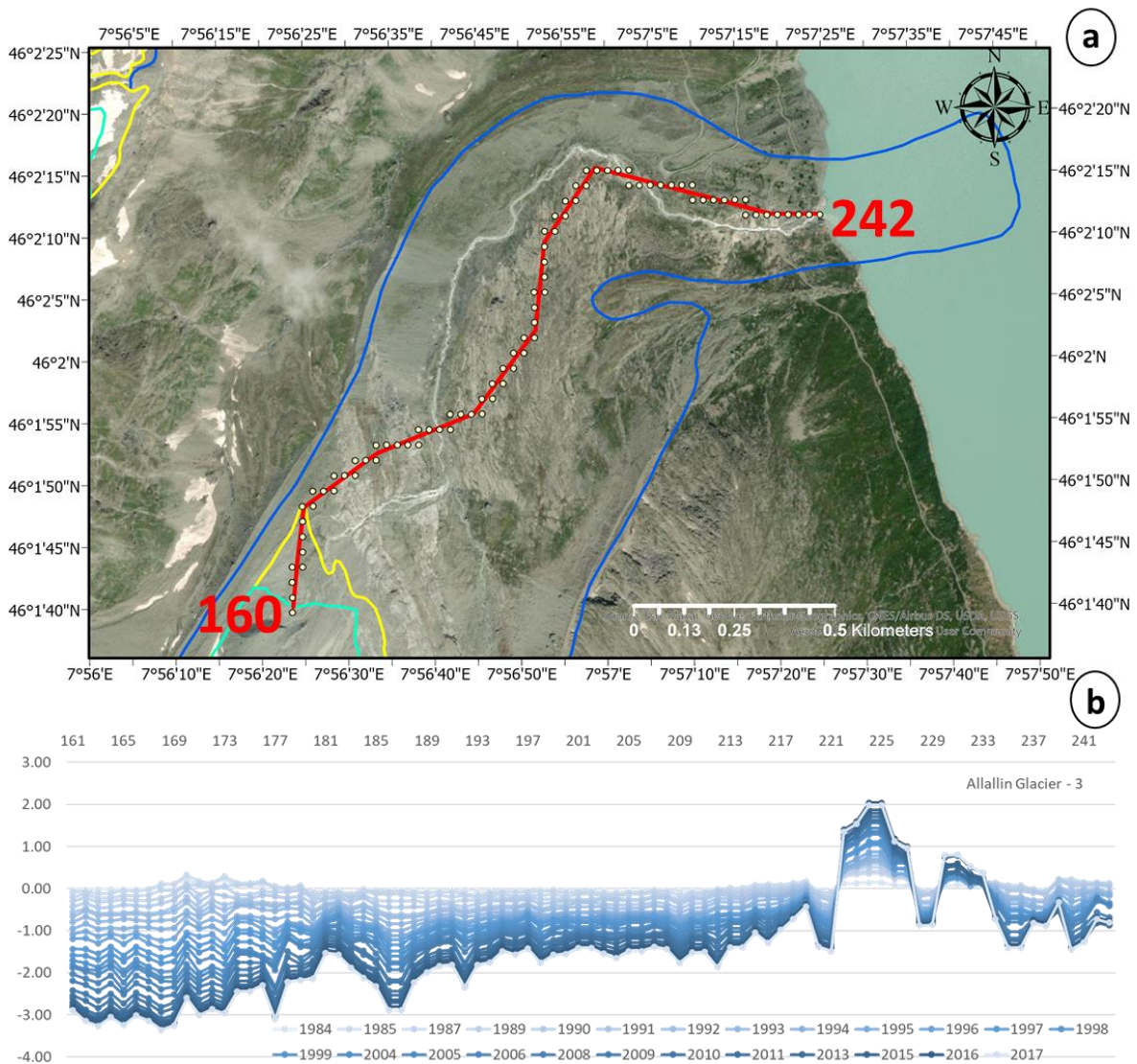


Figure 20 - a: Detail of Allalin Glacier – 3 profile illustrating the transect and the respective sampling points. b: Stacked line chart where the y-axis represents the cumulative NDVI values while the x-axis the number of each point in the profile. Therefore, each line represents a sampling year which are represented by a blue sequential colour scale going from light blue, to dark blue.

3.1.4 Aletsch Glacier

The Aletsch glacier extends for approximately 22 kilometres and represents one of the largest glaciers in Europe. A transect was proposed at the southwestern end of the glacier (Figure 21), passing through 5 kilometres in the central part of the valley sampling the areas now uncovered by the retreat of the glacier.

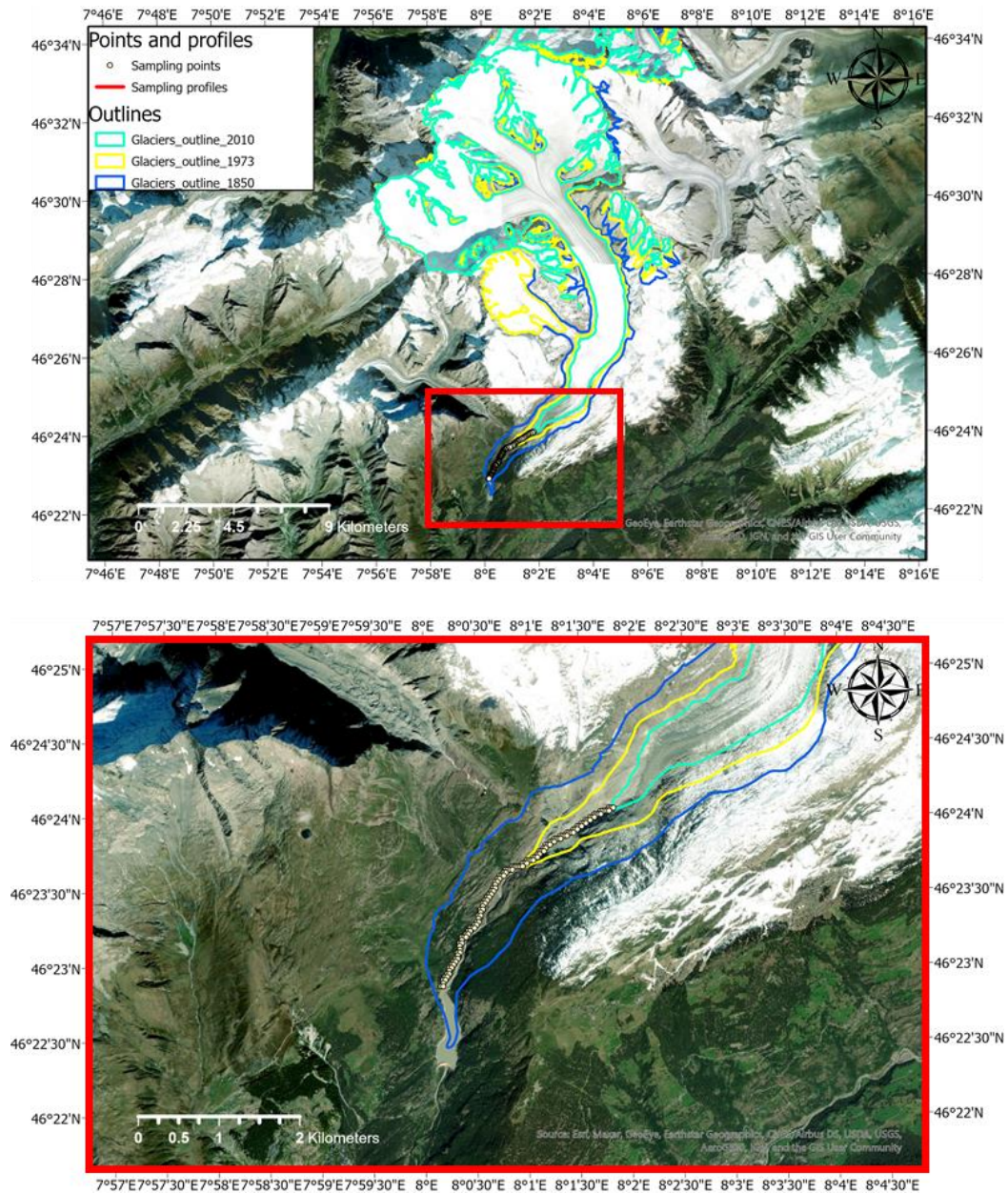


Figure 21 - Overview of Aletsch Glacier illustrating the transect and the respective sampling points. In detail (Red box) the profile and points. Note that the transect cross the glacier fronts in the middle going from 1850 up to 2010 giving us data from the exposed area after glacier retreat.

Looking at the time series of the values recorded in the most southwestern part of the profile (points 1 to 65) we can see a considerable increase of the NDVI values from 1984 to 2017 (Figure 22). This zone represents the glacier retreat area between 1850 and 1973 and have been populated by vegetation which is becoming more and more abundant. Apart from a few points (67 to 80) where the sampled values vary greatly from point to point, the rest of the profile shows an increasingly negative trend.

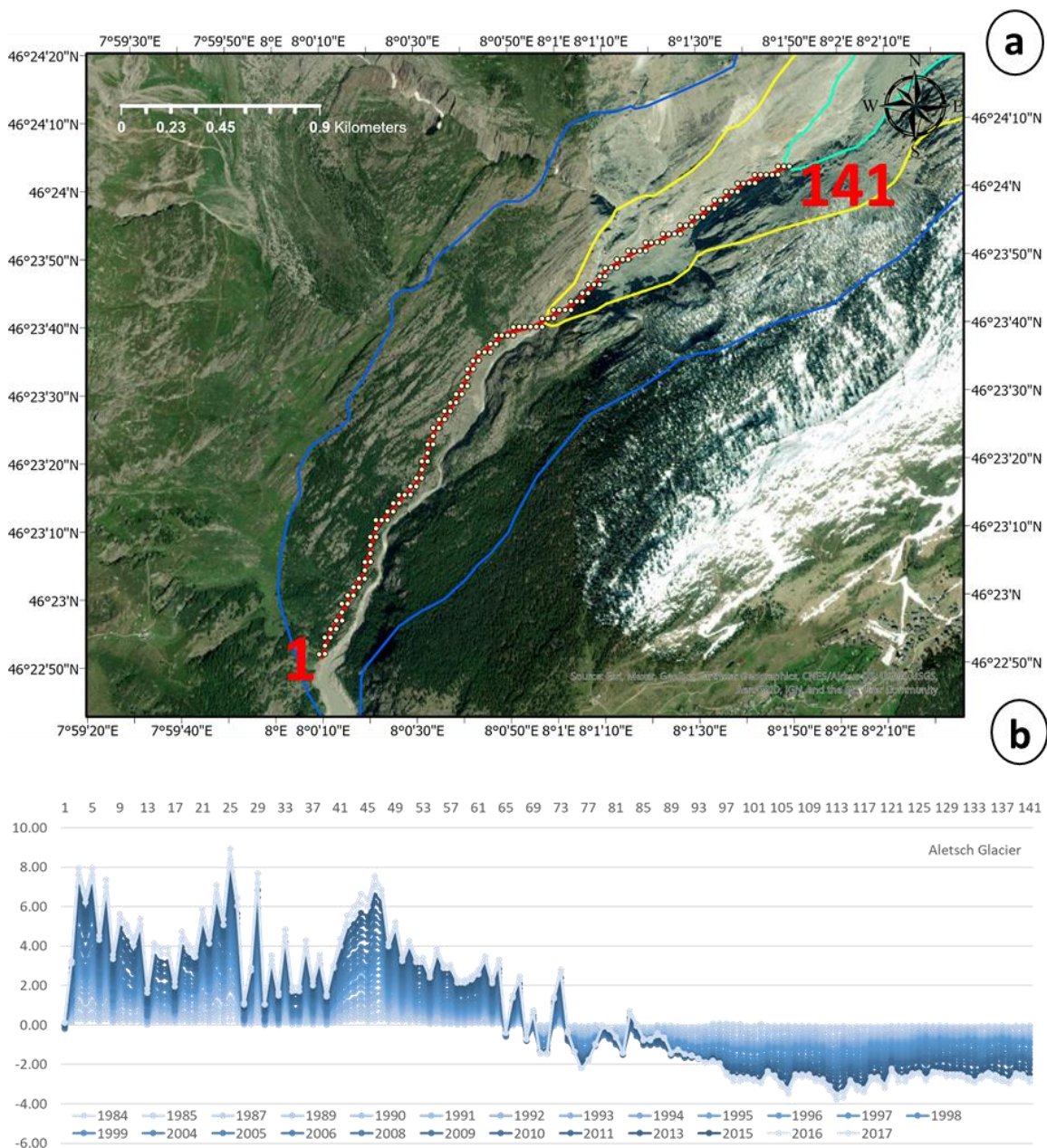


Figure 22 - a: Detail of Aletsch Glacier profile illustrating the transect and the respective sampling points. b: Stacked line chart where the y-axis represents the cumulative NDVI values while the x-axis the number of each point in the profile. Therefore, each line represents a sampling year which are represented by a blue sequential colour scale going from light blue, to dark blue.

3.1.5 Grindelwald Glacier

To analyse the Grindelwald glaciers (upper and lower parts) two transects with sampling points passing through the central part of the glacier valleys have been proposed (Figure 23). Relief breaks (mountain escarpment) present at the area exposed by glacier retreat influence in the acquired NDVI values.

