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Master’s Degree in Environmental and Land Engineering
Curriculum “Climate Change”

Master of Science Thesis

Glacier Retreat Analysis Using Satellite Images:

Study of the Adamello Glacier and a Patagonian Case

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1. Introduction

A glacier is a massive body of ice that forms through the accumulation and compaction of snow over thousands of years. Glaciers are primarily found in polar regions and high-altitude mountainous areas.

Beyond being a strategic freshwater reservoir - usable for agricultural, civil, energy, and industrial purposes - glaciers serve as valuable climate proxies. They are highly sensitive to climatic and environmental variations, responding to external forcings by altering their shape and size. Alpine glaciers, in particular, are composed almost entirely of ice at temperatures near the melting point (i.e., temperate glaciers), which makes them especially sensitive indicators of global change. [1]

Additionally, glaciers can pose risks to downstream populations: glacier-fed lakes may overflow or breach their moraine dams, leading to catastrophic flooding events. Such hazards appear to be increasing in certain regions, as glacial lakes expand due to glacier retreat. [2]

For these reasons and many others, it is crucial to continuously monitor and analyze glacier dynamics. This allows researchers and policymakers to:

- Quantify the reduction in glacier extent
- Assess the risks associated with glacier retreat
- Propose appropriate mitigation and adaptation strategies
- Share open data to support further research and comparative case studies
- Improve water resource management in glacier-fed basins
- Validate and calibrate climate models, by comparing simulated glacier mass balance with observed data
- Monitor contributions to sea level rise

1.1. Study area

The study focuses on the Adamello Glacier, the largest glacier in the Italian Alps. It is situated between approximately 3530 and 2550 meters above sea level and extends primarily within the Lombardy region, specifically in the Camonica Valley (Province of Brescia). A smaller portion of the glacier, known as the Mandrone unit, lies within the Trentino-Alto Adige region. Due to its size and altitudinal range, the Adamello Glacier plays a significant role in the regional hydrological system and serves as a key indicator of climate change impacts in the Central Alps.

Figure 1 - Study area (sources: https://earth.google.com)

The *Italian Glacier Committee* in his 1961 cadaster subdivided the Adamello Glacier in 6 units: *Miller Superiore, Corno Salarno, Salarno, Adamello* or *Pian di Neve* and *Mandrone.*

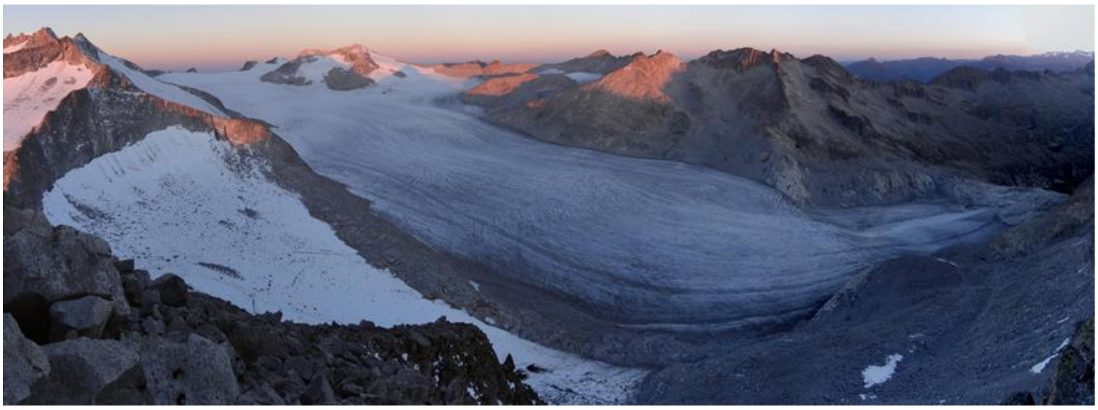

Figure 2 - Panoramic view of the Mandrone tongue (on the left) and of inferior Pian di Neve (on the right), photo of A. Lendvai taken from Lobbia Alta on 08/09/2018. [3]

The Adamello Glacier is currently considered to be a single apparatus, with a morphology referable to that of a Scandinavian-type glacier, characterized by a vast ice plateau of considerable thickness, from which numerous tongues radially depart. [4]

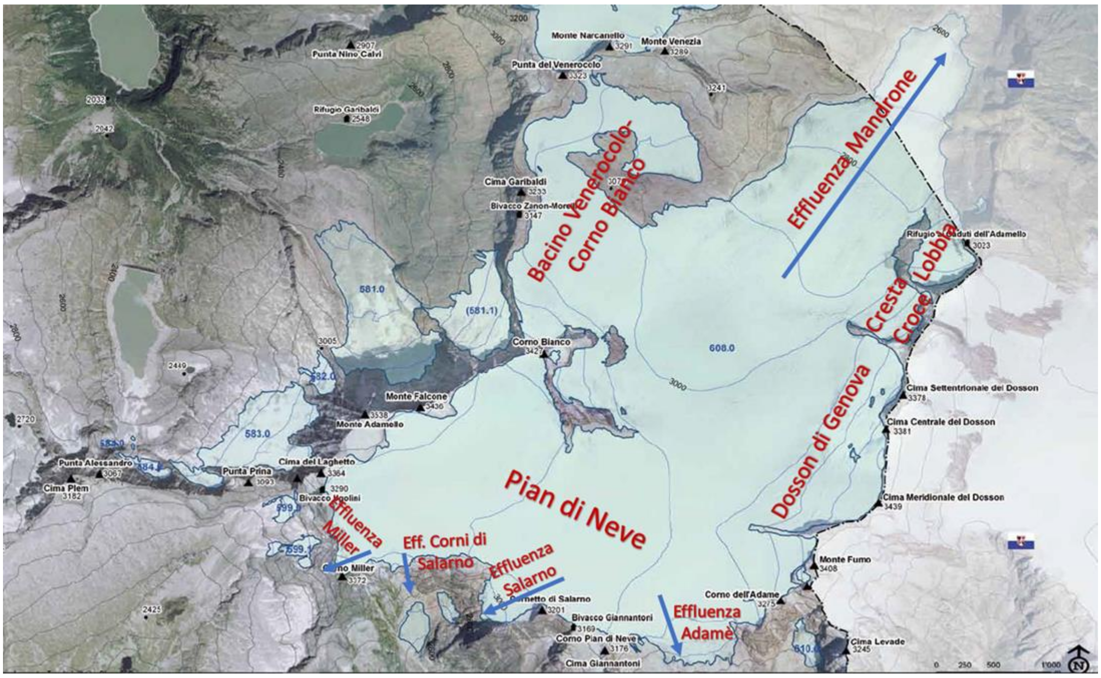

Figure 3 - Adamello Glacier topography [3]

1.2. Objective

The goal of this thesis is to develop a methodology able to assess the shrinkage of glaciers through satellite images, using only free open-source datasets and software. The choice to perform the analysis with this approach isn't a case: free access to all the materials is a fundamental point behind the idea of this project, being a primary prerequisite for giving everyone the possibility to freely perform a similar work.

1.3. Possible applications

The proposed methodology could be a starting point for assessing shrinkage analysis on glaciers using satellite images, especially in those contests in which the environment management and monitoring is not treated univocally. For example, for the Adamello Glacier case, the available online data in geoportals is divided for the region of belonging. In this way, it is not possible to download and manage data to assess an analysis, because it's quite improbable that the two geoportals of the regions have the same type of data, e.g. an orthophoto, for the same day and year of the region of interest; and, in the remote case in which this could be possible, we should be sure that the data was retrieved and managed with the same instruments and methodologies.

2. State of the Art

2.1. Actual contest and previous studies

There are plenty of case studies related to the shrinkage analysis of glaciers and they differ for goals, methodologies, data and instruments used.

For example, in a case study of the Rutor Glacier, the main objective was to estimate glacier volume and assess morphological changes over time. To achieve this, a *Digital Elevation Model (DEM)* was generated from vector data. A DEM represents the topography of a region by assigning an elevation value to each pixel, allowing for the analysis of elevation differences on a pixel-by-pixel basis. This approach enabled the estimation of glacier volume and the evaluation of topographic variations.
Additionally, a long-term analysis of the glacier perimeter was carried out over a time span of approximately 140 years, from 1864 to 2004. The perimeter was reconstructed using a combination of historical maps, terminus reconstructions by various authors (dating back to the second half of the 19th century), orthophotos, and field surveys. [5]

Another interesting work using DEMs to evaluate volume changes was conducted for a thesis at Politecnico di Torino. The focus of this project is to evaluate the reliability of DEMs derived from two different remote sensing approaches for estimating glacier volume change over time. Specifically, DEMs were generated using:

- Stereo optical image pairs from the SPOT 5 satellite, representing a passive remote sensing technique.
- *Synthetic Aperture Radar (SAR)* interferometry using Sentinel-1 radar imagery, representative of active remote sensing.

The study aims to assess and compare the quality of DEMs produced by these two technologies, and to determine their suitability for calculating glacier volume loss between 2003 and 2016. [6]

On the other hand, for a project on the Adamello Glacier, four surface area records are available, corresponding to the years 1983, 1991, 1999, and 2003. The objective of the study was to document and analyze glacier area changes over time by compiling consistent spatial datasets. The 1983, 1999, and 2003 records were produced by delineating glacier outlines from color aerial photographs taken during respective flight campaigns and integrating them into a *Geographic Information System (GIS)* environment.

The 1983 glacier area was derived through the analysis of aerial photographs (scale approximately 1:20000) using an optical stereoscopic system, allowing for a three-dimensional interpretation of the glaciated area. In contrast, the 1999 and 2003 records were generated by combining manually digitized glacier boundaries from registered color orthophotos (provided by *Compagnia Generale Riprese Aeree - CGR*) with Differential Global Positioning System (DGPS) field surveys. These orthophotos were standard commercial products with a nominal planimetric resolution defined as 1 pixel of variable size, depending on the image scale and quality.

The 1991 glacier area data were obtained from a pre-existing regional inventory published by the *Servizio Glaciologico Lombardo* (SGL, 1992) and were used to complement the temporal sequence of glacier observations. [7]

Another valuable study about the Adamello Glacier aims to monitor the amount of snow remaining on the Adamello Glacier at the end of the summer season, in order to assess mass accumulation that may contribute to the formation of new ice. To achieve this, approximately one hundred satellite images acquired between August and October from 1983 to 2021 were analyzed. The imagery was sourced from Landsat 4, 5, 7, and 8 as well as Sentinel-2 missions.

By exploiting the near-infrared (NIR) and shortwave infrared (SWIR) bands, "false color" composites were generated, enhancing the differentiation between surface materials and overcoming the limitations of true-color visualization. For each year, the most suitable image was selected, and the snow line was delineated to estimate annual snow accumulation.

This process was carried out using a semi-automatic classification approach, specifically the *Interactive Supervised Classification* method, implemented in GIS software. Individual pixels were classified into categories such as snow, ice, rock, and firn. Manual corrections were applied in areas affected by shadowing, which interfered with the automated classification. [3]

Mass balance studies on the Adamello Glacier haven't only been conducted with satellite images. For example, in another study the aim was to reconstruct recent accumulation trends on the Adamello Glacier by analyzing a 46 m ice core (ADA16) drilled in 2016 at Pian di Neve. A multi-proxy dating approach, based on annual layer counting using pollen and black carbon, and supported by 210Pb and 137Cs radionuclide markers, was used to build the core chronology. Results revealed that the uppermost 20 years of accumulation are missing, indicating significant recent mass loss. The site, previously in the accumulation zone, is now likely below the equilibrium line due to climate warming. The study highlights the effectiveness of combining particulate and radiometric tracers to date temperate alpine glaciers undergoing rapid change. [8]

Finally, it's been considered a study that aims to summarize the main results of the *New Italian Glacier Inventory*, a fundamental tool for describing and managing glacierized areas in the Alps and for assessing the impacts of climate change. The new inventory also enables direct comparisons with previous national glacier datasets, such as the *Italian Glacier Inventory* compiled by the CGI between 1959 and 1962, the Italian data submitted to the *World Glacier Inventory (WGI)* in 1985, and the most recent inventories from 1994 and 1997, also developed by the CGI.
To address the need for updated and consistent glacier data, the *New Italian Glacier Inventory* project was launched and published in 2015. The main data sources used to delineate glacier boundaries and calculate glacier areas were high-resolution color orthophotos, provided by regional and local authorities. These orthophotos were collected during various campaigns:

- 2005: Valle d'Aosta (RAVA flight)
- 2007: Lombardia (digital color orthophotos by BLOm-CGR S.p.A., IIT2000/VERS.2007)
- 2008: Provincia Autonoma di Bolzano – Alto Adige (PAB flight)

- 2009: Veneto (LiDAR survey by Regione Veneto – ARPAV, Centro Valanghe di Arabba)
- 2009-2011: Regione Piemonte (ICE flight)
- 2011: Provincia Autonoma di Trento (PAT flight)

These orthophotos were analyzed in a GIS environment, where glacier boundaries were digitized and their areas computed. The resulting data, along with supplementary attributes such as glacier name, ID code, coordinates, and drainage basin, were compiled into a database forming the *New Italian Glacier Inventory*. [9]

2.2. Ongoing research

Building on the legacy of the ADA270 project, which in 2021 successfully extracted a 224-meter-long ice core from the Adamello Glacier, the *ClimADA (Climatic and Environmental Reconstruction of the Adamello Area)* project aims to reconstruct the climatic and environmental history of the central Alps over past centuries. This ambitious objective is pursued through a collaborative effort involving academic institutions, environmental agencies, and local authorities.

The project focuses on multiple aspects of long-term environmental change, including the climatic evolution of the region, the anthropogenic impact on high-mountain ecosystems, vegetation dynamics, and the historical occurrence of large-scale forest fires. These reconstructions are grounded in data obtained from the deep ice core, which serves as one of the most complete environmental archives in the Italian Alps. In addition to the core sample, the presence of a fiber optic probe installed within the glacier enables continuous monitoring of the ice mass, providing detailed thermal and deformation profiles. When integrated with conventional glaciological measurements and data from global climate models, these observations facilitate a better understanding of glacier dynamics under changing environmental conditions and help project the future evolution of the ice mass in the context of ongoing global warming. As the deepest glacier in Italy, the Adamello represents a unique case study and a natural climate archive for the Italian Alps, particularly in the region of Lombardy.

A further distinctive aim of the ClimADA project is to bridge scientific research with civic engagement. Beyond academic dissemination, the project is committed to

involving local communities by organizing conferences, thematic workshops, educational activities, and exhibitions. These initiatives are designed to engage policymakers, environmental professionals, educators, associations, and especially younger generations, fostering awareness about climate change and its implications for ecosystem resilience and water resource availability in the Alpine region.
The project is coordinated by *Fondazione Lombardia per l'Ambiente* and developed in partnership with the *University of Milan-Bicocca* (particularly the EuroCold Laboratory), the *Comunità Montana della Valle Camonica* (managing authority of the Adamello Regional Park), the *Politecnico di Milano*, and the *University of Brescia*, with a particular focus on the glacier's geodynamic modeling and fiber optic monitoring systems. [10]

Another important case to be mentioned is an automatic meteorological station which has been recording, since the summer of 2008, climatic variables such as atmospheric pressure, humidity and wind velocity. This data is fundamental to understanding local climatic conditions and to support the numerical modelling of glacial changes. [11]

Finally, a significant and recent project is *A Sound in Extinction*, a multimedia installation conceived in 2020 by researcher and sound artist Sergio Maggioni. The work, set to be inaugurated on July 4 2025 at the Geologic Museum of the Dolomites in Predazzo, aims to merge art and science by capturing and presenting the sounds of the retreating Adamello Glacier. Installed in the heart of the glacier itself, the piece seeks to raise awareness of glacial melting by offering an immersive auditory experience that translates natural processes associated with climate change into sound. This project stands as a contemporary and innovative example of how artistic practices can contribute to scientific communication and environmental reflection. [12]

2.3. Gap analysis

Despite the significant amount of research dedicated to glacier monitoring in the Italian Alps, several gaps can still be identified in the existing literature.

Most previous analyses limited their analyses until many years ago, leaving a gap in the study of recent and ongoing glacier shrinkage, due to more accentuated climate change effects.

Furthermore, the available studies focus on specific glaciers, instead of conducting comparative analyses between different case studies or creating a methodology applicable to any other glacier.

Another peculiarity of existing works is that they concentrated on surface or volume changes, without expanding the study towards climatic variables.

Finally, from a methodological point of view, previous works rely mainly on manual delineation of glacier outlines, orthophotos, field surveys or ice cores, restricting the replicability of the studies.

Considering these limitations, this study aims to address part of these gaps by analyzing glacier reduction using the most recent and open-source data available from MODIS and Sentinel-2, in order to assess their current condition. It further seeks to develop a transferable methodology applicable to any glacier, and to compare the outcomes derived from the Adamello and Grey glaciers. Finally, the study explores possible correlations between the observed retreat and relevant climatic variables.

3. Instruments and tools

3.1. MODIS

The *Moderate Resolution Imaging Spectroradiometer (MODIS)* is a pivotal instrument onboard NASA's *Terra* and *Aqua* satellites, launched to support Earth observation within the framework of the *Earth Observing System (EOS)*. Terra follows a sun-synchronous orbit crossing the equator from north to south in the morning, while Aqua passes in the opposite direction in the afternoon. Together, these platforms enable near-daily global coverage, with MODIS capturing data across 36 spectral bands ranging from visible to thermal infrared wavelengths (0.405–14.385 µm), at spatial resolutions of 250 m, 500 m, and 1000 m. With a swath width of 2330 km, MODIS provides consistent, synoptic-scale observations of the Earth's surface, atmosphere, and oceans.

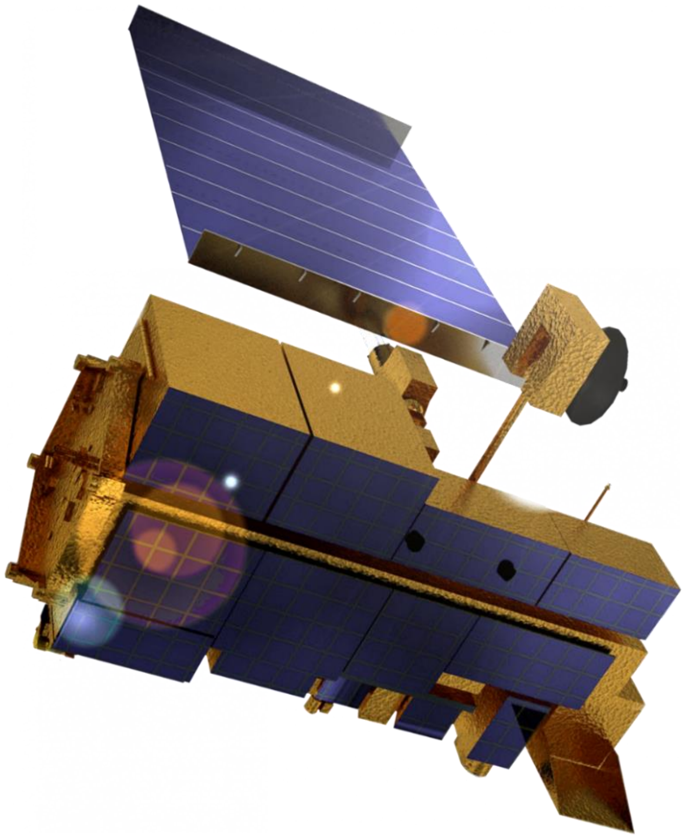

Figure 4 - Terra spacecraft (sources: https://mmadelin.github.io/EECIST23_EXP2/EXP2_statsbivar.html#/exemple-dapplication-deux-sources-utilis%C3%A9es).

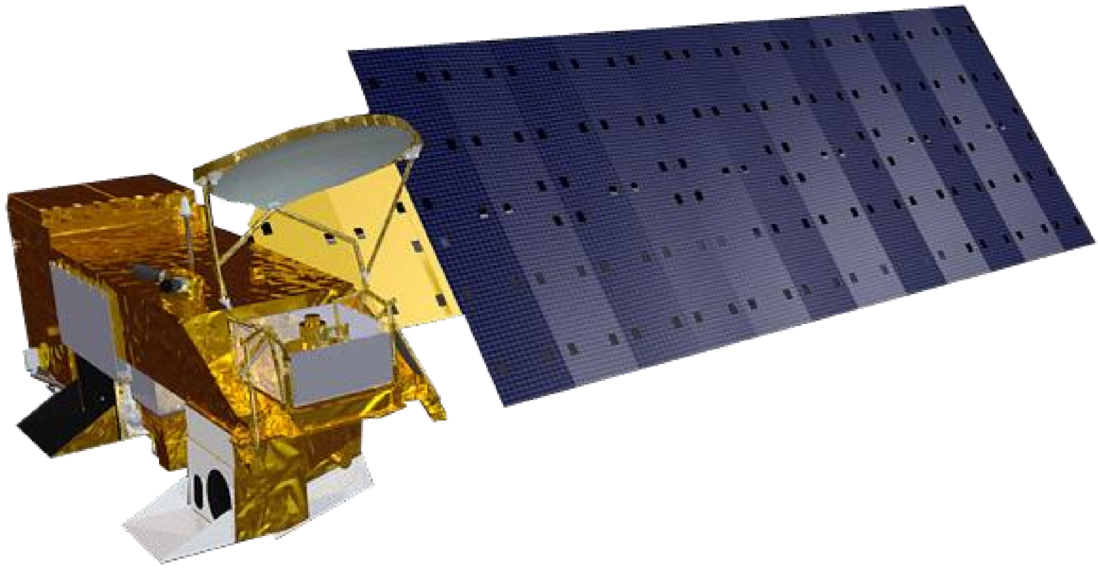

Figure 5 - Aqua spacecraft (sources: https://suoe.ir/%D9%85%D8%B9%D8%B1%D9%81%DB%8C-%D9%85%D8%A7%D9%87%D9%88%D8%A7%D8%B1%D9%87-modis/).

Data acquired by MODIS are transmitted through the *Tracking and Data Relay Satellite System (TDRSS)* to ground stations and further processed at NASA's *Goddard Space Flight Center*. Specialized systems such as the *MODIS Adaptive Processing System (MODAPS)* and the *Ocean Color Data Processing System (OCDPS)* generate a suite of calibrated products, which are subsequently disseminated through various *Distributed Active Archive Centers (DAACs)*. These products include, among others, land surface reflectance, atmospheric parameters, ocean color, and cryospheric indicators such as snow and ice cover. Thanks to its broad spectral range, high temporal frequency, and extensive spatial coverage, MODIS has become a cornerstone in Earth system science, supporting research on climate dynamics, land cover change, and cryospheric processes at both regional and global scales. [13]

3.2. Sentinel-2

The Sentinel-2 mission, part of the *European Union's Copernicus Earth Observation Programme*, is designed to provide high-resolution, multi-spectral optical imagery for land surface monitoring.