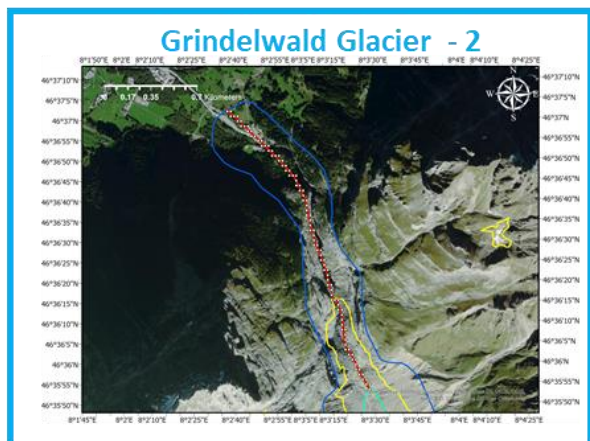
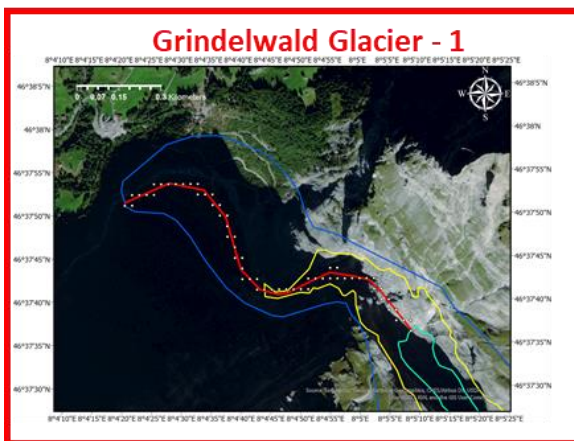
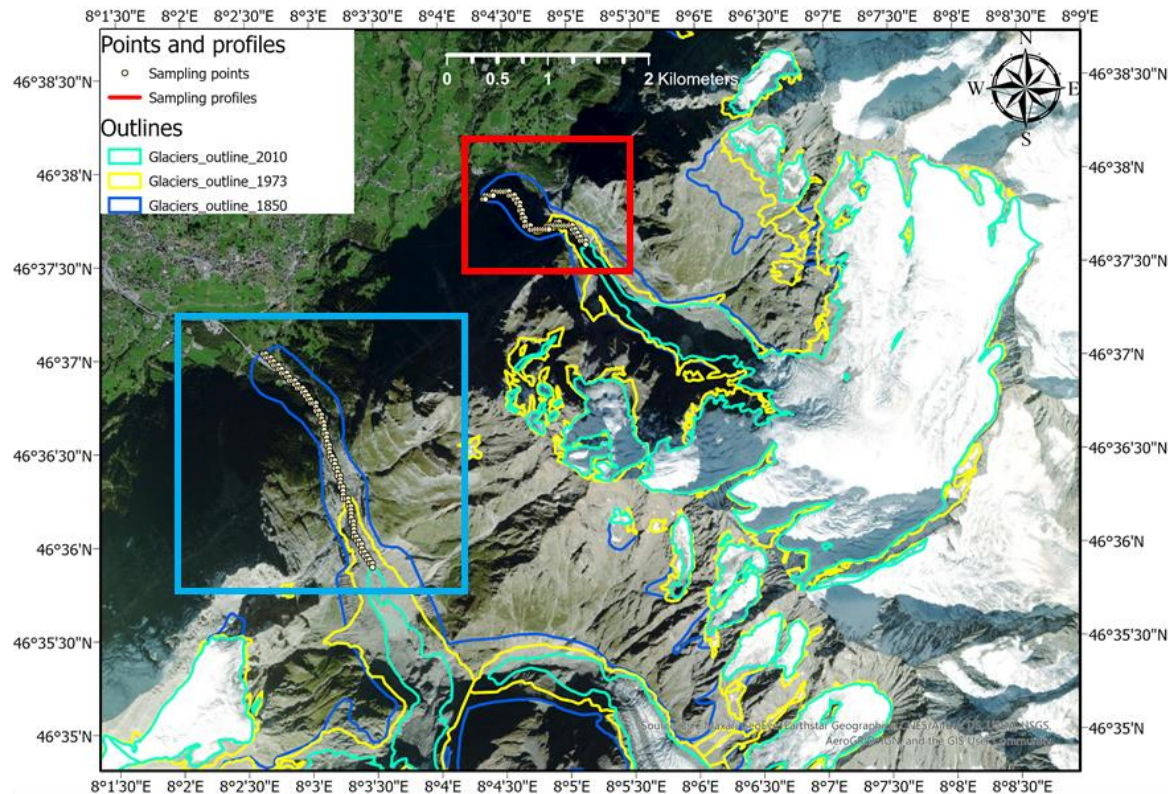


Figure 23 - Overview of two glaciers (Lower and upper Grindelwald) that together make up the Grindelwald glacier. In detail, the profiles Grindelwald Glacier 1 (upper) and 2 (Lower), on the glacier fronts. Note that the transects cross the glacier fronts in the middle going from 1850 up to 2010 giving us data from the exposed area after glacier retreating.

The Grindelwald - 1 profile samples the area exposed by the Upper Grindelwald glacier retreat and extends for approximately 1 kilometers (Figure 24). The points present at the beginning of the profile (points 1 to 27), the glacier retreat zone between 1859 and 1973, demonstrate a strong positive trend over the years. The rest of the transect is separated by the mountain escarpment and samples the area of glacier retreat between 1973 and 2010 of more irregular relief.

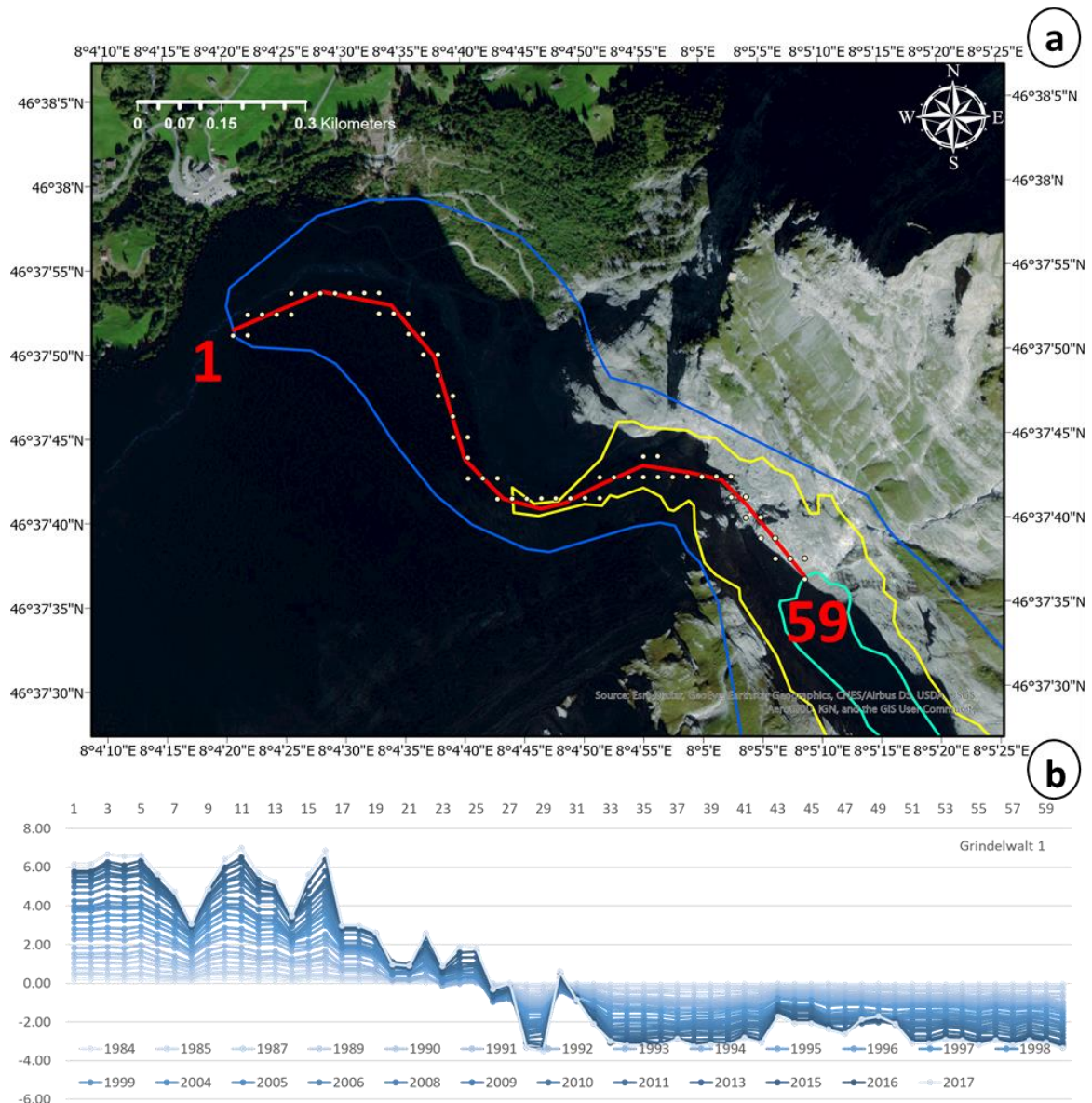
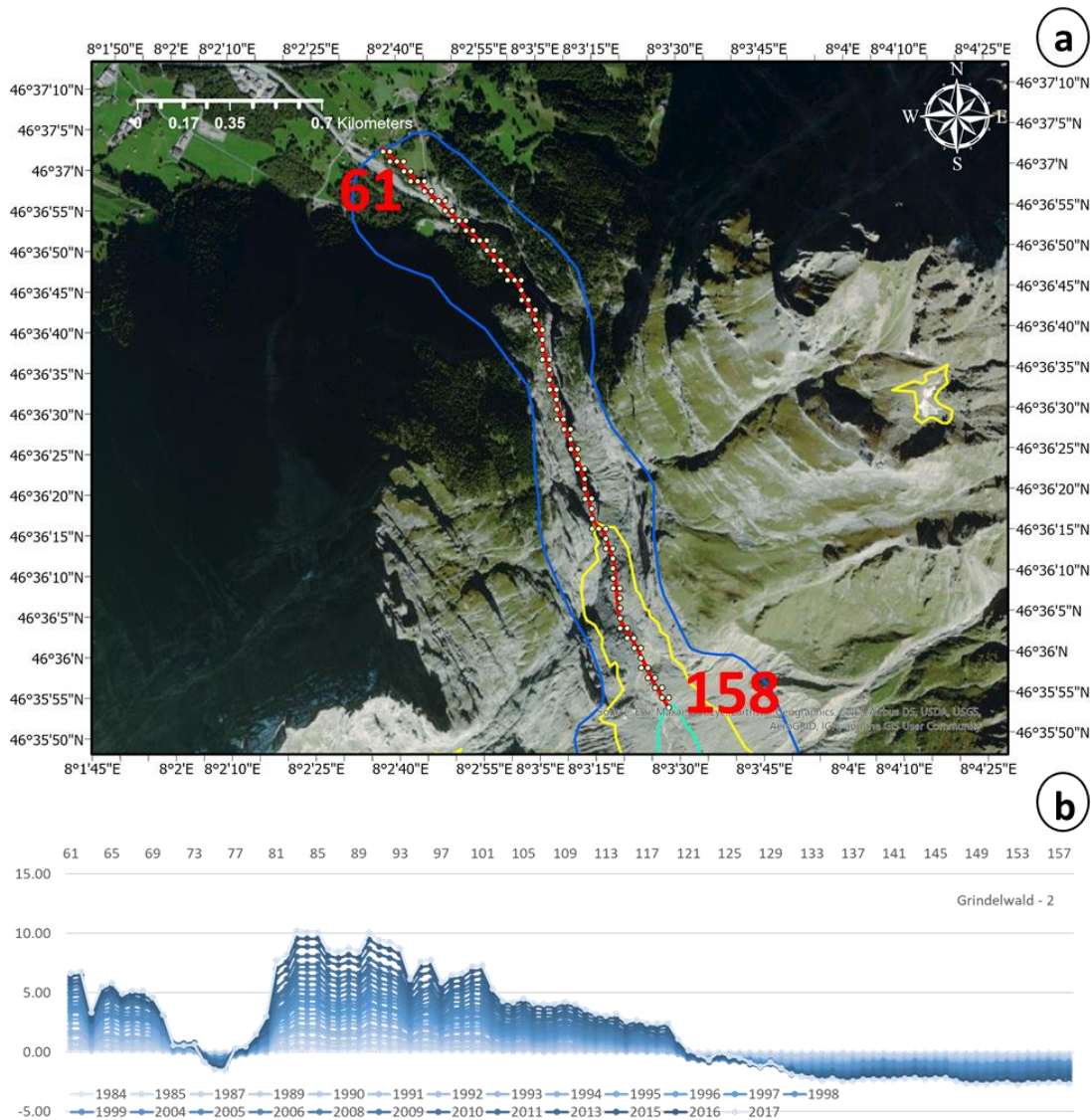


Figure 24 - a: Upper Grindelwald Glacier profile illustrating the transect and the respective sampling points. b: Stacked line chart where the y-axis represents the cumulative NDVI values while the x-axis the number of each point in the profile. Therefore, each line represents a sampling year which are represented by a blue sequential colour scale going from light blue, to dark blue.

The Grindelwald - 2 profile samples the area exposed by the Lower Grindelwald glacier retreat and extends for approximately 2 kilometers (Figure 25). The points present in the plain and vegetated areas (points 61 to 119) show a strong positive trend over the years except for the points 70 to 79, which lie on a river plain. The rest of the transect is separated by the mountain escarpment and samples the area of glacier retreat between 1973 and 2010 of more irregular relief. The cumulative NDVI values in these points show a general negative trend, however, in the area between points 121 and 129 we can observe a slightly negative trend (Figure 25 b), which becomes more positive along the years.



3.1.6 Morterash Glacier

The Monterash and Pers glaciers join to form a tongue which runs down the Monterash valley. Currently, the glacier extends for approximately 6 kilometres and the transect passes through 2.6 kilometres at the central part of the uncovered area exposed by the glacier retreat (Figure 26).