Figure 6 - Schematic view of the deployed Sentinel-2 spacecraft (sources: [14]).

It consists of a constellation of polar-orbiting satellites: Sentinel-2A, launched in 2015, and Sentinel-2B, launched in 2017, with Sentinel-2C launched in 2024 and 2D under development. Together, these satellites ensure a high revisit frequency of five days at the equator, and even more frequent coverage at mid-latitudes, which is particularly advantageous for time-series analysis and change detection in dynamic environments such as glaciers.

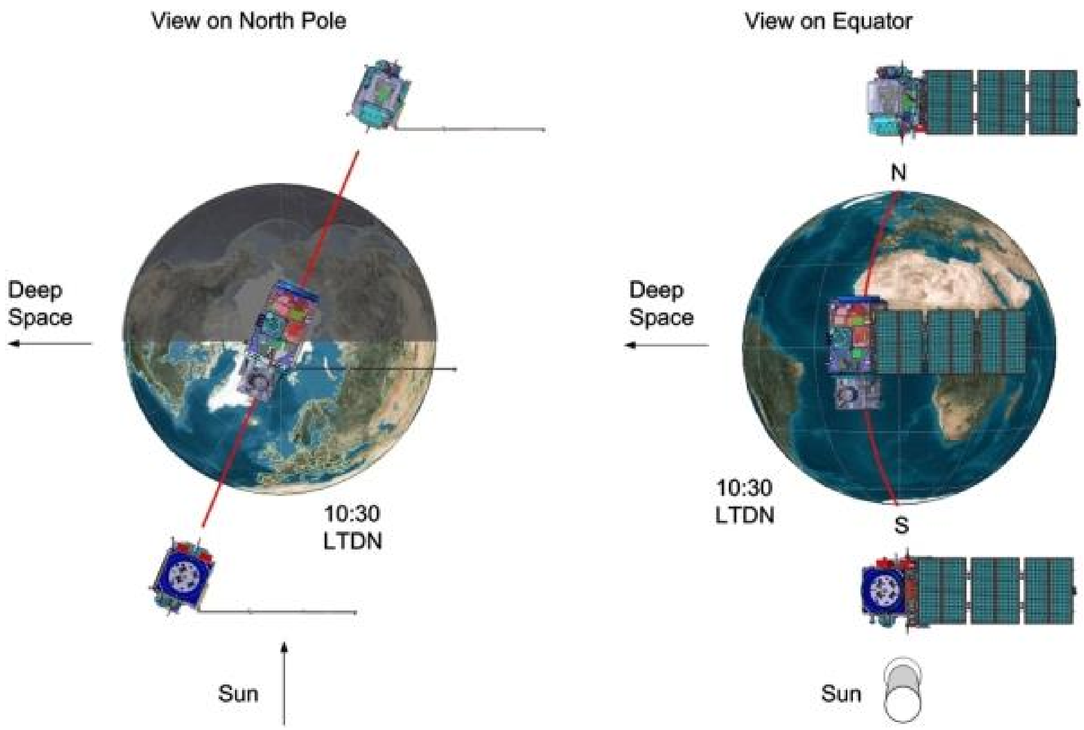

Figure 7 - The twin-satellite Sentinel-2 orbital configuration (sources: [14]).

Each Sentinel-2 satellite carries a *MultiSpectral Instrument (MSI)* capable of acquiring data in 13 spectral bands ranging from visible (VNIR) to shortwave infrared (SWIR) regions. These bands are distributed across three spatial resolutions: 10 meters (for four visible and near-infrared bands), 20 meters (for six red-edge and SWIR bands), and 60 meters (for three atmospheric correction bands). The MSI's swath width of 290 km allows for large-scale, cloud-free mosaics with minimal geometric distortion, enabling comprehensive spatial analyses over wide geographic areas.

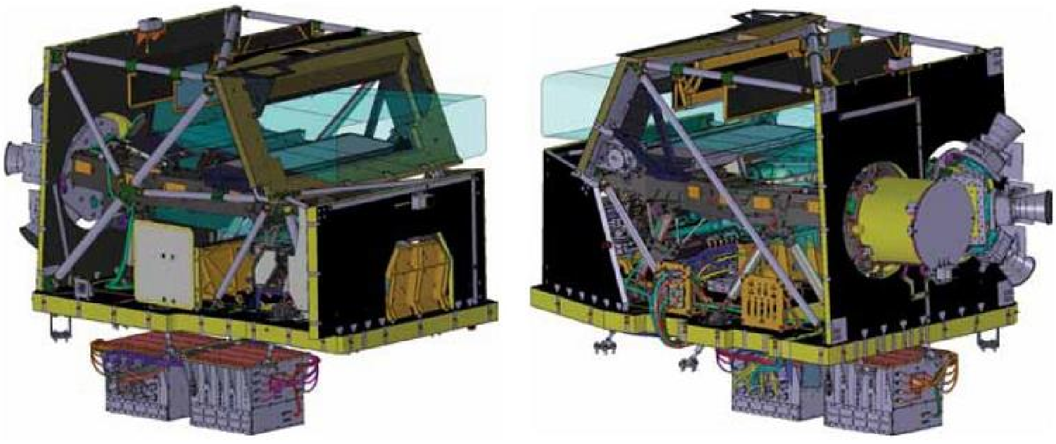

Figure 8 - The MultiSpectral Instrument (sources: [14]).

For applications in environmental monitoring and Earth system science, the Level-2A products, used in this thesis, are of particular relevance. These products provide surface reflectance values corrected for atmospheric effects, including aerosols and water vapor, using the Sen2Cor processing algorithm. Delivered in cartographic geometry, Level-2A data also include scene classification layers that identify features such as clouds, cloud shadows, vegetation, bare soils, snow, and water. These auxiliary layers are essential for quality assurance and for masking undesirable elements in downstream analyses.
The combination of high spatial resolution, frequent temporal coverage, and detailed spectral information makes Sentinel-2 particularly well suited for cryospheric applications. In glaciology, Level-2A products enable accurate mapping of snow extent, ice boundaries, and seasonal variability, as well as the monitoring of long-term trends in glacier retreat and mass balance. Moreover, the free and open access to Sentinel-2 data under the Copernicus Programme policy promotes reproducibility and long-term research, making it a cornerstone for the observation and understanding of climate-induced changes in alpine and polar environments. [14]

3.3. QGIS

QGIS (Quantum Geographic Information System) is an open-source software application for processing and analyzing digital geographic data, classified as a

Geographic Information System (GIS). It enables users to visualize, edit, and interpret spatial data by integrating geographic features with associated attribute information. QGIS works with various data formats, including raster data (georeferenced imagery) and vector data (points, lines, and polygons linked to attribute tables), allowing for detailed investigation of spatial phenomena at local or global scales. Among its core capabilities are the creation of customized maps, integration of data from external sources (such as satellite imagery or geospatial databases), and execution of complex spatial analyses, including overlay operations, surface and distance calculations, and temporal change detection.

Being both free of charge and open source, QGIS represents a highly accessible and adaptable solution for spatial data analysis, with no licensing restrictions and a growing base of contributors worldwide. [15]

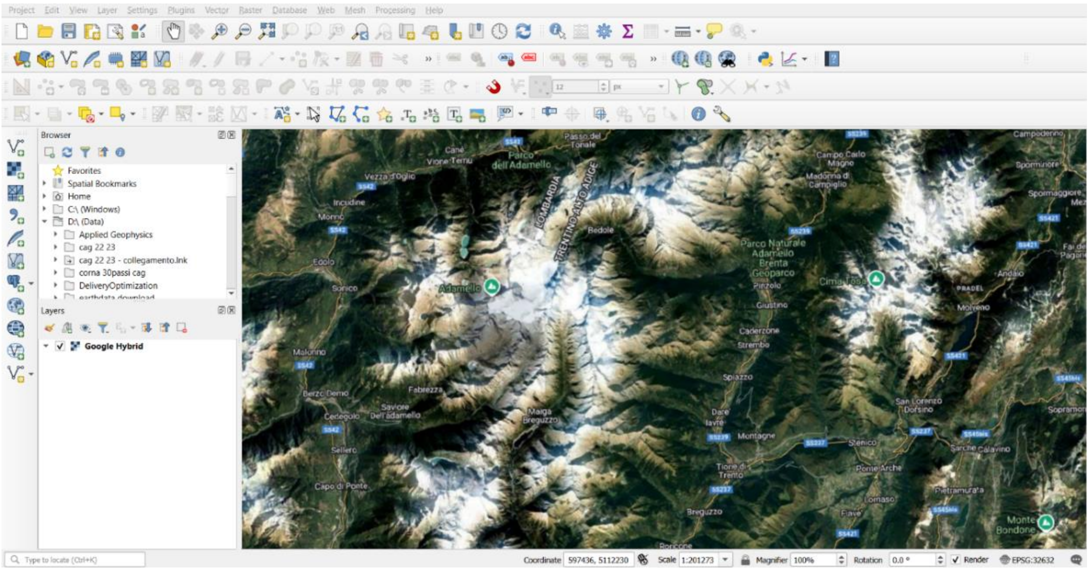

Figure 9 - QGIS Interface with a view of the study area

4. Methodology

This thesis aims to develop a methodology based entirely on the use of open-source datasets (MODIS and Sentinel-2) and software (QGIS). Open data refers to information that can be freely used, reused, and redistributed by anyone and it's subject, at most, to requirements for attribution and sharing under similar terms to preserve its provenance and openness.

The use of open data and open-source software represents a significant advantage for research and analysis, as it ensures accessibility for a wide range of users, including individuals, institutions, and communities with limited resources. This approach fosters transparency, reproducibility, and collaboration, and allows scientific studies to be conducted and replicated without the barrier of proprietary tools or restricted datasets. [16]

In the context of climate change research, the use of open-source tools is particularly relevant. Satellite-based Earth observation data, such as those provided by the Copernicus and NASA programs, are essential for monitoring environmental processes over time, including glacier retreat, land cover change, and temperature anomalies. The accessibility of this data supports global efforts in environmental assessment and decision-making.

4.1. MODIS

MODIS data were retrieved from NASA's *Earthdata Search* portal by selecting the *MOD09GA* temporal dataset. To capture the annual minimum extent of the glacier, images from the summer months were prioritized, following a chronological order of preference: July, August, September, and finally June. The area of interest corresponding to the glacier was defined using the spatial filter tool available on the portal.

The selected product, *MODIS/Terra Surface Reflectance Daily L2G Global 1km and 500m SIN Grid V061*, provides daily surface spectral reflectance for MODIS Bands 1 t0 7. These values are corrected for atmospheric effects such as gases, aerosols, and Rayleigh scattering. During the image selection process, scenes with minimal or no cloud cover were prioritized to ensure data quality. Occasionally, some images appeared significantly brighter or darker than others due to atmospheric or sensor-related variations. In such cases, basic visual enhancement was applied to improve interpretability.

The *MOD09GA* product offers surface reflectance at a 500-meter spatial resolution and includes additional 1-kilometer observation bands and geolocation information. The geographic coverage of each scene is 1200 km x 1200 km, and the dataset has been available continuously since 2000. [17] [18]

Once downloaded, the data was imported into QGIS. For visualization and initial analysis, Bands 1 (red), 4 (green), and 3 (blue) were selected. A virtual raster was created using the *Build Virtual Raster* tool, assigning the bands in the RGB order: Band 1 as red, Band 4 as green, and Band 3 as blue.

Initially, the MODIS raster files are referenced in a sinusoidal projection (ESRI:54008), as indicated in the metadata. After assigning the correct projection, the images appeared in a gridded layout. The rasters were then reprojected to the *UTM Zone 32N (EPSG:32632)* using the *Warp (Reproject)* tool. This transformation is necessary to align the imagery with local mapping standards and to account for the curvature of the Earth.

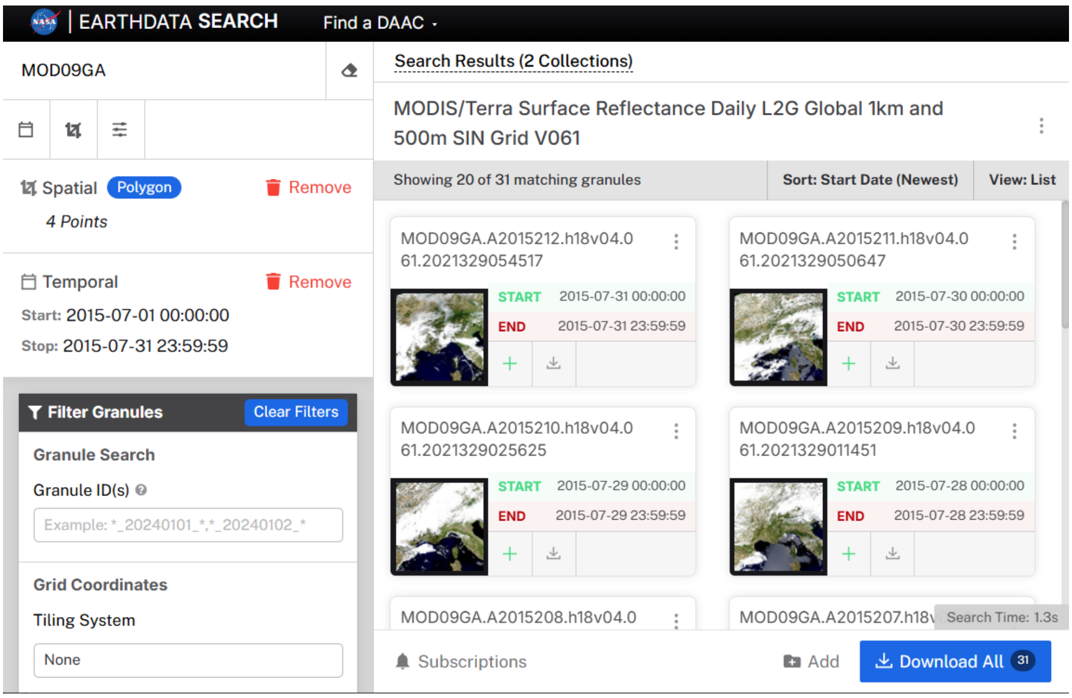

Figure 10 - NASA Earthdata Search portal (sources: https://search.earthdata.nasa.gov/search)

4.2. Sentinel-2

Sentinel-2 imagery was acquired using data from Sentinel-2B, part of the Earth observation mission of the Copernicus Programme, operated by the *European Space Agency (ESA)*. The satellite is equipped with the *MultiSpectral Instrument (MSI)*, which captures high-resolution optical imagery for land monitoring applications.

Data was downloaded from the *Copernicus Browser*, selecting the Level-2A product. This processing level provides *Bottom-Of-Atmosphere (BOA)* reflectance, which corresponds to surface reflectance values already corrected for atmospheric effects such as selective scattering. For this reason, Level-2A products are preferable to Level-1C, which require additional atmospheric correction before being used for surface analysis.

Sentinel-2 provides imagery at multiple spatial resolutions: 10 m, 20 m, and 60 m. For this study, only the 10-meter resolution bands were used, to ensure the highest spatial detail in the delineation of glacier boundaries.

As with MODIS, the selection of images focused on cloud-free scenes during summer months, to identify the minimum annual extent of the glacier. Preference was given to July and August, the warmest months of the year in the Northern Hemisphere, followed by September and June when necessary. Sentinel-2 data are available starting from 2015 to the present.

Once downloaded, the relevant bands were imported into QGIS. In particular, Bands 4 (red), 3 (green), and 2 (blue) were used to build a true color composite. A virtual raster was generated using the "Build Virtual Raster" tool, arranging the bands in the correct RGB order: 4 (red), 3 (green), and 2 (blue), to facilitate visual analysis of the glacier surface.

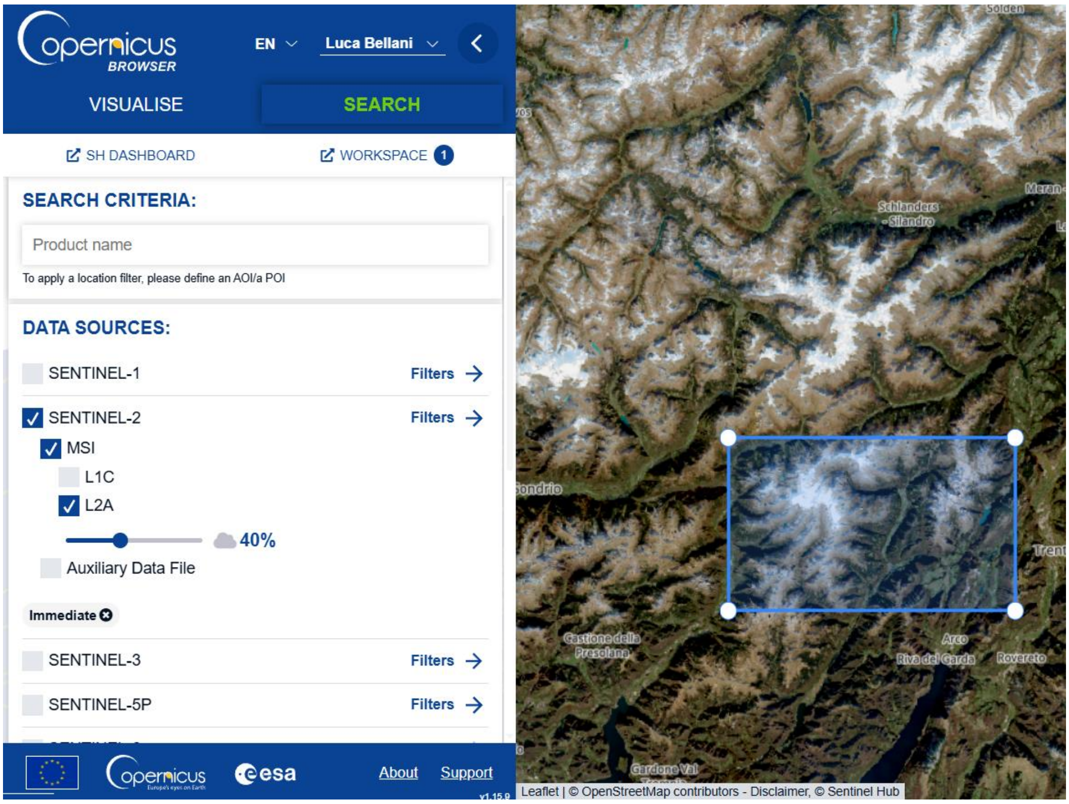

Figure 11 - Copernicus Browser portal (sources: https://browser.dataspace.copernicus.eu)

4.3. MODIS and Sentinel-2 confrontation

The main differences between the two products can be summed up as follows:

- **Spatial Resolution**: MOD09GA offers moderate resolution at 500 m (with ancillary 1 km data), whereas Sentinel-2 provides much finer spatial detail, particularly at 10 m for visible and NIR bands.
- **Temporal Resolution**: MODIS achieves near-daily global coverage (1-2 day revisit), while Sentinel-2 revisits every 5 days with its dual-satellite constellation.
- **Spectral Characteristics**: MODIS includes a broader set of spectral bands (up to 36) covering visible to thermal infrared ranges, useful for large-scale and multi-purpose applications. Sentinel-2, while narrower in spectral range, has carefully chosen bands (e.g., red-edge) optimized for vegetation and surface analysis at high spatial resolution.

- **Product Processing Level**: Both MOD09GA and Sentinel-2 Level-2A provide surface reflectance corrected for atmospheric effects, but Sentinel-2's Level-2A is designed to be user-ready at high resolution.
- **Geographic and Temporal Extent**: MOD09GA spans from 2000 to present with daily coverage; Sentinel-2A launched in 2015 and Sentinel-2B in 2017, so Sentinel-2 data start only from mid-2015 onward.

Thus, for applications requiring high spatial detail, such as precise glacier boundary delineation, Sentinel-2 Level-2A is advantageous due to its fine resolution and atmospheric correction. However, for temporal analysis or large-scale trend detection, MODIS daily coverage and long temporal record remain valuable. [17] [19] [20]

Figure 12 - MODIS (left) and Sentinel-2 (right) 2015 image confrontation of the Adamello Glacier, scale 1:100000

4.4. Contour delineation

Two different methods were employed in QGIS to delineate the Adamello Glacier area using both MODIS and Sentinel-2 datasets:

- **Visual Method**: After setting the map scale to 1:100000, a new polygon vector layer was manually created by tracing the glacier perimeter. This delineation was performed visually, relying solely on visual interpretation to define the glacier boundaries.

Figure 13 – Visual method for the 2015 MODIS image of the Adamello Glacier, scale 1:100000

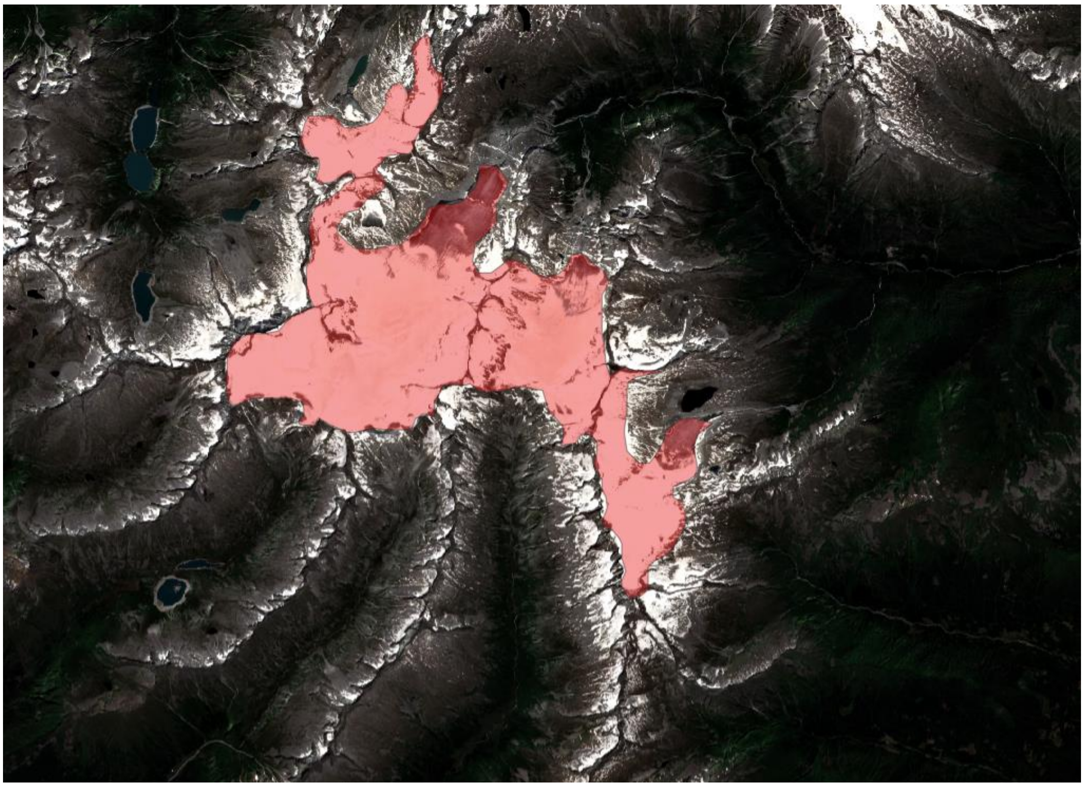

Figure 14 - Visual method for the 2015 Sentinel-2 image of the Adamello Glacier, scale 1:100000

- **Automatic Method**: Starting with the 2015 dataset, a new raster layer was generated using the "Raster Calculator" tool. A binary raster was created by applying threshold values to selected bands, assigning a value of DN=1 to pixels within the chosen reflectance range (presumably corresponding to glacier ice), and DN=0 to all others. The thresholds were empirically determined based on pixel values in grayscale, selecting ranges close to white tones: B1 ≥ 0,5463; B4 ≥ 0,5187; B3 ≥ 0,4323. The resulting binary raster was then converted into a vector layer and only features with DN=1 were retained using the *Filter* tool.