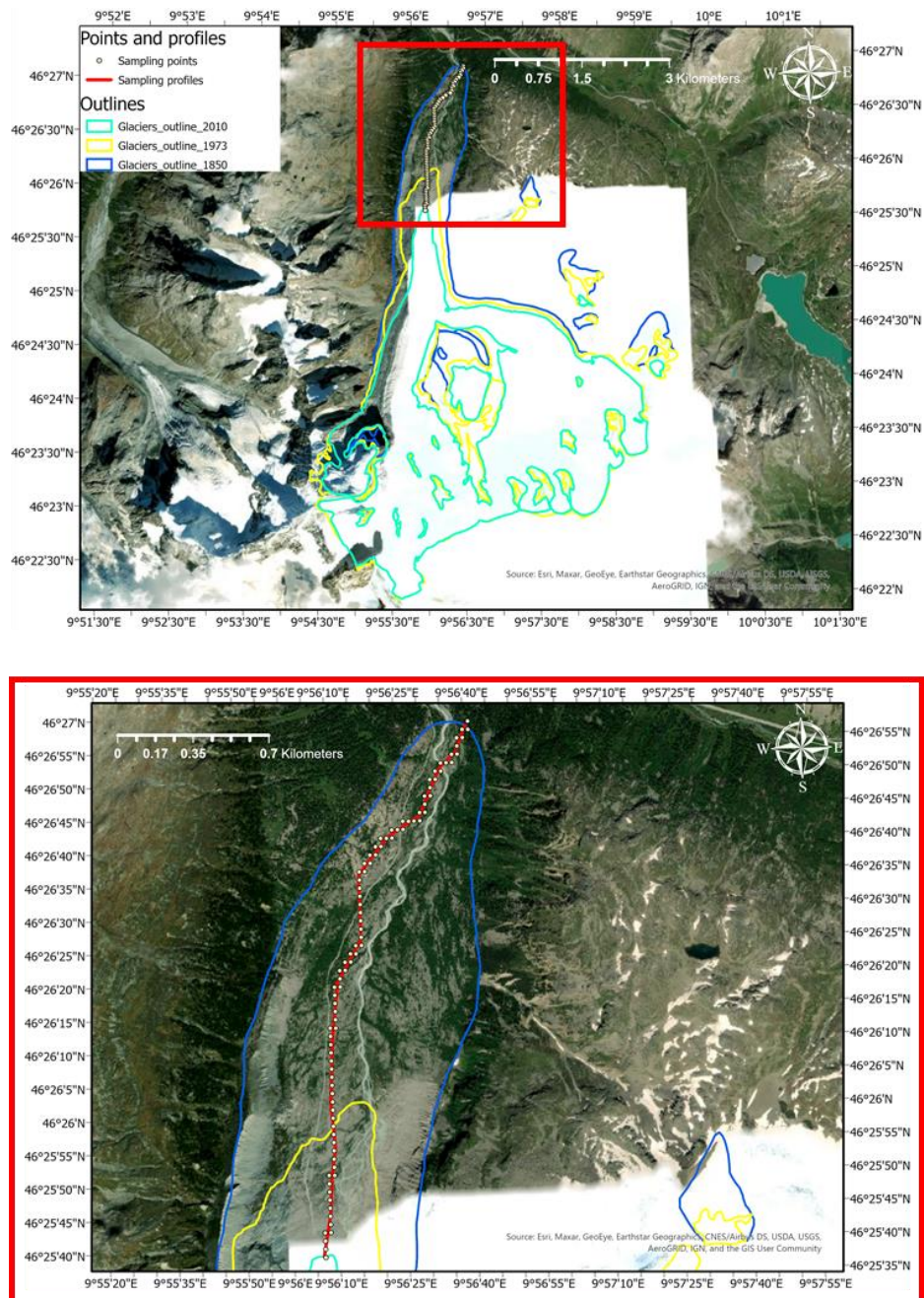


Figure 26 - Overview of Monterash Glacier (westernmost sector) joining Pers Glacier (easternmost sector) to form the glacier front that runs down the valley. In detail (Red box) the profile and sampling points.

Looking at the time series of the values recorded between the points 1 to 19 we can see a general negative trend, while the rest of the points show an overall positive trend (Figure 27). However, it is possible to observe that in certain sections of the profile (points 21 to 25 and 77 to 87), trends of negative values begin an inversion to a positive values trend from the end of the 90s.

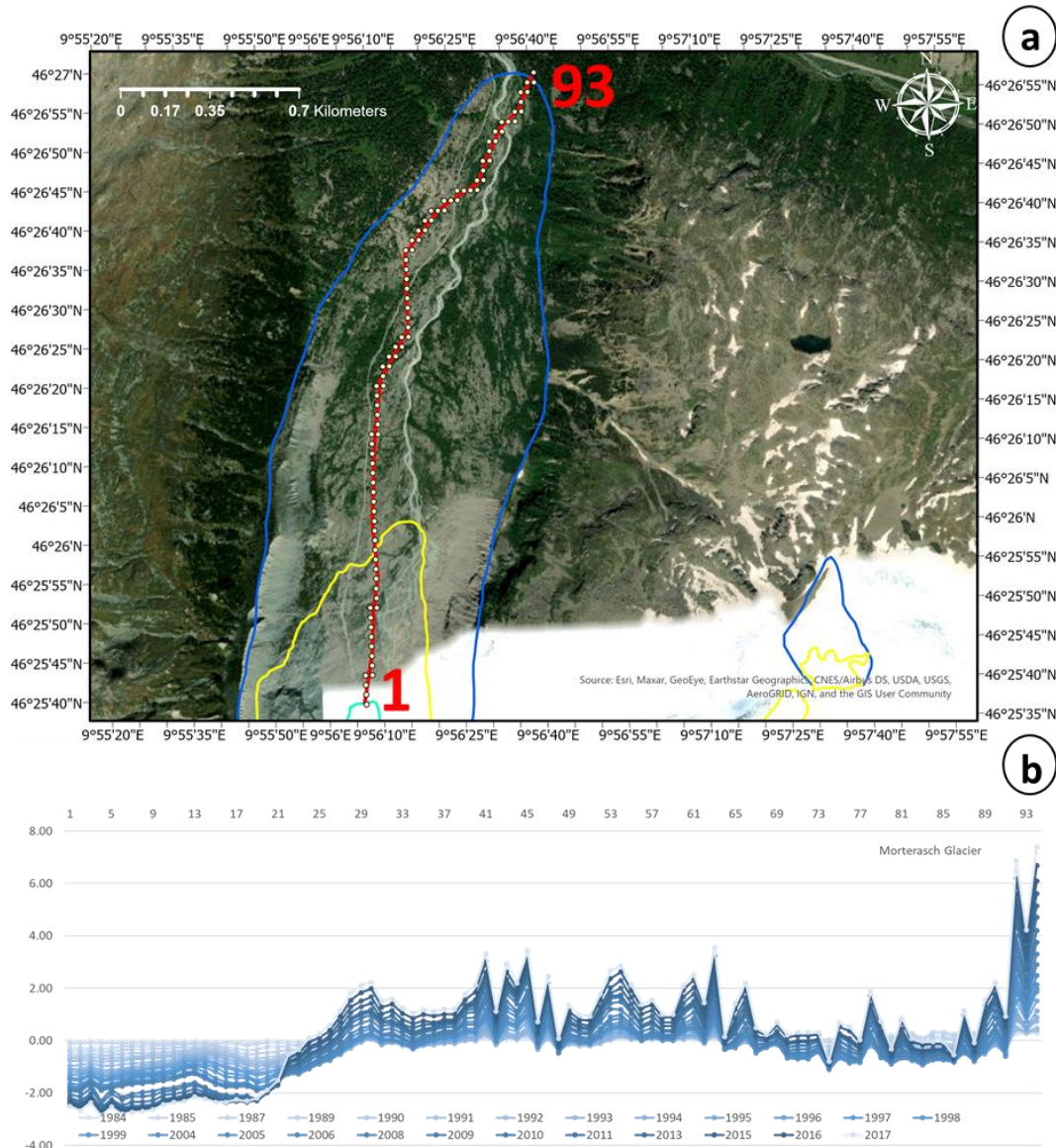


Figure 27 - a: Morterastch Glacier profile illustrating the transect and the respective sampling points. b: Stacked line chart where the y-axis represents the cumulative NDVI values while the x-axis the number of each point in the profile. Therefore, each line represents a sampling year which are represented by a blue sequential colour scale going from light blue, to dark blue.

3.1.7 Chablais Glaciers

In the westernmost area of the Swiss Alps, the Chablais group of glaciers represents a challenge to use this sampling method. The geographic arrangement of the glacier fronts makes the sampling extremely difficult. Therefore, to solve the problem, 4 transects were proposed (Figure 28) and together they give more homogeneous and realistic results.

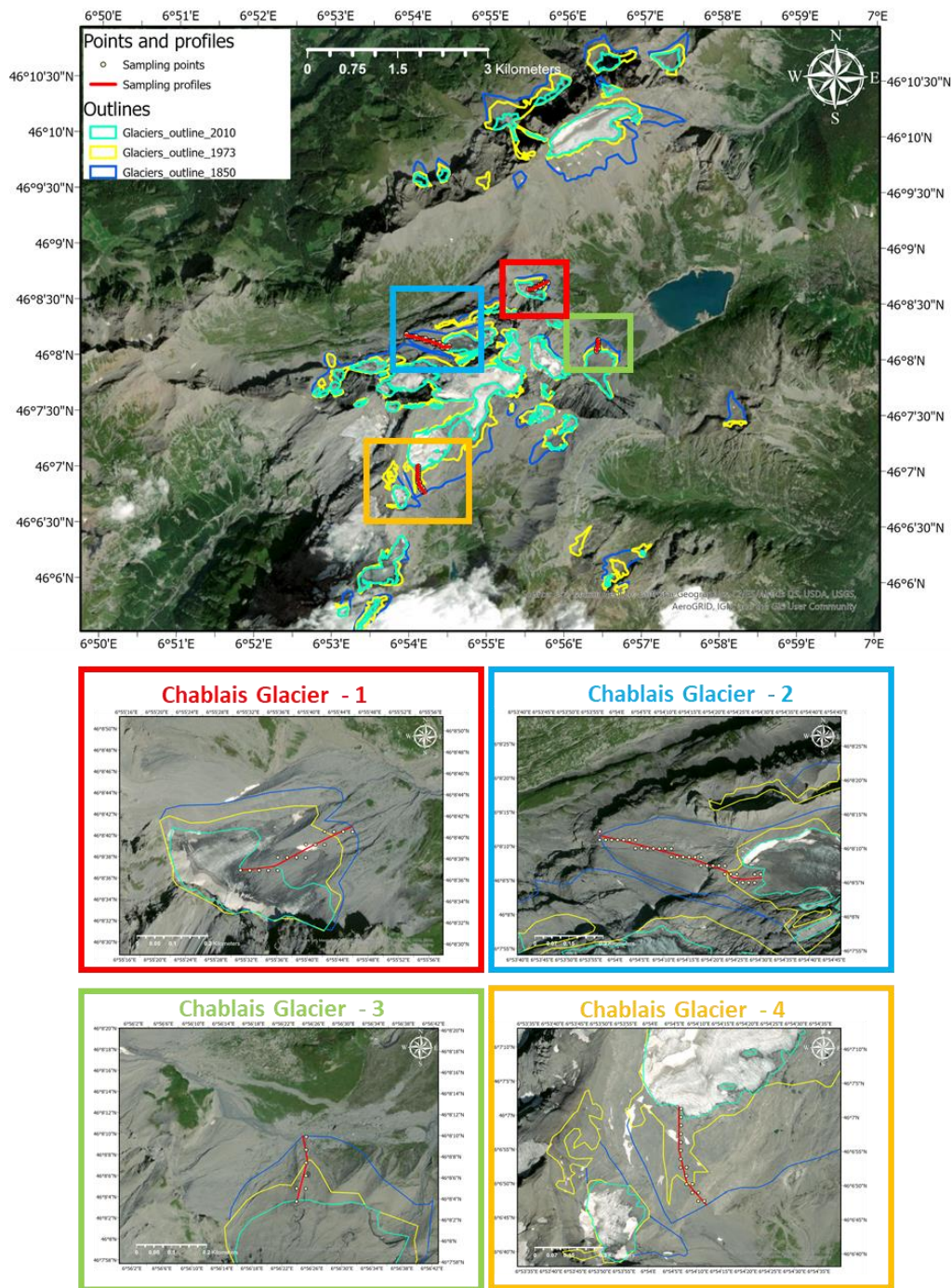
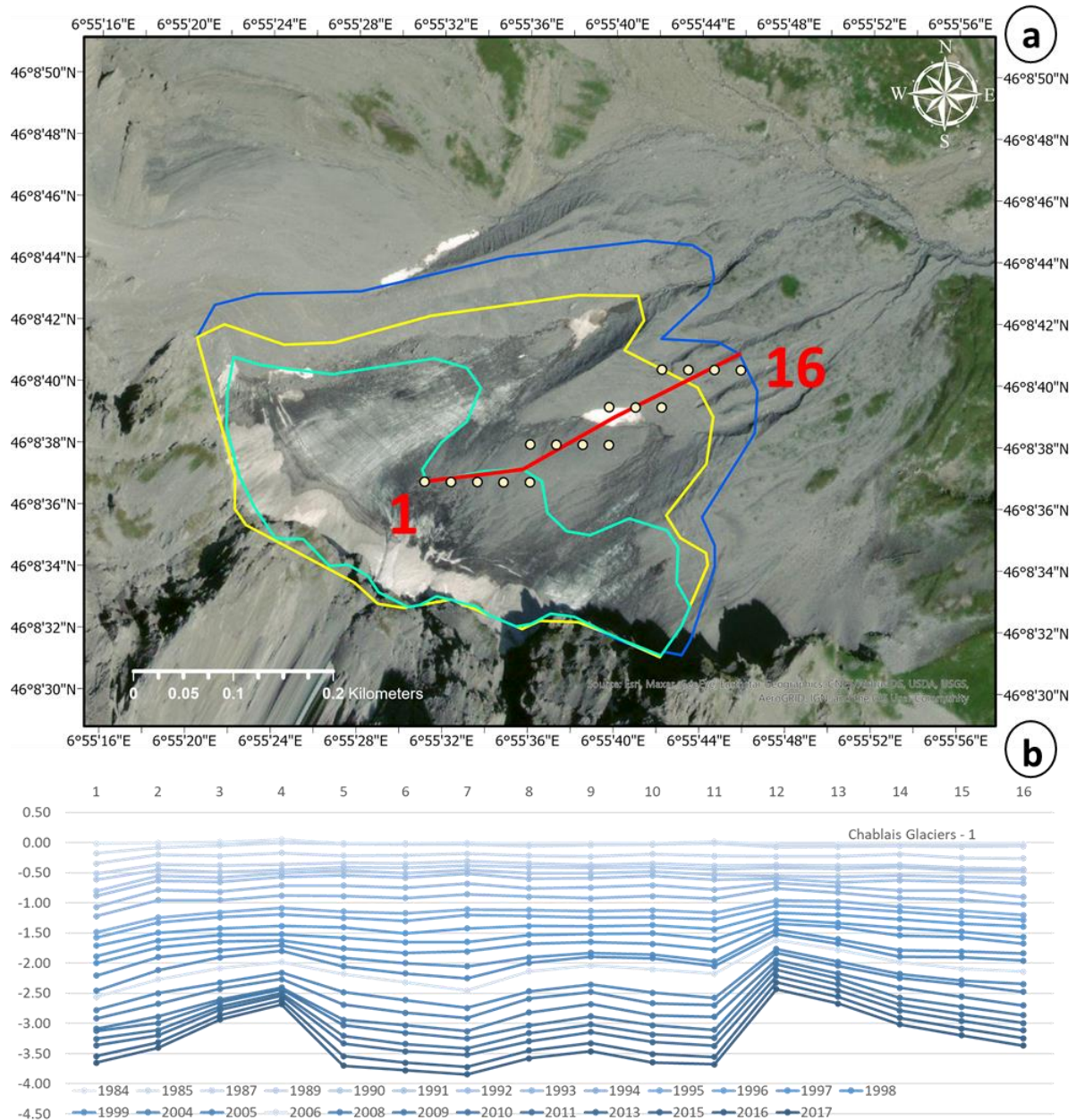