  The same procedure was repeated for 2020 (B1 ≥ 0,5472; B2 ≥ 0,5179; B3 ≥ 0,4640) and 2024 (B1 ≥ 0,5221; B2 ≥ 0,4574; B3 ≥ 0,3492) datasets. For consistency and comparison, 2020 and 2024 datasets were also processed using the 2015 threshold criteria to evaluate the influence of threshold selection on the resulting glacier area.

  Additionally, a seasonal comparison was conducted for the year 2020, contrasting a summer scene with a winter image, in order to assess the glacier's maximum and minimum extent due to seasonal snow cover variability.

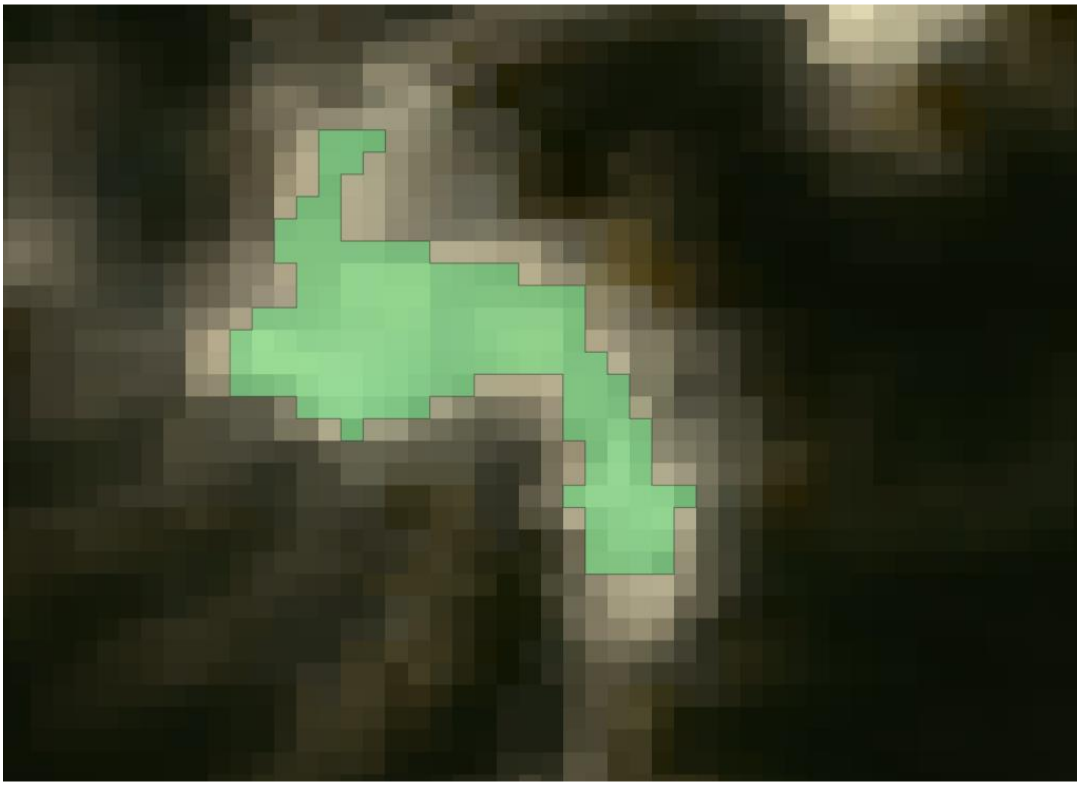

Figure 15 - Automatic method for the 2015 MODIS image of the Adamello Glacier, scale 1:100000

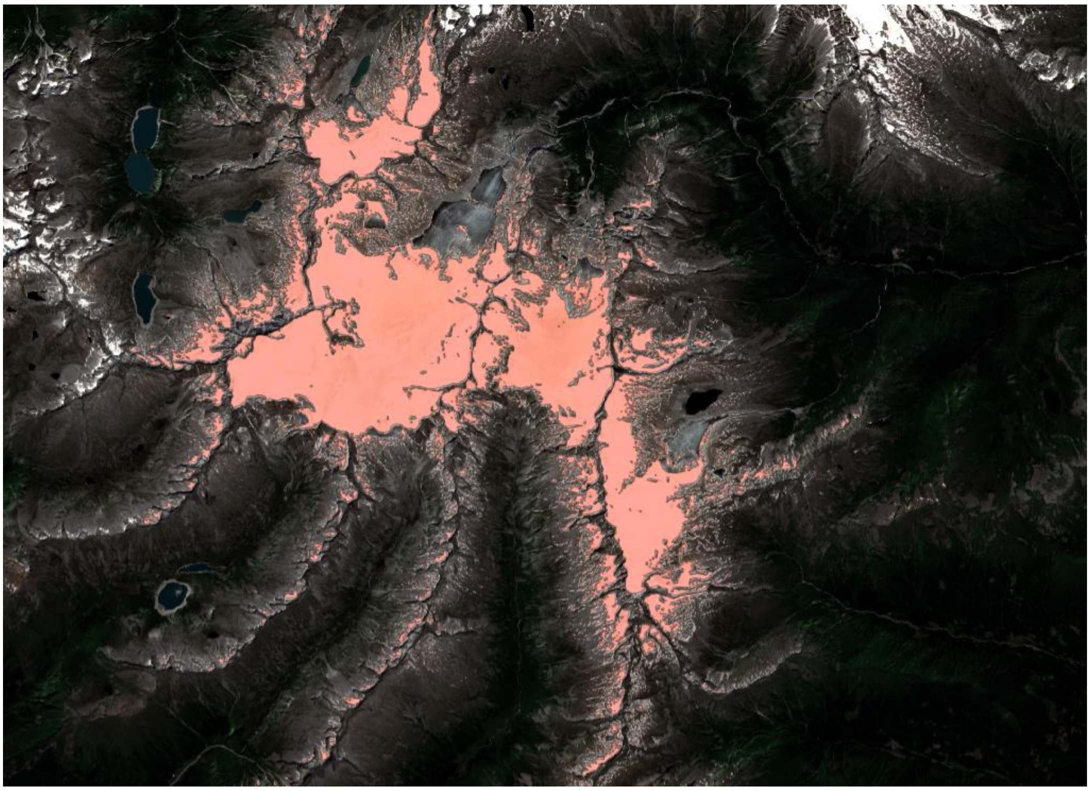

Figure 16 - Automatic method for the 2015 Sentinel-2 image of the Adamello Glacier, scale 1:100000

4.5. Percentage error calculation

The final step involves calculating the percentage error of the glacier area for a specific year. The main objective is to evaluate the reliability of the developed methodology by comparing the glacier extent values derived from the analysis with reference data reported for that year. Moreover, this procedure can also serve as a useful tool for comparing glaciers that differ in their geographical and climatic contexts.

After retrieving a reference value of glacier surface extent from the literature, the percentage error is computed using the following formula:

$$E = \frac{|A_{calc} - A_{ref}|}{A_{ref}} \times 100$$

The resulting value provides a quantitative measure of the accuracy of the proposed approach in assessing glacier area.

5. Results and Discussion

The outcomes derived from the two methodological approaches are represented as vector layers, which provide a spatially explicit depiction of the glacier's extent. An example of these outputs is presented in the following figure, illustrating the way in which the applied procedures translate the raster information into vectorial representations suitable for further quantitative analysis.

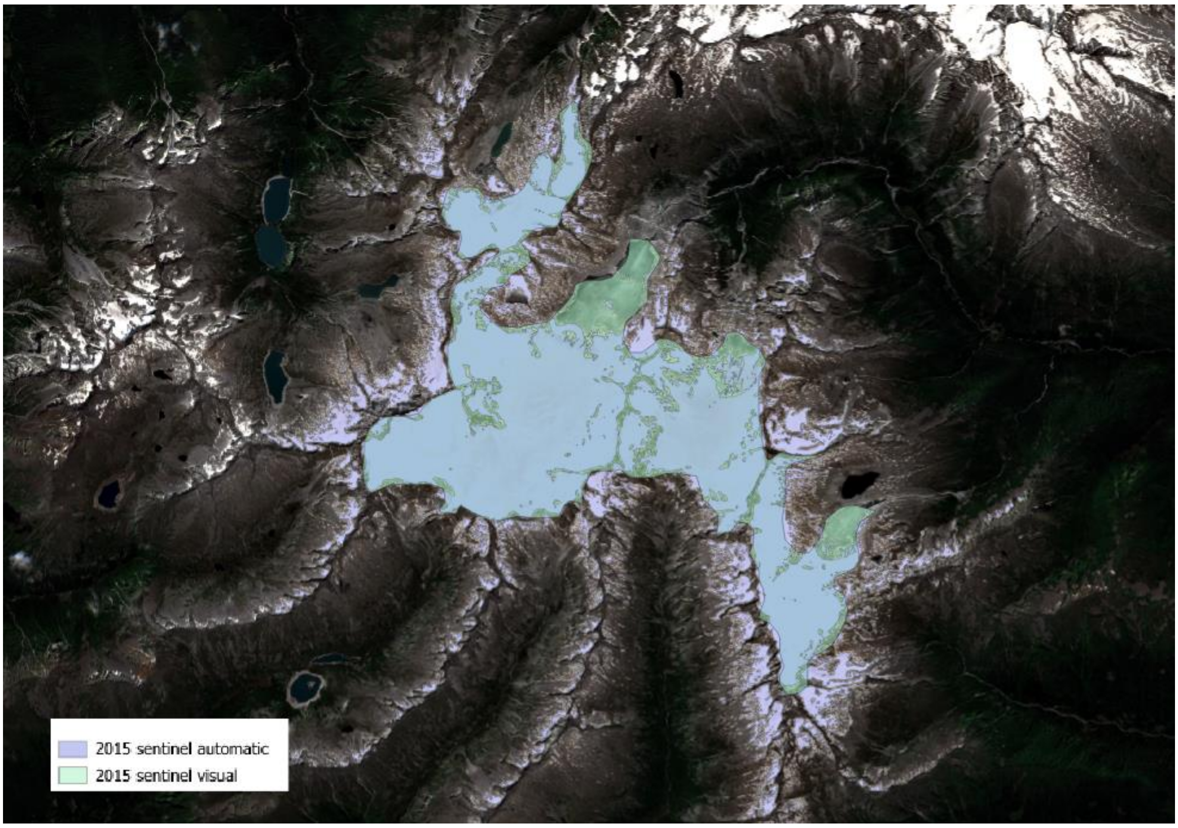

Figure 17 – Sentinel-2 2015 output confrontation between the two methods, scale 1:100000

Subsequently, a new attribute field was generated in QGIS using the *Field Calculator* tool, where the formula *$area* was applied to compute the surface area associated with each dataset. Once this operation was completed, the results were systematically organized into tables to facilitate further analysis and discussion.

Table 1 presents a comparative overview of the glacier's area across the three years under investigation, as well as a distinction between the two applied methodological approaches.

Table 1 - Area confrontation between the 2 methods for different years and satellites

Area confrontation between the 2 methods			
	MODIS [km^2]	Sentinel-2 [km^2]	
2015	27,98	37,84	*automatic method*
2020	16,27	14,95	
2024	26,59	32,88	
2015	30,01	32,04	*visual method*
2020	24,64	25,94	
2024	22,42	28,17	

An initial observation emerging from both methodological approaches and satellite sources is the significant retreat of the glacier between 2015 and 2020, followed by an unexpected increase in 2024. This anomalous rise is likely attributable to an exceptional snowfall event that occurred during the preceding months. The only divergence from this general trend is provided by the MODIS dataset analyzed through the visual procedure, which instead indicates a continuous reduction in glacier area across the entire period. The maximum extent recorded corresponds to 37,84 km^2, derived from the 2015 Sentinel-2 dataset processed with the automatic approach, an area comparable in size to the *Cinque Terre National Park* in Liguria.

Table 2 presents the percentage variation of the glacier area across the different years and methods.

Table 2 – Area variation between different years

Variation between different years			
	MODIS	Sentinel-2	
2015/2020	-41,84%	-60,49%	*automatic method*
2020/2024	63,41%	119,94%	
2015/2024	-4,96%	-13,11%	
2015/2020	-17,88%	-19,02%	*visual method*
2020/2024	-9,02%	8,60%	
2015/2024	-25,29%	-12,05%	

These findings reinforce the outcomes of the previous analyses and underscore a substantial increase in glacier extent between 2020 and 2024 when assessed through the automatic procedure, with growth rates of 63,41% for MODIS dataset and 119,94% for Sentinel-2 dataset.

Notably, as illustrated in *Table 1*, except for 2020 under the automatic approach, the areas derived from Sentinel-2 imagery consistently exceed those obtained from MODIS. This discrepancy can likely be attributed to the higher spatial resolution of Sentinel-2, which enables a more accurate delineation and clearer visualization of the glacier margins. Such differences are further detailed in *Table 3*, which reports the percentage variations between the two satellite products. The largest divergence is observed for the 2015 dataset, where Sentinel-2 yields a glacier area 35,22% greater than that derived from MODIS.

Table 3 – Area variation between MODIS and Sentinel-2

Variation between MODIS and Sentinel-2		
	MODIS/Sentinel-2	
2015	35,22%	*automatic method*
2020	-8,15%	
2024	23,63%	
2015	6,77%	*visual method*
2020	5,29%	
2024	25,68%	

On the other hand, no consistent trend emerges when comparing the results of the automatic and visual approaches, with the notable exception of the year 2020. Indeed, as shown in *Table 4*, the glacier area for 2020 derived through the visual procedure is over 50% larger for the MODIS dataset and exceeds 70% for the Sentinel-2 dataset compared to the area estimated using the automatic approach.

Table 4 – Area variation between visual and automatic methods

Variation between visual and automatic methods		
	MODIS	Sentinel-2
2015	7,22%	-15,34%
2020	51,40%	73,55%
2024	-15,71%	-14,31%

Subsequently, two additional analyses were conducted focusing exclusively on the output derived from the automatic approach. The first analysis involved recalculating the glacier areas for 2020 and 2024 using the spectral band range originally applied to the 2015 dataset. The results of this procedure are presented in

Table 5, providing a basis for assessing the consistency of the automatic method across different years.

Table 5 - Area confrontation with 2015 bands range

Area confrontation with 2015 bands range			
	MODIS [km^2]	Sentinel-2 [km^2]	
2015	27,98	37,84	
2020 (range 2015)	18,66	17,14	*automatic method*
2024 (range 2015)	22,03	29,43	

When comparing these values with those previously reported in *Table 1*, only minor differences are observed, the largest being 4,56 km^2 for the 2024 MODIS dataset. In contrast, an examination of the percentage variations presented in *Table 6* reveals that the 2015/2020 comparison remains largely consistent with the corresponding values in *Table 2*. However, the 2020/2024 and 2015/2024 comparisons exhibit a notable reduction in the magnitude of area change relative to the data reported in *Table 2*.

Table 6 – Area variation between different years with 2015 bands range

Variation between different years with 2015 bands range			
	MODIS	Sentinel-2	
2015/2020	-33,33%	-54,70%	
2020/2024	18,08%	71,68%	*automatic method*
2015/2024	-21,28%	-22,24%	

The second and final analysis focused on comparing the glacier area for 2020 derived from the automatic approach with the corresponding dataset acquired during the winter season. This comparison aimed to assess the seasonal variability of the glacier's extent between the two opposite periods. The results of this investigation are summarized in the two subsequent tables:

Table 7 – Area confrontation between summer and winter

Area confrontation between summer and winter			
	MODIS [km^2]	Sentinel-2 [km^2]	
2020 summer	16,27	14,95	*automatic method*
2020 winter	219,76	176,66	

Table 8 – Area variation between summer and winter

Variation between summer and winter			
	MODIS	Sentinel-2	
2020 summer/winter	1250,33%	1081,73%	*automatic method*

As expected, the glacier area during the winter season is substantially greater, with the difference being particularly pronounced for the MODIS dataset.

5.1. Percentage error calculation

The reference glacier area value adopted for the Adamello Glacier is 14,35 km^2 (year 2020), as reported in the literature. [21]

The calculations were performed using Microsoft Excel, and the results are summarized in *Table 9*:

Table 9 – Percentage error 2020

Percentage error 2020				
MODIS [km^2]	Sentinel-2 [km^2]	MODIS [%]	Sentinel-2 [%]	
16,27	14,95	13,41	4,17	automatic method
24,64	25,94	71,71	80,79	visual method

The data indicate that, in this specific case, the automatic approach accurately detected the Adamello Glacier area, particularly when using the Sentinel-2 dataset, with a percentage error of only 4,17%. Conversely, the visual delineation method clearly overestimated the glacier surface, especially for Sentinel-2, resulting in a percentage error of 80,79%.

6. Patagonian case

The next objective is to apply the methodology developed for the Adamello Glacier to a second case study, the Grey Glacier in Chilean Patagonia. This glacier was selected not only for its scientific relevance and contrasting environmental context, but also because of a personal connection established during my exchange period in Chile. The opportunity to directly observe this glacier and the surrounding pristine landscape inspired me to include it as part of this research, linking my academic work with a meaningful personal experience.

Figure 18 - Personal visit to Grey Glacier, sources: Luca Bellani

6.1. Study area

Grey Glacier, spanning over 6 km in width and towering up to 30 m in height, it's one of the main glaciers of the Southern Patagonian Icefield, the world's second largest contiguous extra polar ice field located between Chile and Argentina, as highlighted in red in *Figure 19*. [22] [23]

Figure 19 – Southern Patagonian Icefield (red), scale 1:7700000, sources: https://www.google.it/maps

The Southern Patagonian Ice Field is a critical water source for the region and Grey Glacier plays an important role in maintaining the local ecosystem.

Grey Glacier is classified as a valley glacier: a stream of flowing ice confined within steep-walled valleys. [24]

It is located on the western side of Torres del Paine National Park (Chile), along the northern shore of the homonymous lake, as shown in *Figure 20*.

Grey Lake is a proglacial lake, meaning that it originated from glacial activity and significantly influences the glacier's dynamics. In fact, a study on the Pukaki Glacier in New Zealand, based on simulations using the BISICLES ice-flow model, demonstrated that the presence of an ice-contact lake can increase grounding-line retreat by more than fourfold and ice velocities by up to eight times, compared to simulations of a land-terminating glacier under the same climatic conditions. [25]

Figure 20 – Glacier Grey, Torres del Paine National Park, sources: https://parquetorresdelpaine.cl/mapa-2023-2024/

Torres del Paine National Park is located in the Última Esperanza province, in the Magallanes y Antártica Chilena region, 400 km northwest from Punta Arenas and 112 km northwest from Puerto Natales.

It was established in 1959 and from 1973 it's administrated by the *Corporación Nacional Forestal*, which take care and protect the entire area, in pursuit of the conservation of biological diversity, along with natural and cultural resources.

Currently, thanks to its incredible variety of landscapes, flora and fauna, it's an unmatched touristic destination; indeed, the number of visitors multiplicated over the last decades, reaching almost 300000 tourists per year. [26]

The site can be accessed through various routes and trails. Visitors may travel by car along the main road or explore the area on foot via designated pathways. Several options are available, including daily trekking excursions or, for a more immersive experience, two multi-day circuits: the W trek (3-5 days) and the O trek (8-10 days), respectively highlighted in orange and red in *Figure 20*. Regardless of the itinerary chosen, both the park's main attractions, Las Torres del Paine (*Figure 21*), and the Grey Glacier (*Figure 22*) can be visited.

Figure 21 - Las Torres del Paine, sources: Luca Bellani

Figure 22 – Grey Glacier observed from a boat tour, sources: Luca Bellani

Given the site's considerable touristic importance, as previously discussed, it is essential to recognize the potential hazards associated with climate change. A substantial increase in glacier melt could lead to a significant rise in the lake's water level, potentially causing flooding in nearby areas. In the worst-case scenario, the progressive retreat or eventual disappearance of the glacier could reduce the park's touristic appeal, depriving it of one of its most iconic natural attractions.

In 2019, two icebergs broke off from Grey Glacier within a span of only fifteen days. The first iceberg covered an area of approximately 8,8 hectares (equivalent to about twelve football fields), while the second measured around 6 hectares. Although the detachment of ice from glaciers is a natural phenomenon, the increasing frequency of such events has raised concern within the scientific community, indeed the previous separation of ice from Grey Glacier took place in November 2017, and it was an even larger iceberg. According to Ricardo Jana, a researcher and climate change expert at the *Chilean Antarctic Institute (INACH)*, these calving events were likely triggered by above-average air temperatures, intense rainfall, and a rise in the lake's water level. [27]

More extreme touristic activities like ice-hiking have already been banned for a glacier by Chile's *National Forestry Corporation* on 31 October 2023, due to the rapid and destabilizing melting of the ice, excluding safe conditions for ecotourism activities.

However, this is not an isolated case. Ice climbers and mountaineers worldwide are increasingly being forced to adapt to the consequences of rising temperatures. In July of the same year, a section of the Marmolada Glacier in the Dolomites (Italy), approximately the size of an apartment building, collapsed onto a popular hiking route, resulting in eleven fatalities. Similarly, during that same summer, several agencies suspended ascents of Mont Blanc due to the destabilization of ice and the increased frequency of rockfalls associated with glacier melting. [28]

6.2. Results and discussion

As previously mentioned, the developed approach was applied to the Grey Glacier case study, with the only difference being that the same band range was used for all datasets in the automatic classification process. Subsequently, as done for the Adamello Glacier, all area-related data were organized into tables to facilitate a clearer analysis and discussion of the results.

Table 10 – Area confrontation between the two methods for different years and satellites

Area confrontation between the 2 methods			
	MODIS [km^2]	Sentinel-2 [km^2]	
2016	45,07	59,21	*automatic method*
2021	45,18	57,83	
2025	43,54	58,64	
2016	49,82	65,33	*visual method*
2021	54,22	61,65	
2025	43,10	59,95	

According to *Table 10*, the largest glacier extent was obtained from the 2016 Sentinel-2 dataset using the visual delineation method, resulting in an area of 65,33 km².