Figure 28 - Overview of the Chablais Glaciers. In detail, the four profiles on the glaciers of interest. The transects were planned in order to get the best areas of sampling despite the heterogeneous spatial distribution of glaciers.

The Chablais Glacier - 1 transect is located in the NE part of the glacier group and represents data from the lower part of the Noir Glacier. In general, the acquired values show a negative trend along the years (Figure 29). Observing the evolution of the values in detail, between 1990 and 1997 the cumulative NDVI values get even more negative, which repeats itself from 2005 onwards.



The Chablais Glacier - 2 transect is located in the NW part of the glacier group and represents data from Mont du Ruan Glacier. In general, the acquired values show a negative trend (Figure 30) along the years.

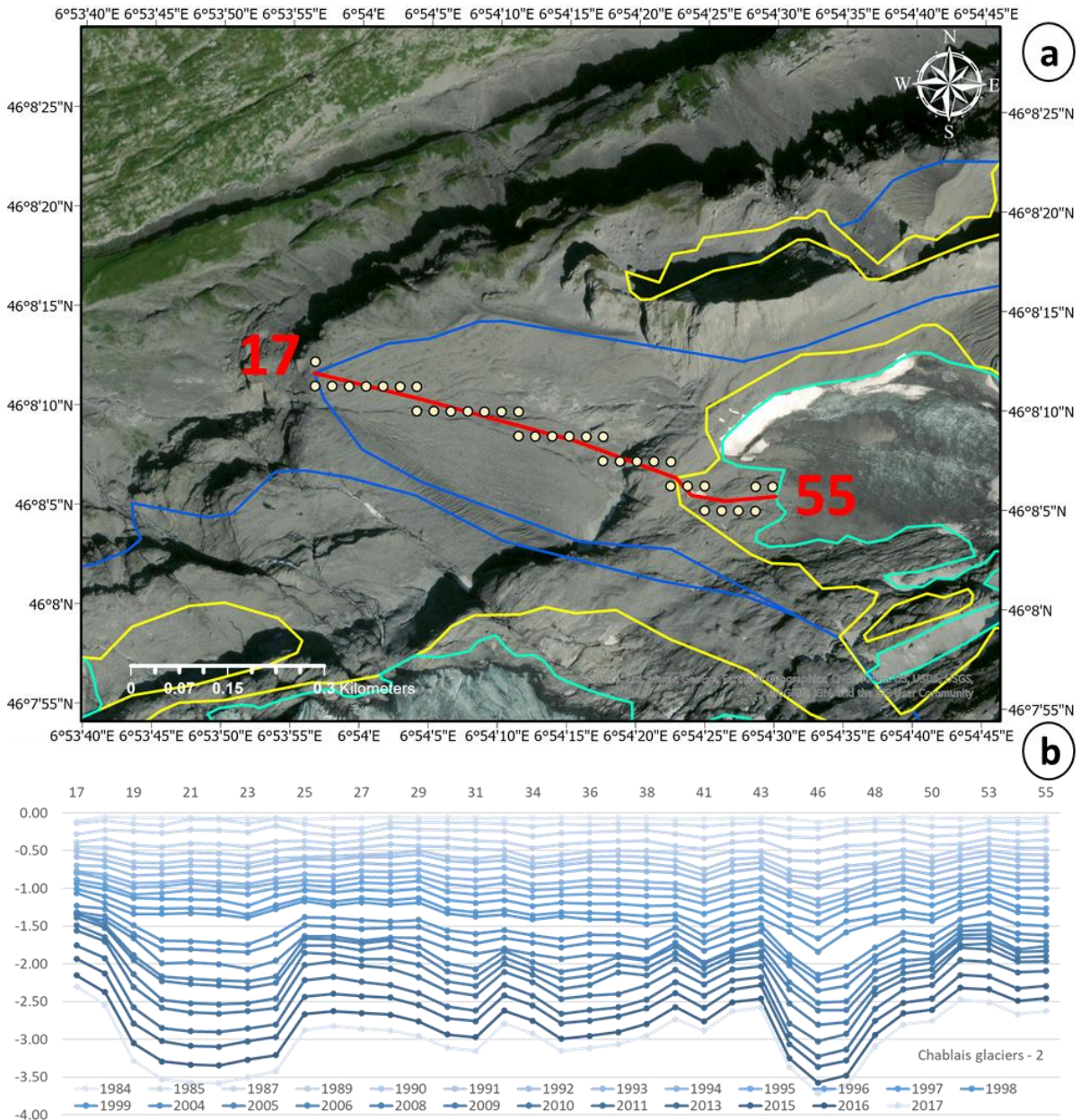


Figure 30 - Chablais Glacier – 2 profile illustrating the transect and the respective sampling points on the northwest part of the glacier. b: Stacked line chart where the y-axis represents the cumulative NDVI values while the x-axis the number of each point in the profile. Therefore, each line represents a sampling year which are represented by a blue sequential colour going from light blue, to dark blue.

The Chablais Glacier - 3 transect is in the east part of the glacier group and represents data from Noir Glacier. In general, the values tends to get more negative (Figure 31) along the years.

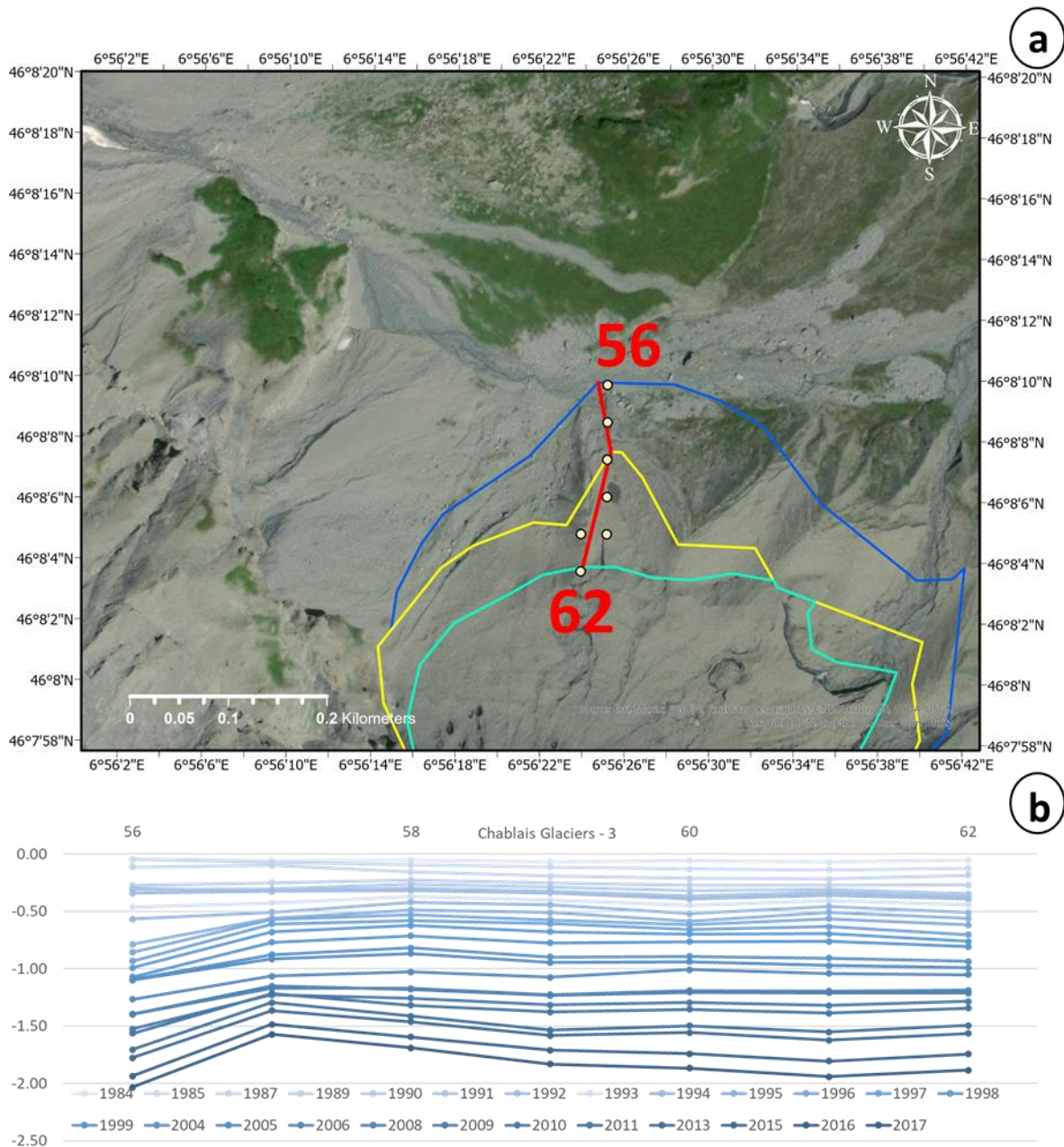


Figure 31 - Chablais Glacier – 3 profile illustrating the transect and the respective sampling points on the est part of the glacier. b: Stacked line chart where the y-axis represents the cumulative NDVI values while the x-axis the number of each point in the profile. Therefore, each line represents a sampling year which are represented by a blue sequential colour scale going from light blue, to dark blue.

The Chablais Glacier - 4 transect is in the SW part of the glacier group and represents data from “De Fonds” Glacier. In general, the values are negative and tends to get more negative along the years. Nevertheless, we can observe a difference between the values along the profile (Figure 32). From point 78 towards point 63, the values become gradually more negative.

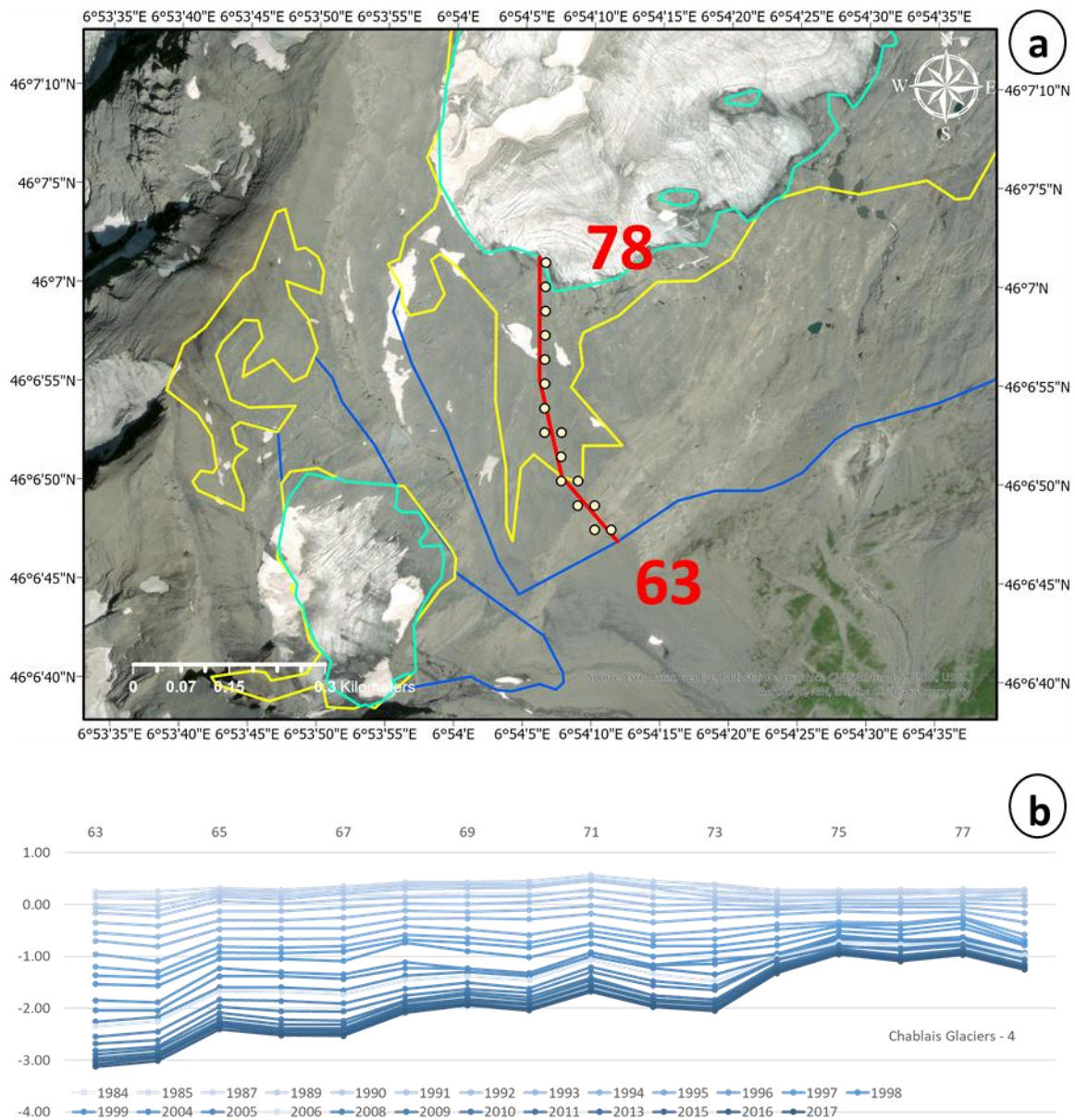


Figure 32 - a: Chablais Glacier – 4 profile illustrating the transect and the respective sampling points on the southwest part of the glacier. b: Stacked line chart where the y-axis represents the cumulative NDVI values while the x-axis the number of each point in the profile. Therefore, each line represents a sampling year which are represented by a blue sequential colour scale going from light blue, to dark blue.

3.2 Zonal statistics

Zonal statistics are widely used to analyse the variation of large datasets within an area of interest. In the present project, the performed analyzes provided good results allowing the production of a data set which represents the variation of NVDI annual mean values within the 3 zones of interest from 1984 to 2018 (Figure 33).

The results were provided in the form of tables, which allow this information to be loaded into excel and later modified and organised in the most convenient way for the project, obviously without changing the values.

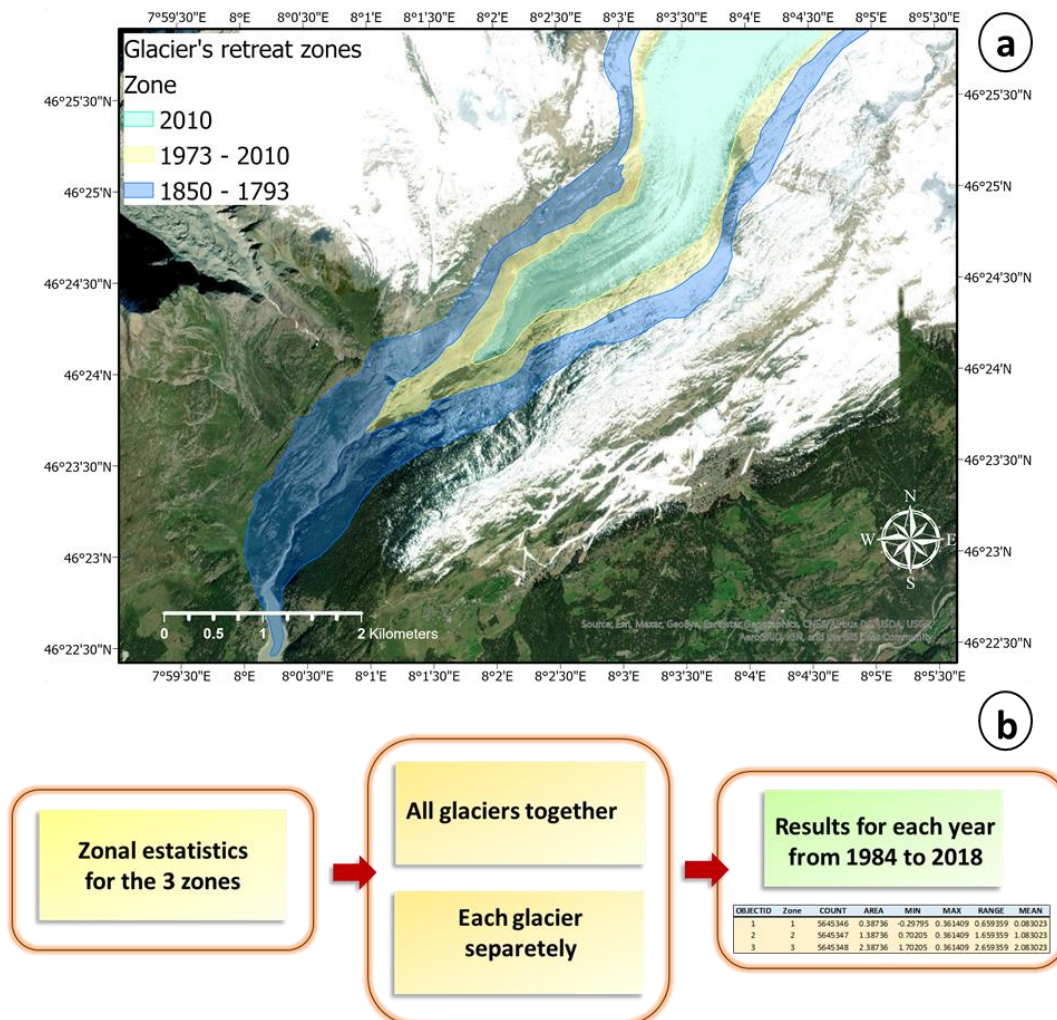


Figure 33 - Map illustrating the showing the 3 zones of interest on the Aletsch glacier. b: Workflow explaining the processing steps.

In order to obtain data representing the overall variation of NDVI values in the Swiss Alps, all three zones of interest have been analysed for all the glaciers of the study together. After that, each glacier has been analysed separately, which allows us to observe the statistics in more detail for each region of the Swiss Alps (Figure 33).

Basically, the zonal statistics give us the following results for each established zone: count, area, minimum, maximum, range, mean, standard deviation and sum. For this study it was decided to use only the minimum, maximum, range and mean.

To obtain a better visual representation of the data obtained, the numeric tables were converted into column graphs (Figure 34) where for each year (X – axis) we have four columns (Y – axis): minimum (MIN), maximum (MAX), mean (MEAN) and range (RANGE).

3.2.1 Swiss Alps

The results obtained for the 3 zones, using all the six glaciers, are very consistent and allow us to observe the behaviour of NDVI values over the years. In general, the three study zones presented negative mean values during all the years, but the mean varies slightly from year to year. It is also possible to observe that the mean values in zone 3 are closer to zero (less negative) than in zones 2 and 1. The years in which the range values are higher show that the difference between the maximum and minimum values sampled in the zone in that year was greater.

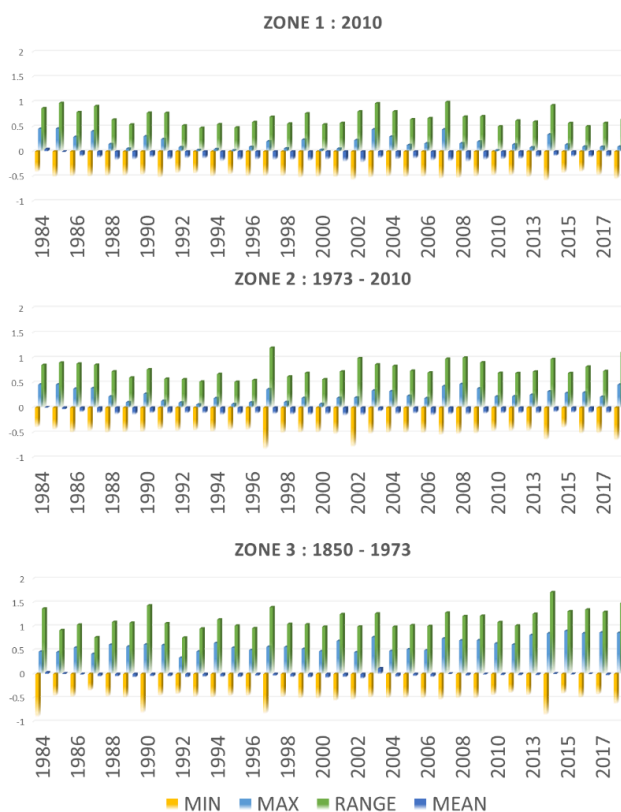


Figure 34 - a: Bars charts illustrating the results of the zonal statistics for all glaciers together. On the x-axis are represented the sampling years, and on the y-axis the minimum, maximum, range and mean values. Note the colour scale on the lowest part of the figure.

3.2.2 Arolla Glacier

The Arolla glacier presents in general negative mean values with an increasingly negative trend over the years for all the zones (Figure 35). Except for zone 3, the maximum values are always close to zero reaching more positive values only in the years 1984 to 1986. On the other hand, the minimum values are always close to -0.5 apart from the year 2007, where we observe a break in the trend, which from 2008 returns to the range of values of previous years.

Zone 3, differently from the others, presents higher maximum values throughout the entire sequence of years, which reflects in the mean values that are closer to zero (less negative) in this zone.

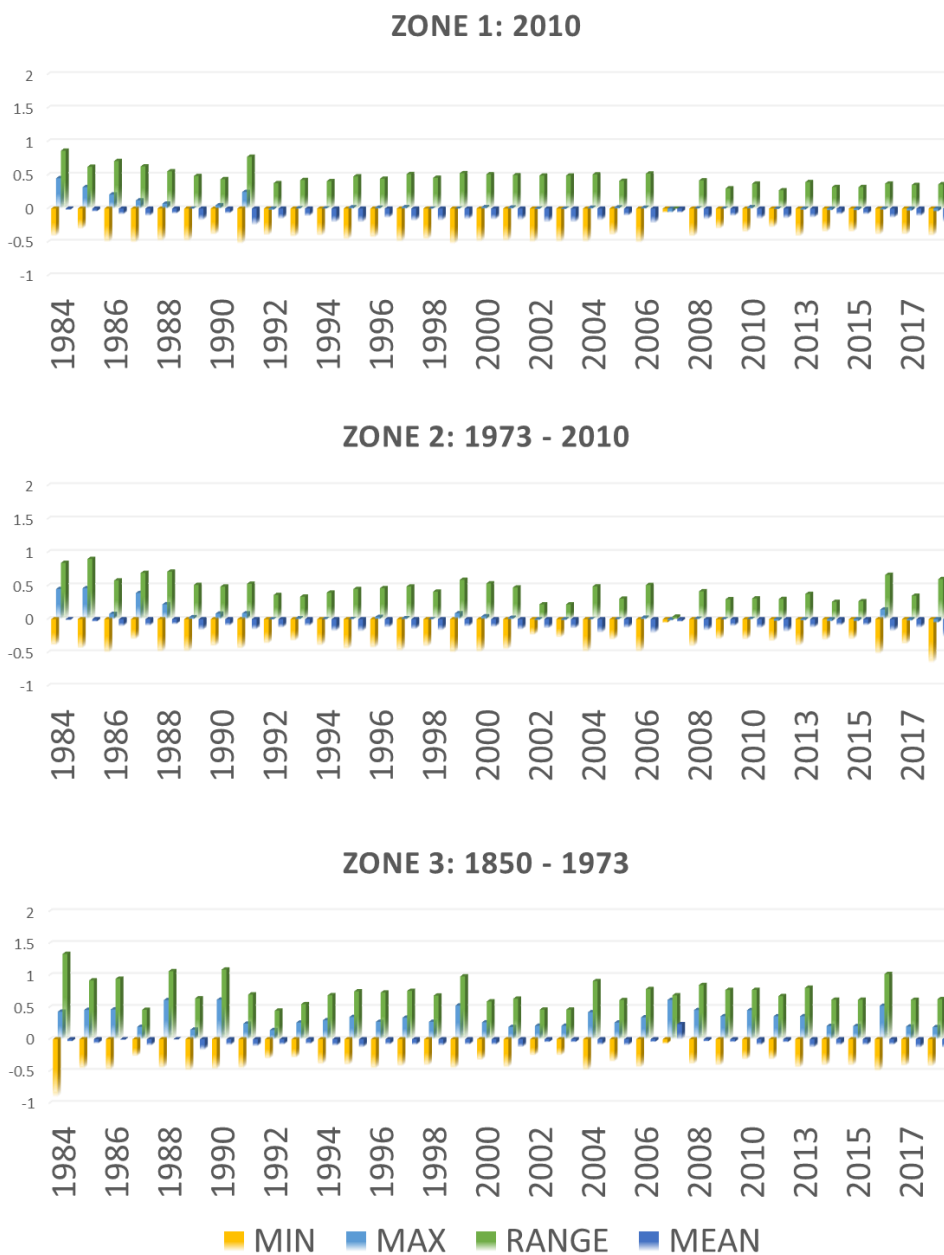


Figure 35 - a: Bars charts illustrating the results for Arolla Glacier zonal statistics. On the x-axis are represented the sampling years, and on the y-axis the minimum, maximum, range and mean values. Note the colour scale on the lowest part of the figure.