A general retreat, although not entirely uniform, can be observed from 2016 to 2025 across all analyzed cases. While the shrinkage does not display a strictly consistent numerical trend, it becomes more evident when observing the position of the glacier terminus over the years (*Figure 23*).

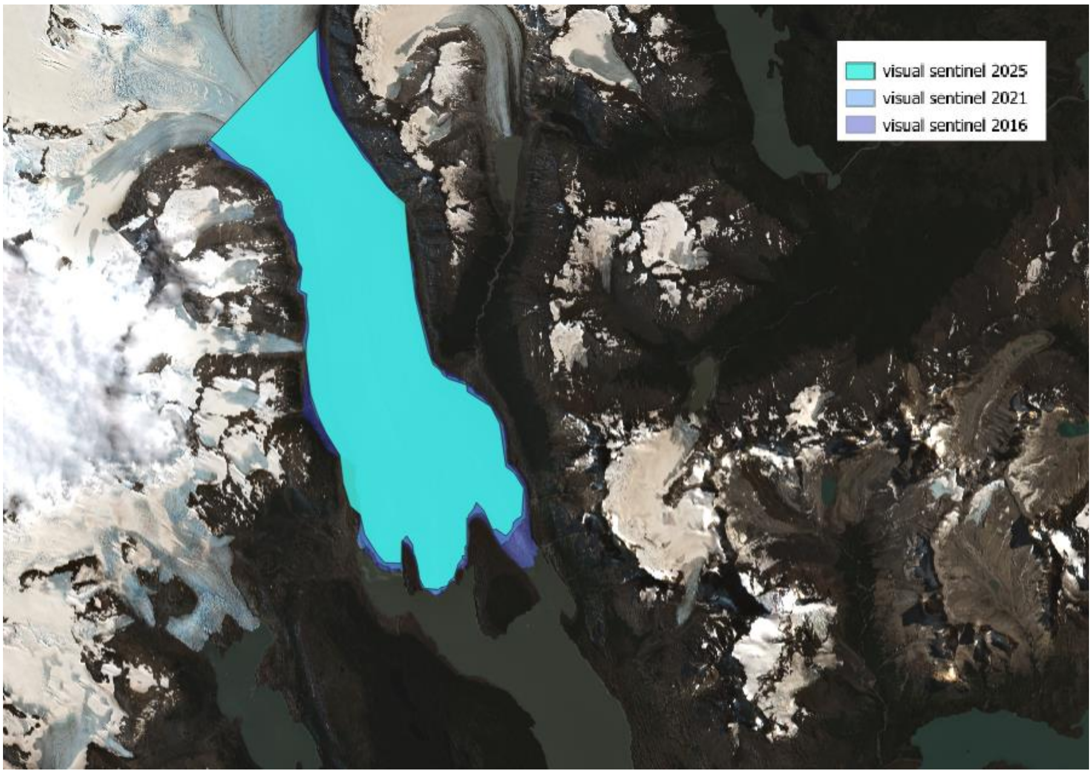

Figure 23 – Area variation of Grey Glacier, visual method, Sentinel-2, scale 1:150000

In the image above, it is clearly visible how the terminal part of the glacier, in contact with the lake, has progressively retreated over the years as a consequence of climate change.

Table 11 reports the percentage variations in glacier area between the reference years. It emerges that a consistent retreat was observed only when applying the visual method to the Sentinel-2 dataset. Nevertheless, for both datasets and methods, a general shrinkage is evident from 2016 to 2025, corresponding to an overall reduction of -8,23%.

Another noteworthy observation is that the three highest variations were recorded using the visual approach applied to MODIS data, suggesting that these values are likely outliers. This assumption is supported by the fact that the largest variation, −20,50% between 2021 and 2025, exceeds by more than five times the second-highest difference (−3,63% between 2016 and 2021).

Table 11 – Area variation between different years

Variation between different years			
	MODIS	Sentinel-2	
2016/2021	0,24%	-2,33%	*automatic method*
2021/2025	-3,63%	1,40%	
2016/2025	-3,40%	-0,96%	
2016/2021	8,82%	-5,62%	*visual method*
2021/2025	-20,50%	-2,77%	
2016/2025	-13,49%	-8,23%	

Table 12 below shows the percentage variation in glacier area between visual and automatic approaches. It appears that, except for a very slight difference in 2025, the visual method generally tends to overestimate the glacier surface compared to the automatic one. The largest discrepancy, approximately 20%, was observed for the 2021 MODIS dataset. It is also worth noting that in 2016 both the MODIS and Sentinel-2 datasets exhibited a similar difference between the two methods, amounting to around 10%.

Table 12 – Area variation between visual and automatic methods

Variation between visual and automatic methods		
	MODIS	Sentinel-2
2016	10,54%	10,33%
2021	19,99%	6,62%
2025	-1,02%	2,23%

Finally, *Table 13* presents a percentage comparison between the two methods. It is clear that, in all analyzed cases, the glacier area derived from MODIS imagery was significantly larger than that obtained from Sentinel-2. This discrepancy can reasonably be attributed to the lower spatial resolution of MODIS images, which likely led to an overestimation of the glacier perimeter.

As observed previously, in 2016 the variations are quite similar, around 31%. Conversely, in 2025 a slight difference of approximately 5 percentage points was detected, while in 2021 the MODIS/Sentinel-2 variation obtained through the automatic approach was considerably higher than that derived from the visual method.

Table 13 – Area variation between MODIS and Sentinel-2

Variation between MODIS and Sentinel-2		
	MODIS/Sentinel-2	
2016	31,36%	*automatic method*
2021	27,99%	
2025	34,67%	
2016	31,12%	*visual method*
2021	13,72%	
2025	39,09%	

A final analysis was conducted to further investigate the automatic approach applied to the Sentinel-2 dataset, by retrieving and processing data for the missing years within the 2016-2025 period. The aim was to extend the study to include all available data from this dataset, thereby enabling a comparison of the results and an observation of the glacier's behavior over time. The corresponding results are reported in *Table 14* below.

Table 14 – Sentinel-2 automatic method 2016-2025 analysis

Year	Area [km^2]
2016	59,21
2017	58,84
2018	61,51
2019	57,83
2020	57,84
2021	57,83
2022	57,01
2023	57,76
2024	56,59
2025	58,64

It can be observed that the glacier area exhibits a rather regular pattern, with no significant positive or negative trend. In particular, the surface area remained almost constant between 2019 and 2021, varying by only 0,01 km² in 2020. The highest value recorded in this analysis occurred in 2018, with an estimated area of 61,51 km². However, this value is likely to be an overestimation, probably caused by the presence of a thin cloud layer in the contact zone between the glacier and the lake. The potential error was minimized by cropping the affected portion of the image as much as possible, as this was the best dataset available for that year.

Conversely, the lowest surface area was recorded in 2024, amounting to 56,59 km², followed by a slight increase in the subsequent year.

It is also worth noting that a substantial change in Grey Glacier between 2017 and 2018 was observed during this final analysis. Specifically, the eastern tongue of the glacier in contact with the lake appeared much smaller in the 2018 image. As shown in *Figure 25*, this reduction was due to a large portion of ice that had detached and remained floating in the lake. This event is consistent with previous observations: as discussed in *Section 6.1*, in November 2017 a major ice block calved from the Grey Glacier [27], which is the same one visible in the image taken only a few months later.

Figure 24 – Grey Glacier 2017 Sentinel-2, scale: 1:150000

Figure 25 – Grey Glacier 2018 Sentinel-2, scale 1:150000

6.3. Percentage error calculation

As carried out for the Adamello Glacier, the percentage error of the glacier area was also intended to be calculated for the Grey Glacier, with the aim of enabling a comparison between the two glaciers and assessing the accuracy of the developed methodology.

The reference glacier area value adopted for the Grey Glacier is 243 km² (year 2021), as reported in the literature. [29]

However, it was immediately observed that this value is considerably higher than those obtained in this study, approximately five times greater than the areas estimated using the methodology proposed in this thesis.

As previously discussed in Section 6.1, *Study Area*, the Grey Glacier is part of the Southern Patagonian Icefield. Therefore, the large discrepancy is likely due to the fact that the reference area reported in the literature includes a much wider glacier extent than the one considered in this work. In delineating the Grey Glacier for this study, no specific references were found in the literature regarding the perimeter to be used. Consequently, the boundary reported in the *OSM Standard* map, the same shown in the Torres del Paine map reported in *Figure 20* with the green dotted line, was adopted.

For these reasons, it was not possible to calculate the percentage error for the Grey Glacier.

6.4. Climatic variables analysis

After retrieving and processing data on the glacier extent, the next objective was to investigate possible correlations between this information and relevant climatic variables, such as temperature, using maps and graphs to identify patterns of interest for the study. Climatic data were obtained from the *Explorador Climático* portal, an online platform that provides access to climate datasets [30]. It was developed by the *Centro de Ciencia del Clima y la Resiliencia (CR)2* and implemented by *Meteodata*. The tool is designed for both the general public and users with advanced meteorological knowledge, aiming to serve as a useful instrument to support climate analysis and decision-making. Specifically, it allows users to access meteorological databases, perform basic calculations and statistical analyses, visualize the results as maps or time series, and export them in different formats. An example of its interface is shown in *Figure 26* below.

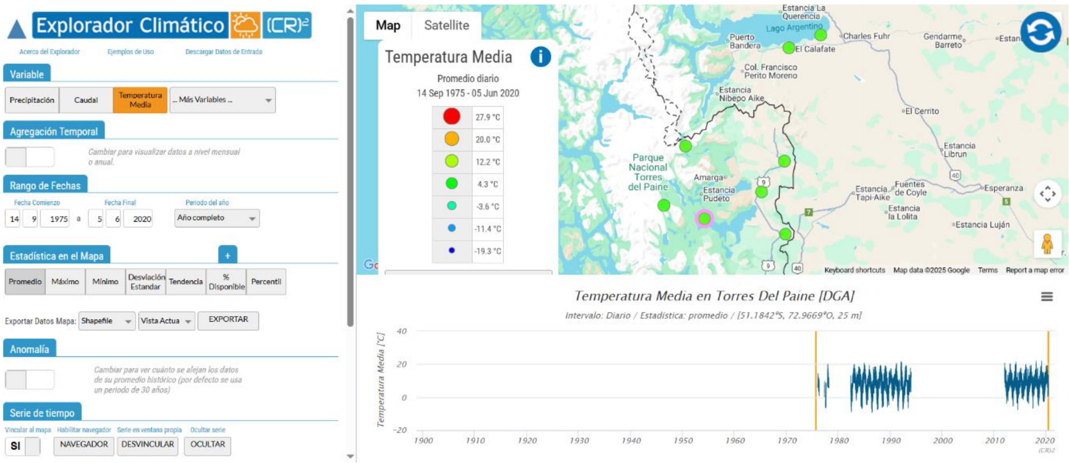

Figure 26 - Explorador Climático, sources: https://explorador.cr2.cl/

Among the available climatic variables are precipitation, river discharge, and temperature (mean, maximum, and minimum). For the purposes of this research, attention was focused on temperature. After selecting "maximum temperature" in the variable section, the closest meteorological station to the Grey Glacier (*Torres del Paine)* was chosen on the map. As a result, a graph was automatically generated below the map, as shown in *Figure 27*.