3.2.3 Allalin Glacier

All the analysed zones of the Allalin glacier present values which behave in a cyclic way with the passing of the years. We can observe, looking at the range values, a cyclic variation, that repeat itself in a frequency of 5 years (1984 till 1989, 1990 till 1995, 1996 till 2001...)

The zone 3 is the only zone where the maximum values increase significantly throughout the years. At the same time, the zone 3 presents minimum values that become less and less negative along the throughout time. These characteristics are reflected in the average values, which become less and less negative until it turns positive in the year 2018 (Figure 36).

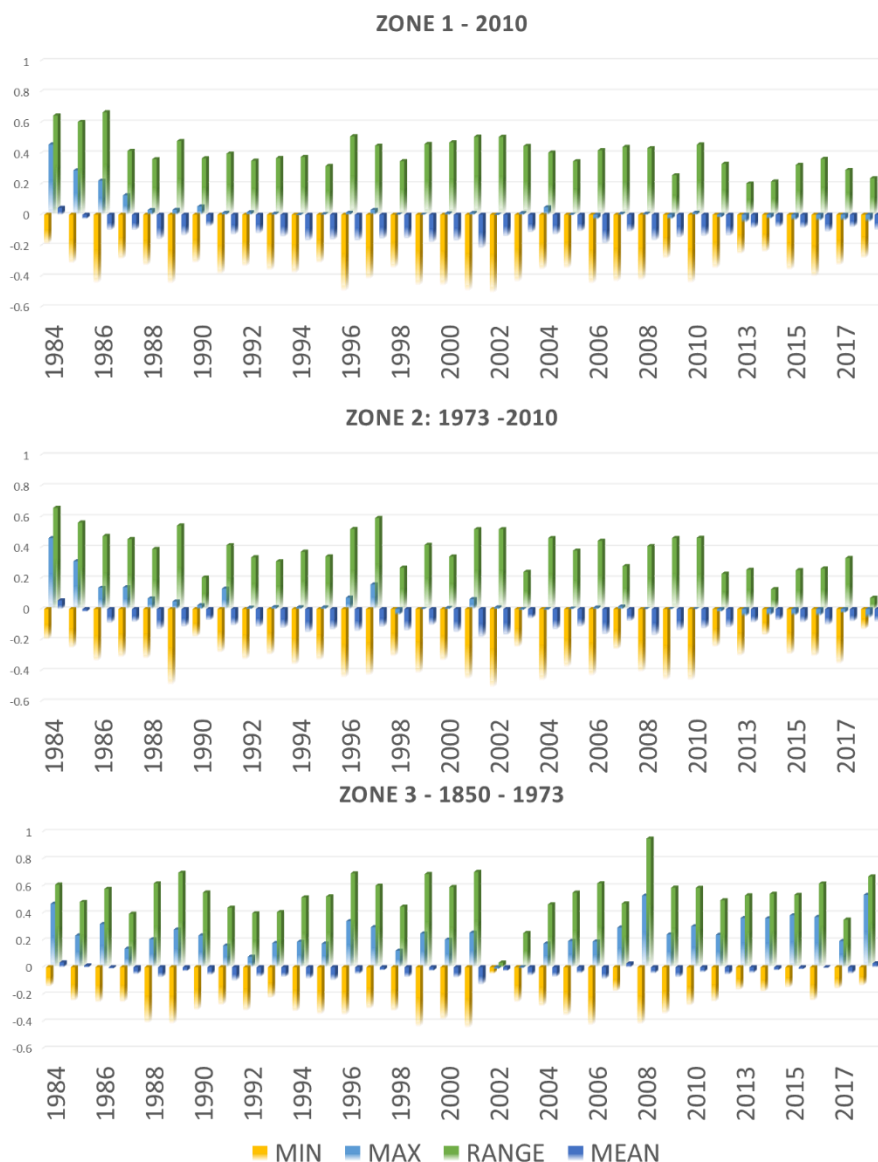


Figure 36 - a: Bars charts illustrating the results for Allalin Glacier zonal statistics. On the x-axis are represented the sampling years, and on the y-axis the minimum, maximum, range and mean values. Note the colour scale on the lowest part of the figure.

3.2.4 Aletsch Glacier

The statistical analyses promoted on the Aletsch glacier gave very distinct results for each zone. The maximum values in zone 1, apart from the years 1984 to 1987, are always close to zero, while the minimum values are always close to -0.5. Therefore, the average values are positive only between 1984 and 1987 remaining negative (Figure 37) throughout the years and reaching almost zero between 2013 and 2018.

The zone 2 presents higher maximum values than zone 1 in general, but these values vary greatly over time reaching their peaks in the periods 1984 to 1987 and 2009 to 2018. The minimum values are more constant around -0.5 and approach zero after 2013. The mean values become more negative between the years 1987 and 2008, but in the other years where the maximum values are higher, the mean is very close to zero.

In zone 3, the average values are in general very close to zero, even reaching positive values in 1984. This positive trend of mean values reflects the highest maximum values of the 3 zones.

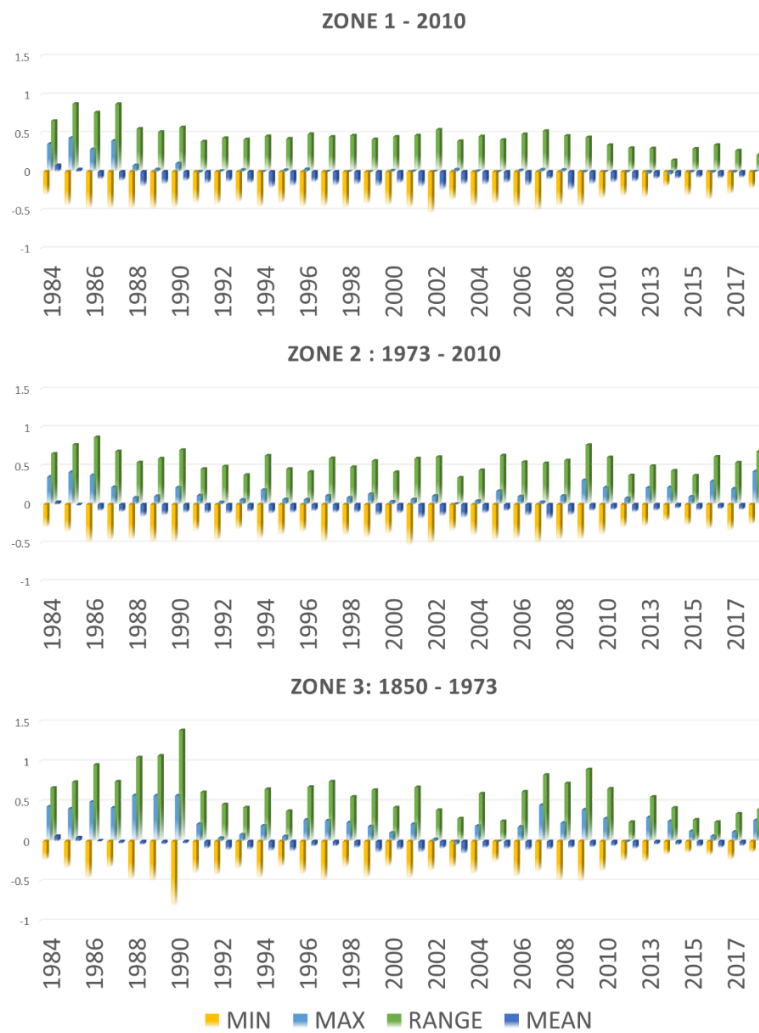


Figure 37 - a: Bars charts illustrating the results for Aletsch Glacier zonal statistics. On the x-axis are represented the sampling years, and on the y-axis the minimum, maximum, range and mean values. Note the colour scale on the lowest part of the figure.

3.2.5 Grindelwald Glacier

The results of zone 3 of the Grindelwald glaciers differ clearly from the other two zones. With very high maximum values, between 0.5 and 1, zone 3 presents negative mean values in general, but very close to 0 reaching positive values in 5 different years (1986, 1988, 2007, 2009 e 2014).

The zones 1 and 2 present in general similar values (Figure 38), however they are differentiated by the maximum values, which in zone 1 are always very close to zero. On the other hand, in zone 2 the maximum values are in general higher while the minimum values are very similar to zone 1.

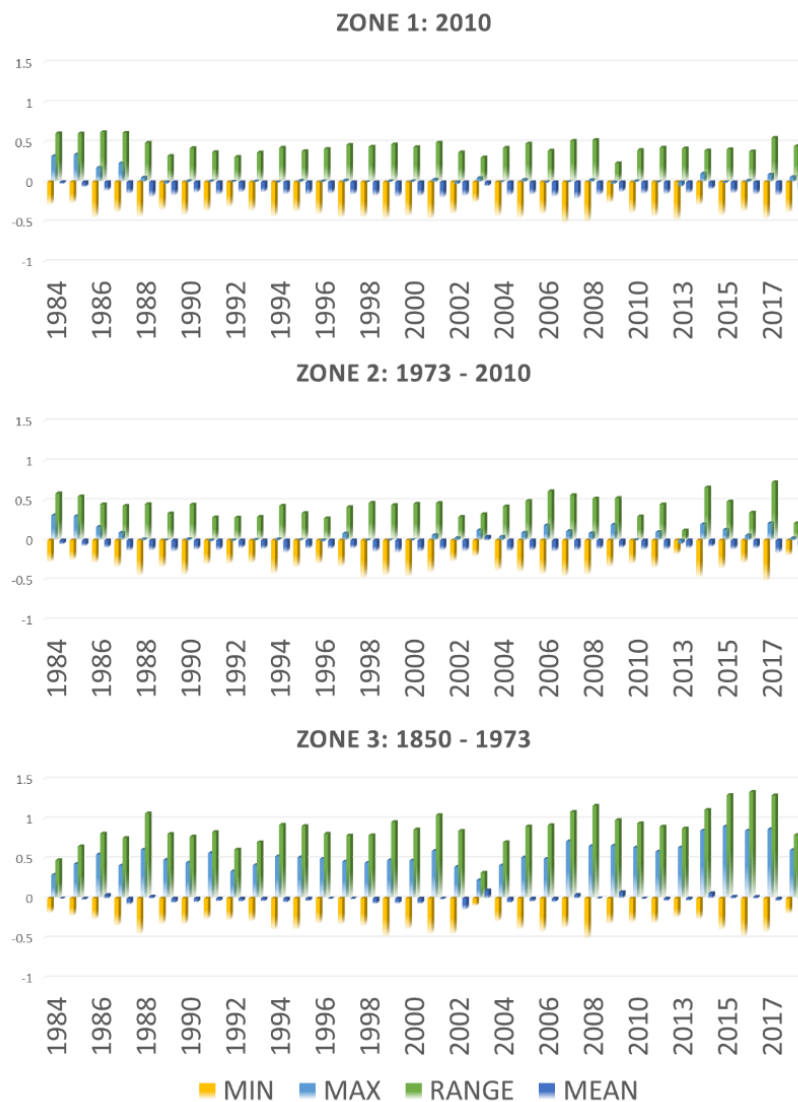


Figure 38 - a: Bars charts illustrating the results for Grindelwald Glaciers zonal statistics. On the x-axis are represented the sampling years, and on the y-axis the minimum, maximum, range and mean values. Note the colour scale on the lowest part of the figure.

3.2.6 Monterastch Glacier

The statistical analyses promoted on the Monterastch glacier gave very distinct results for each zone. The maximum values in zone 1, apart from the years 1984 to 1987, are always close to zero, while the minimum values are always close to - 0.5. Therefore, the mean values remain negative throughout the years.

The zone 2 presents values broadly in general similar to zone 1 (Figure 39), however, the minimum values are slightly less negative. In zone 3, the mean values are in general very close to zero, even reaching positive values in 2003, 2007, 2008, 2009 and 2016. This positive trend of mean values reflects the highest maximum values of the 3 zones.



Figure 39 - a: Bars charts illustrating the results for Monterastch Glacier zonal statistics. On the x-axis are represented the sampling years, and on the y-axis the minimum, maximum, range and mean values. Note the colour scale on the lowest part of the figure.

3.2.7 Chablais Glaciers

The Chablais glaciers present results which differentiate them from the other studied glaciers. In the three zones, the mean values present a remarkable cyclicity, which is observed approximately every 6 years. With the passing of the years the mean values assume a trend more and more negative that afterwards returns gradually to values near zero (Figure 40). This trend behaviour of the mean values is also observed in the maximum and minimum values. In the three zones, the statistical values are similar and follow the same variation pattern.

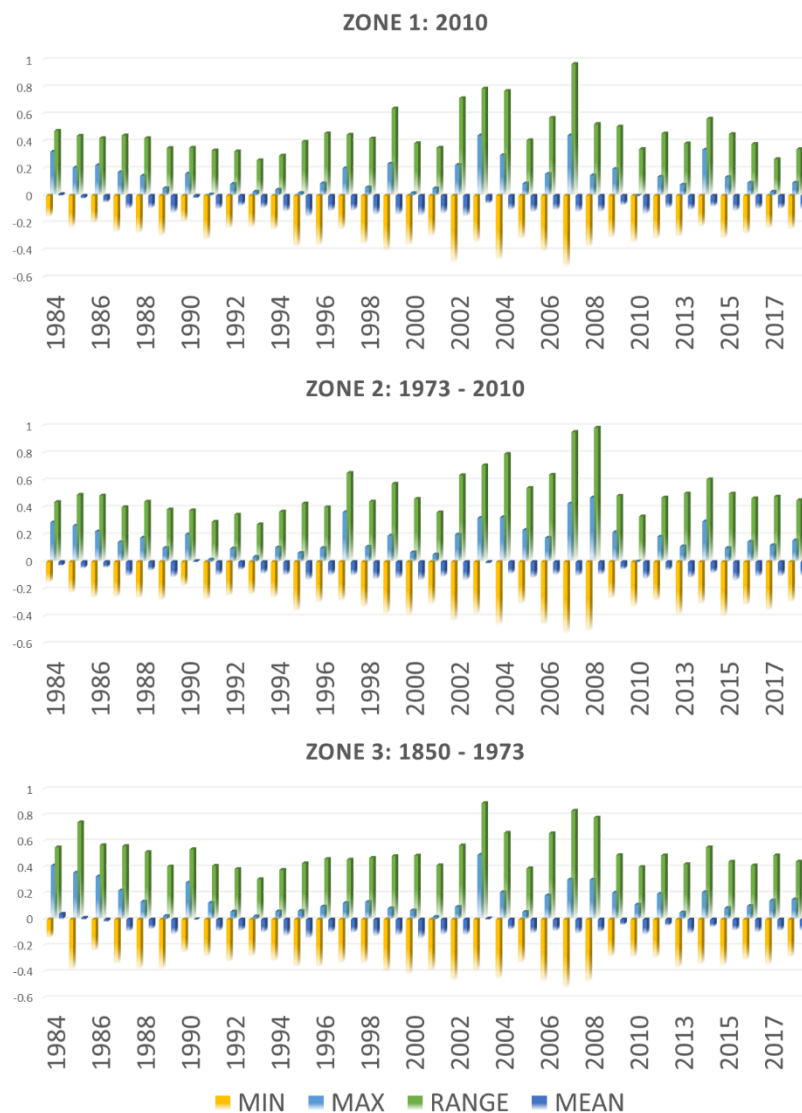


Figure 40 - a: Bars charts illustrating the results for the Chablais glacier's zonal statistics. On the x-axis are represented the sampling years, and on the y-axis the minimum, maximum, range and mean values. Note the colour scale on the lowest part of the figure.

4 INTERPRETATION AND DISCUSSIONS

The current global warming is generating a rapid glacier retreat in the last decades (Stocker et al., 2013). Since their LIA maximum extent in the middle of the 19th century, some glaciers have been retreating, losing more than half of their area (Bauder et al., 2014)

On the Swiss Alps, the retreat rates varied during this period except for two short periods of glacier advances in the 1920s and 1980s (Mauro Fischer et al., 2014). During the last decade, they have retreated at a rate never seen before (Zemp et al., 2015) opening new ground for vegetation which stabilise the paraglacial terrain and allow storage and interception of precipitation.

The acquired results were interpreted and compared with different studies (Haeberli et al., 2019; Paul & Haeberli, 2008; Sommer et al., 2020) promoted on Alpine glaciers. This allowed us to generate information on the annual evolution of glaciers and the vegetation along their fronts.

4.1 Glacier transects

In general, the sampling profiles presented NDVI values that tended to increase over time, but depending on the region where the transects crossed, the sampled values varied in a way that could indicate which type of feature was being investigated. Generally, the sampling points present in the glacier retreat areas between 1850 and 1973 show more positive values, indicating the presence of vegetation in the areas now uncovered by the glaciers retreat. In addition, the trend of cumulative values in this areas becomes more and more positive along the years, indicating a more abundant and fixed vegetation as seen in different studies in the world research (Chu et al., 2007; A. Fischer et al., 2019; Gamon et al., 2013; Gandhi et al., 2015). On the other hand, the points that are on the glaciers retreat zone between 1973 and 2010 present in general a cumulative trend, which becomes more negative as the years go by. This negative tendency is linked to the fact that these points are on relatively new ice melting areas, which are sometimes covered with ice and very unstable, making it harder for vegetation to develop (Liberati et al., 2019).

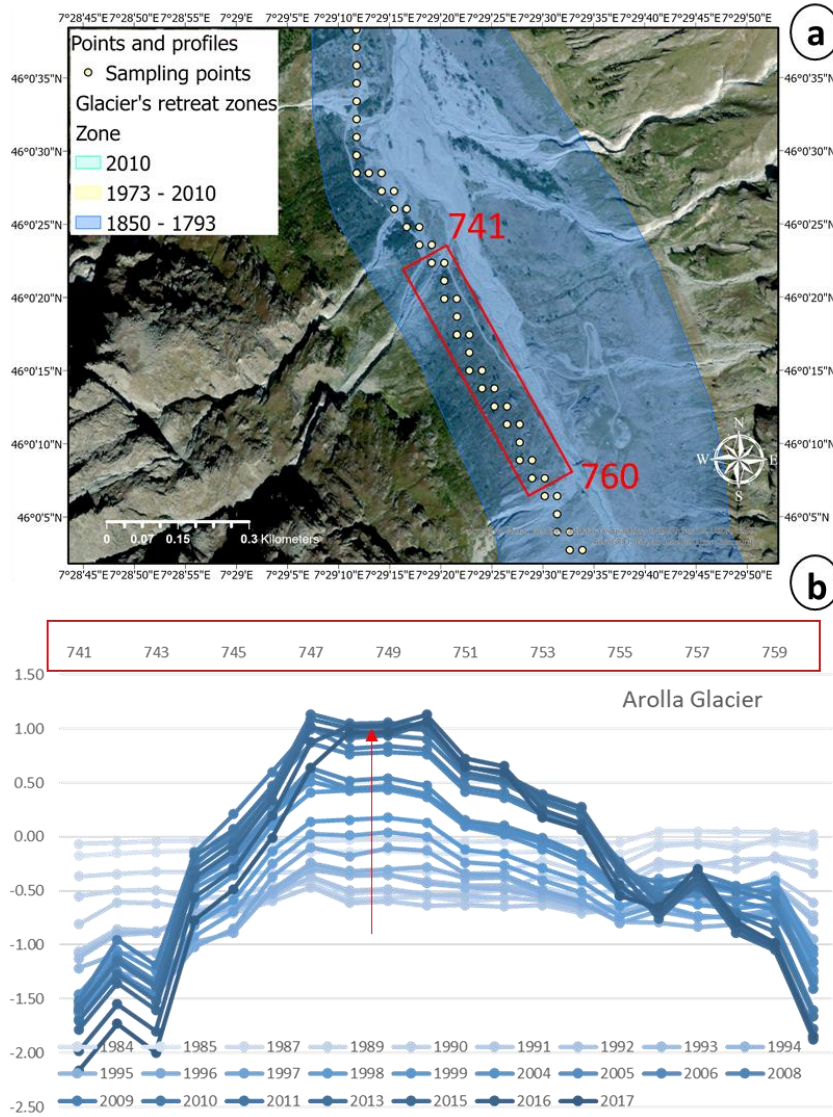


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Profiles Arolla-2 and Chablais 1, 2, 3 and 4 are exceptions where the transects sampled only negative NDVI values with a cumulative negative trend over the years. The Arolla - 2 profile is located on the Trend glacier that joins the main Arolla glacier to flow down the valley. This area is extremely unstable, subject to landslides and debris movements which in turn generate a more negative NDVI response. Despite the overall negative trend this profile can be divided into two sectors (Figure 42) The first within zone 3 (Figure 41) showing more accentuated negative trend and the second, inside zone 2 (Figure 42) with less accentuated negative values. This difference is caused by the type of terrain and the presence of small water bodies resulting from glacier melting. The less negative trend in zone 2 indicates the presence of small rivers generated by glacier melt water, while the presence of soil and debris in zone 3 is reflected in more negative trends.

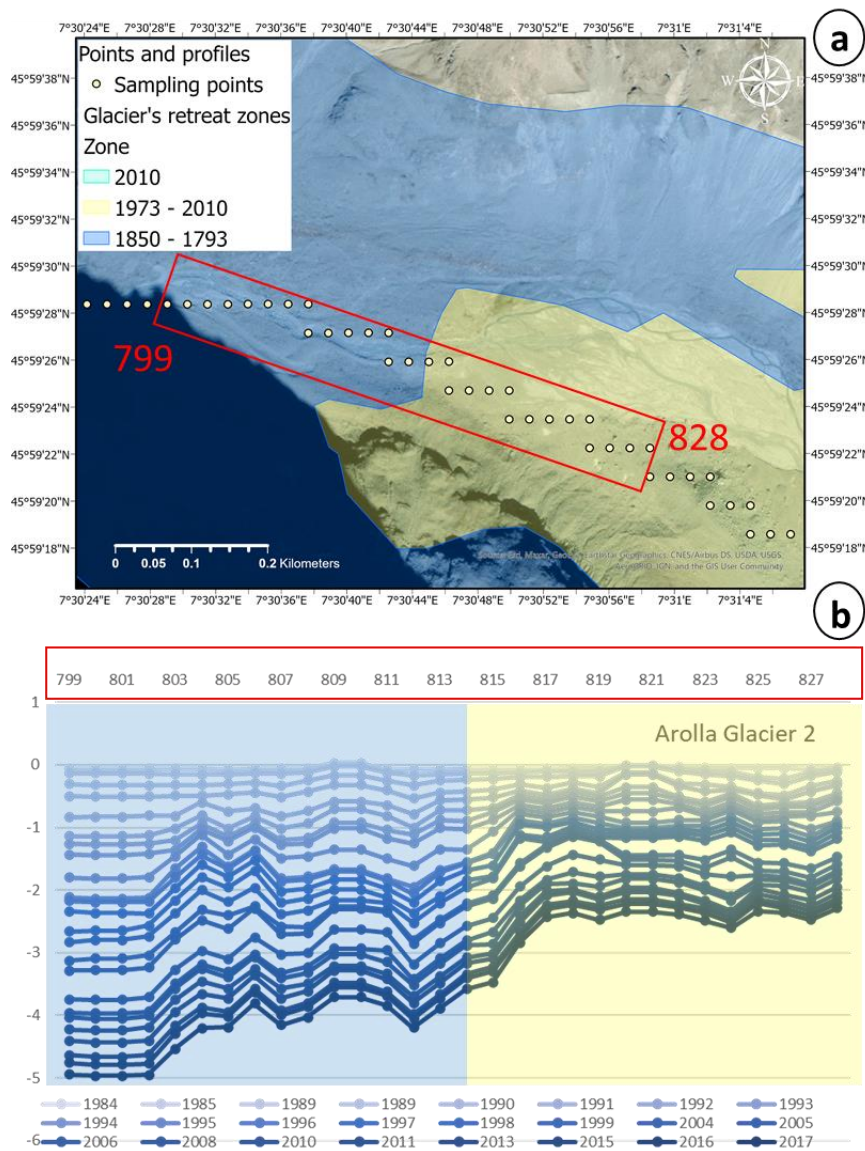


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The glaciers of the Chablais present different spatial distribution which is reflected in their NDVI values sampled by their respective transects. The fact that there are several different glacier fronts which are far from each other and located on uneven ground makes the establishment of vegetation difficult. Therefore, the NDVI values acquired are always negative and vary in the same proportion throughout the years.

4.2 NDVI thresholding

The results obtained by separating the NDVI values into specific classes generated interesting results. The resulting polygons identify automatically and quickly the possible features present in the study areas, but they do not provide a precise indication of the glacier fronts. Therefore, these data were used to identify the main characteristics of each zone of interest, and to better understand their relationship with the acquired NDVI signals.

According to the classification of the NDVI values, zone 1 is mostly covered by glaciers and some debris deposits. Zone 2 represents in general an area of variation of the glacier front and is composed sometimes by exposed soil, sometimes by the glacier itself. Study zone 3 is the most stable zone of all, having vegetated areas that can be divided into grass or fixed.

The results vary from glacier to glacier, but in general they represent well the reality. Comparing for example the results obtained for the year 2010 at the Aletsch and Allalin glaciers we can observe that the front of the glacier (Glacier Class) fits the contour of the 2010 glacier at the Aletsch glacier (Figure 43 in contrast to the Allalin glacier (Figure 44)).