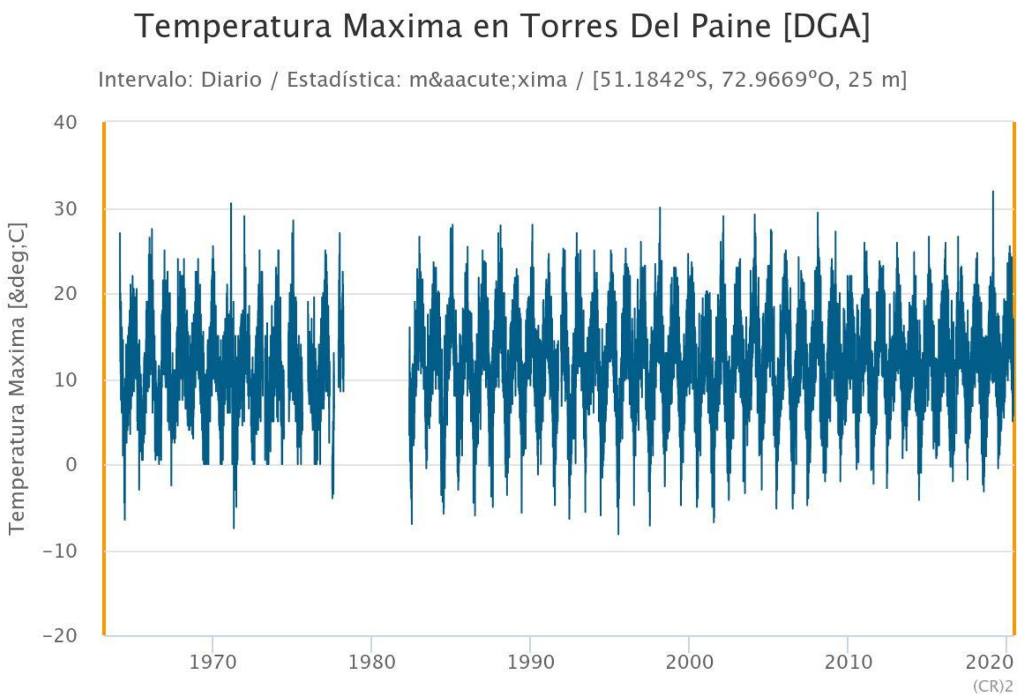

Figure 27 – Maximum temperature in Torres del Paine station, sources: https://explorador.cr2.cl/

Data are available from the mid-1960s to 2020, although a significant gap occurs between the late 1970s and early 1980s. Overall, the trend appears relatively stable, but it can be observed that the highest recorded values correspond to the most recent years, while a slight decrease in the lowest values is noticeable over the last decade.

The same procedure was then applied to the mean temperature, as illustrated in *Figure 28*.

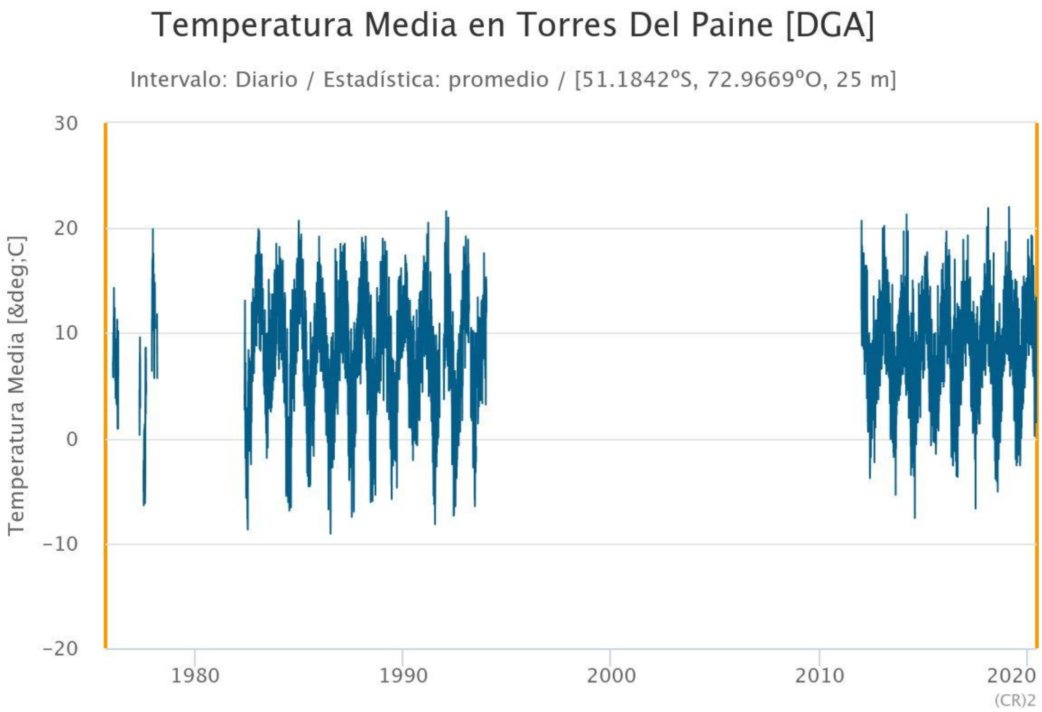

Figure 28 – Medium temperature in Torres del Paine Station, sources: https://explorador.cr2.cl/

In this case, the amount of available data is considerably smaller, with only a few values recorded in the mid-1970s until 1982, followed by a long gap from 1992 to 2012. Despite these limitations, it can again be observed that the highest values were recorded in the most recent years, whereas the lowest ones correspond to the 1980s and 1990s. Therefore, it can be concluded that a general increase in temperature is observed, consistent with the progressive retreat of the glacier.

Interestingly, for the same climatic variable, the temporal availability of data differs substantially between maximum and mean temperature datasets.

Moreover, tabulated values were also available; however, they often lacked key information such as the date or year of measurement, and in some cases presented inconsistencies with the graphical data. For instance, implausible temperature values exceeding 70 °C were reported.

Finally, it is worth noting that when selecting precipitation as a variable, a monitoring station located near Grey Lake appears on the map (*Figure 29*). Therefore, to improve the understanding of Grey Glacier's dynamics, it would be advisable to equip this station with an additional temperature sensor.

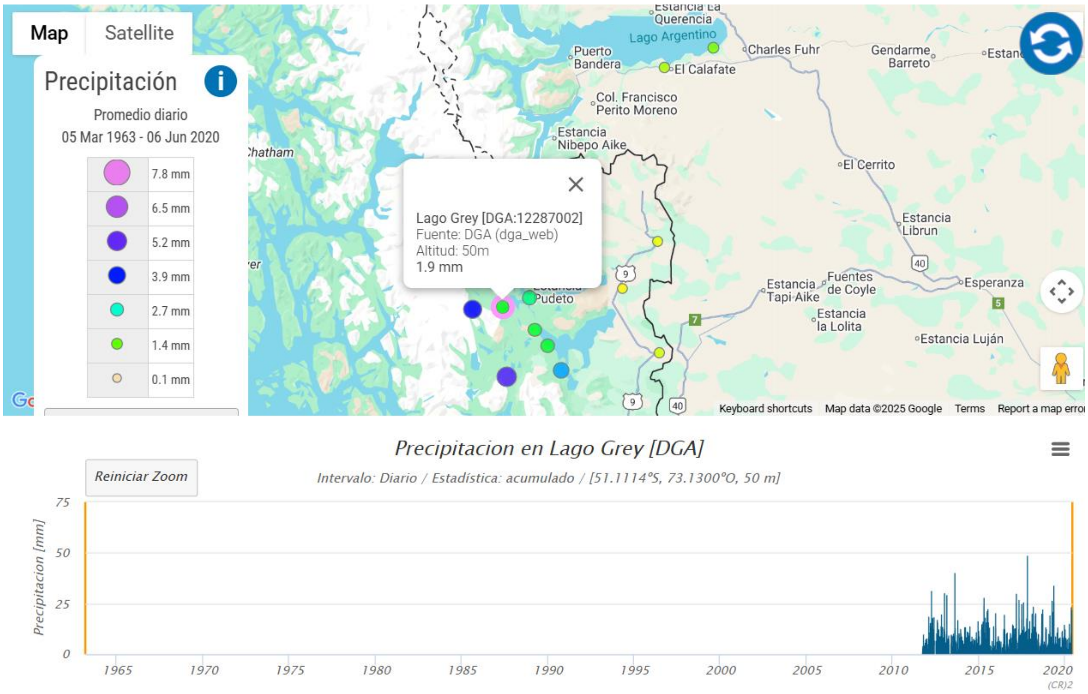

Figure 29 – Precipitation in Grey Lake station, sources: https://explorador.cr2.cl/

7. Conclusions and future trends

This work aimed to create and perform a fully open-source approach to study glacier retreat using freely available satellite images and GIS tools. In detail, the proposed methodology, relying on MODIS and Sentinel-2 datasets processed in QGIS, was applied to two case studies: the Adamello Glacier in the Italian Alps and the Grey Glacier in Chilean Patagonia. The primary goal was to assess whether open and accessible data could provide reliable information on glacier extent and its evolution over time, guaranteeing transparency and reproducibility for future applications.

The study confirmed the remarkable retreat of the Adamello Glacier from 2015 to 2020, followed by an anomalous augment in 2024, probably due to extraordinary snowfall events. Sentinel-2 data proved to be more precise and consistent than MODIS imagery, because of its significant higher spatial resolution.

Regarding the delineation methods, the automatic one yielded the best efficiency, with a percentage error of only 4,17% compared to the reference surface. The visual approach, on the other hand, tended to overestimate the glacier area, specifically in Sentinel-2 images.

The confrontation between MODIS and Sentinel-2 highlighted how lower resolution datasets may lead to systematic overestimations, emphasizing the importance of an appropriate spatial scale for glaciological analyses.

In the Grey Glacier case, a general and slight shrinkage was observed between 2016 and 2025, especially at the glacier terminus in contact with Grey Lake.

Concerning the MODIS/Sentinel-2 and visual/automatic comparisons, the same considerations previously discussed remain valid. However, due to discrepancies in the available reference data, it was not possible to calculate the percentage error for this case.

The climatic data retrieved from *Explorador Climático* portal, although incomplete and sometimes inconsistent, showed an overall warming trend in the Torres del Paine region, consistent with the observed glacier retreat.

Despite the successful development and application of the methodology and the positive results, many limitations came up.

The method's reliability is strongly related to image quality and atmospheric conditions, as well as to the empirical selection of reflectance thresholds for the automatic classification. The lack of in-situ validation data or *Digital Elevation Models (DEMs)* reduced the accuracy assessment and the possibility to differentiate between perennial ice and seasonal snow.

Nevertheless, the developed methodology proved to be a valid, cost-free and reproducible workflow for the assessment of glacier shrinkage.

In future developments, the implementation of additional sensors such as Landsat and Sentinel-1 could remarkably improve the robustness of the proposed approach. Landsat's long historical record would enable to extend the temporal dimension of the analyses and Sentinel-1 radar data would allow glacier mapping under persistent cloud cover or low-light conditions, guaranteeing consistent temporal continuity.

Furthermore, the adoption of machine learning techniques could automate the delineation of glacier perimeter, lowering the subjectivity and improving the scalability of the methodology to bigger or more complex regions.

Finally, the same workflow could be applied to a broader range of glaciers, boosting the creation of a global, open-access monitoring network. This would support both scientific research and social awareness, linking academic knowledge and environmental management.

Overall, this thesis demonstrates that free and open-source tools can effectively strengthen the monitoring of glacier retreat and provide valuable insights into the effects of climate change.

The proposed approach represents a flexible framework that can be shaped to many contexts and improved through further implementations. The continuous monitoring of glaciers is fundamental to understand ongoing environmental transformations and to advance informed decisions toward a more sustainable and resilient future.

Figure 30 – Personal visit to Grey Glacier, sources: Luca Bellani

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