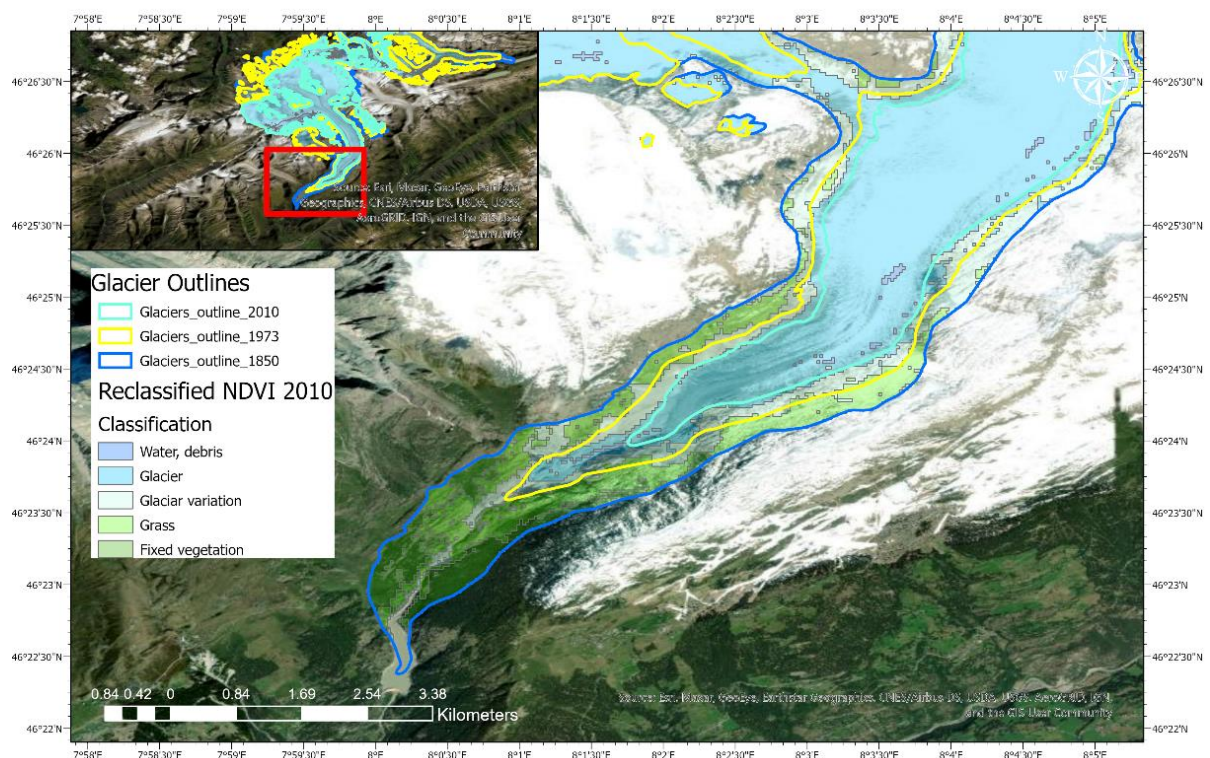


Figure 43 - Map of Aletsch Glacier illustrating the reclassified NDVI values from 2010. The glacier outlines for 1850, 1973 and 2010 are also represented on the map to show the features inside each zone. Note that the glacier front (Glacier class) fits well with the glacier front in 2010.

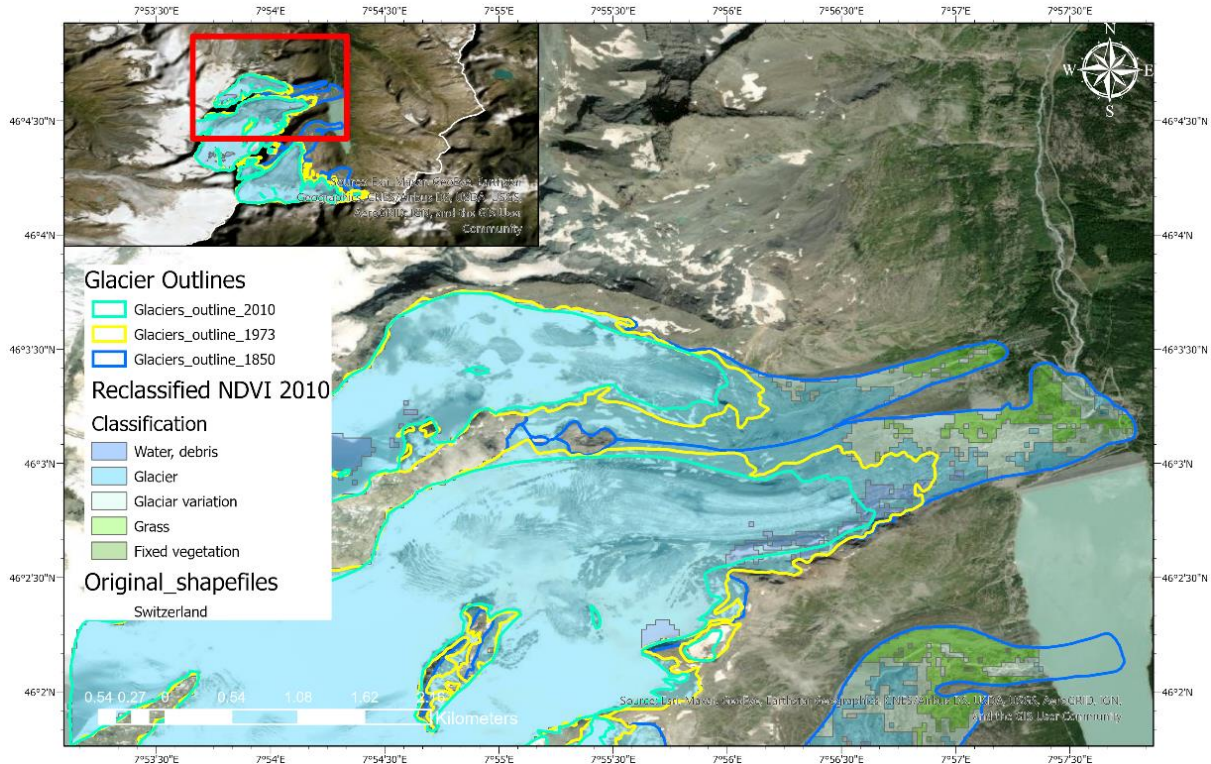


Figure 44 - Map of Allalin Glacier illustrating the reclassified NDVI values from 2010. The glacier outlines for 1850, 1973 and 2010 are also represented on the map to show the features inside each zone. Note that differently from Atetsch glacier, the glacier front (Glacier class) does not fit well with the glacier front in 2010.

4.3 Zonal Statistics

The results of the statistical analysis promoted in the zones of interest 1, 2 and 3 give us important information to understand how the behaviour of the NDVI values can give us clues about the establishment of vegetation and the evolution of glaciers among time within the glaciers retreat areas.

The minimum and maximum values indicate the limits of values acquired within the study areas and therefore give us an indication of the range of NDVI values for each year. For each glacier, the zone 3 presents higher maximum values than zones 1 and 2. This difference is due to the greater presence of vegetation in these areas which are more stable and favourable for their development.

The zones 1 and 2, on the other hand, present more negative minimum values and its maximum values are generally closer to zero, which indicates that these zones do not present vegetation cover and are characterized as exposed soil (debris), ice or water.

The mean values are also very good indicators. Their variation gives us an estimate of the behaviour of glaciers and their surroundings over time. Negative mean values indicate areas where little or no sign of vegetation has been recorded within the study area. On the other hand, positive mean values indicate areas where vegetation is more abundant.

Another interesting perspective is the correlation of the sampled NDVI data and the variation in glacier length. Comparing the two parameters over time it is possible to see that the mean, minimum and maximum values variations follow the glacier length change (Figure 45).

Observing the data of glacier length change provided by Glacier Monitoring Switzerland (2019) it is possible to note that the years where the glaciers had their length reduced coincide with the years where the mean values get higher or positive, while the years where the glacier length increase coincide with the years where the mean values are lower or negative. Six cycles were identified (1984 - 1986; 1987 - 1986; 1990 - 1996; 1997 - 2001 ; 2003 - 2004 ; 2004 - 2006) relating the two datasets (Figure 45). They are observed in all glaciers, but it changes a little from zone to zone.

The current rapid global warming has been drastically affecting glaciers (Nussbaumer et al., 2011), that in the extremely warmer years tend to decline in length and ice mass. In addition, temperature increase is usually linked to the increase in species richness found in high altitudes (Grabherr et al., 1995; Pauli et al., n.d.; Theurillat & Guisan, 2001; Walther, 2003). The glaciers retreat creates space for temporary vegetation (Burga & Conradin, 1999) and releases large quantities of water that flow downstream in a glacial fluvial system. In general, during the last century the global warming has generated an upward migration of the vegetation and an increase in the richness of vascular species in the Swiss Alps (Holzinger et al., 2008), which drives the positive NDVI mean values in zone.

Zone 2 generally lacks vegetation and comprises the areas of annual variation of glacier fronts and is susceptible to landslides and debris accumulation. Therefore, in warmer years these areas tend to be more unstable, presenting more exposed soil and ephemeral channels where the glacier melt water drains. As seen by Fischer et al (2019) in Jamtalferner glacier, these features explain the negative trend on the mean values recorded in this zone.

Therefore, in the end, the NDVI values allow us not only to analyse the vegetation colonising the glacier fronts but also to infer the paleoclimatic conditions of the years analysed and the consequences on the glaciers.

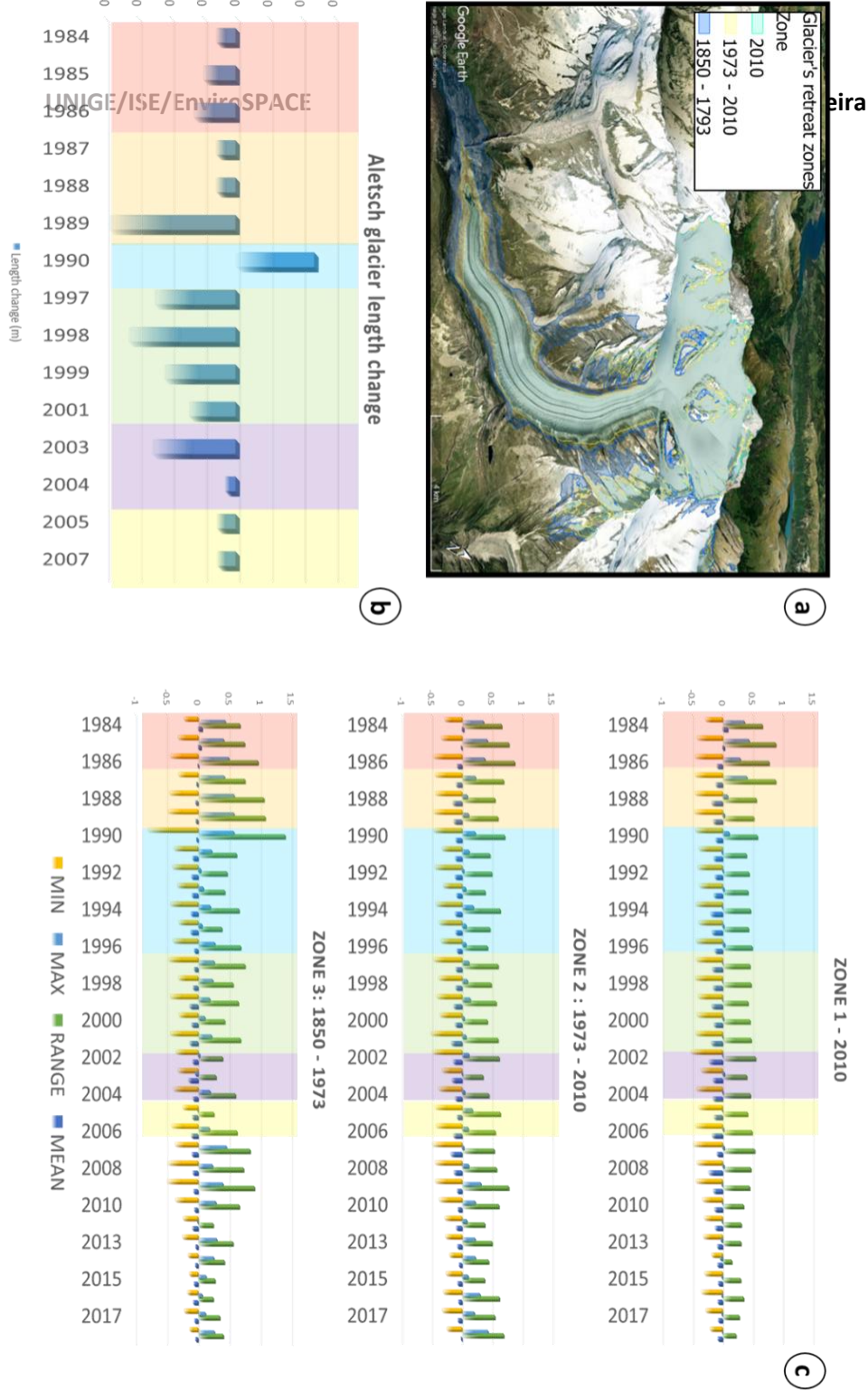


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5 CONCLUSION

The global trend towards the availability and sharing of data allows us to analyse the planet earth's systems and to make this information accessible. This study demonstrates the importance of NDVI analyses as very effective tools to support environmental investigations. The dataset used in the study is fully open and was processed using the ArcGIS PRO software allowing us to generate precise data on the evolution not only of the vegetation of glacier fronts but also of the glaciers themselves, between the years 1984 and 2018.

Three main zones were defined for each glacier based on the glacier outline data for the years 1850, 1973 and 2010. In addition, the NDVI thresholding allowed us to define the main features of each area studied. Therefore, the zone 1 represents the glacier area measured in 2010, which is normally covered by ice generating negative or near zero NDVI signals. The zone 2 represents the area between the 1973 and 2010 outlines, and is generally composed of exposed soil and debris, populated by little to no vegetation. Zone 3 represents the area between the 1850 and 1973 outlines and is composed of soil, some water bodies and both temporary and fixed vegetation. This zone was in fact the most important for the present study providing us with important data on the annual vegetation evolution.

The proposed sampling profiles for the glaciers clearly show the evolution of the NDVI signal along the chronological sequence. In general, with the passing of the years, the NDVI values increased in the sampling points over areas with vegetation, while in the points with more exposed soil the values tend to become more negative. This behaviour confirmed the increase of vegetation in zones 3 and the greater exposure of soil in zones 1 and 2 due to the retreat of glaciers.

The statistical analysis promoted by this study generated important data which allowed us to identify a cyclical pattern in the NDVI signal within the zones of interest. The six cycles identified (1984 - 1986; 1987 - 1986; 1990 - 1996; 1997 - 2001; 2003 - 2004; 2004 - 2006), follow the variation in glacier length, revealing the climatic relationship between the two datasets.

The findings described above have essential implications to the understanding of the climatic phenomena of the last decades and their effects on the Swiss glacial environments. In general, the increase of vegetation and exposed soil on the Swiss glacier's fronts alerts us to the general retreat tendency with emphasis on the Aletsch and Grindelwald Glaciers that stand out as the most affected by global warming in the last decades.

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