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Development of a Glaciological Spatial Data Infrastructure to assess glaciers response to climatic fluctuation

Advisors:
Prof. Mattia De Amicis
Prof. Valter Maggi
Dr. Francesco Zucca

Ph.D. candidate:
Matteo Mattavelli

Università degli Studi di Milano –Bicocca –
Dipartimento di Scienze dell'Ambiente e del Territorio e
Scienze della Terra

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Matteo Mattavelli

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Coordinatore:
Prof. Valter Maggi

Tutori: Prof. Mattia De Amicis
Prof. Valter Maggi
Co-Tutore: Dr. Francesco Zucca

A Paola,

Daniele, Ivan, Luca, Massimiliano, Roberto e Simone.

“The farther backward you can look, the farther forward you are likely to see.”

Sir Winston Leonard Spencer Churchill

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Grazie infine ai miei genitori, che hanno reso possibile tutto questo.

Glossary of main acronyms used in the text

ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
CTR	Carta Tecnica Regionale
DEM	Digital Elevation Model
ELA	Equilibrium Line Altitude
GAR	Greater Alpine Region
GDEM	Global Digital Elevation Model
GDM	Glacier Data Module
GIS	Geographical information system
GLIMS	Global Land Ice Measurements from Space
HKKH	Hindu Kush - Karakorum - Himalaya
IDB1	Ice core Data Base v.1
IDB2	Ice core Data Base v.2
IGM	Istituto Geografico Militare
IPCC	Intergovernmental Panel on Climate Change
k.yr.	Thousands years
LIA	Little Ice Age
MGM	Minimal Glacier Model
NCDC	National Climatic Data Center
NICL	National Ice Core Laboratory
NOAA	National Oceanic and Atmospheric Administration
NSF	National Science Foundation
OGC	Open Geospatial Consortium
RGI	Randolph Glacier Inventory
SOA	Service Oriented Architecture
UNFCCC	United Nations Framework Convention on Climate Change
WDB	Weather Data Base
WFS	Web Feature Service
WGI	World Glacier Inventories
WGMS	World Glacier Inventory
WGS	World Geodetic System
WMS	Web Map Service
Y.B.P.	Years Before Present

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Abstract

The amount of analytical and measured data in any field of climate research, as proxy data for models, has reached a level where mechanisms to manage this vital resource effectively have to be found. For the interpretation of comprehensive datasets, there are paramount requirements to retrieve specific dataset quickly, to determine its relevance and to evaluate it in comparison with other data at local, regional or global scales.

In this context, glaciological data retrieval from non-polar ice cores and data derived by in situ and remote sensing observation of glaciers body present the same requirements.

To answer at the requirements of the glaciological community, during this a methodology for recovery, storage, easily and quickly access and disseminate glaciological data was developed. A spatial data infrastructure (SDI) was set-up and was used to study the evolution of the glaciers in relation with climate change.

So, the first part of the research was aimed to understand how to built a geodatabase containing ice cores data, useful as proxy data. At the end a structure (called Ice core Database IDB1) that contain data about world non-polar ice core characterization was implemented. However, IDB1 showed some weakness due to the fact that was thought to archive only chemical and physical data and not data related to glaciers or other spatial entities that was not the exact point were ice cores was drilling. To overtake IDB1 critical issues a new structure (IDB2) was implemented with this improvements: A repositioning methodology was set-up to increase the accuracy of coordinates of the ice cores, different entities with information about project of perforation, drilling-site, references of data and additional information about ice core were added to the structure. The new geodatabase IDB2 was linked with glaciological dataset of glaciers containing spatial, geomorphometric and other information. A new part

was developed to store data coming from geomorphic analysis. To offer a tools for evaluate the geomorphic changes of glaciers during time and to calculate, extrapolate and obtain data that can be useful to calibrate provisional model, a GIS module called GlacierDataModule (GDM) was developed. In particular, this tools was used to obtain data along the glacier flow lines. This data was used to calibrate the Minimal Glacier Models to assess glaciers response to climatic fluctuations and to linkage the geomorphological parameters with climate variability. The developed tool was applied to 34 glaciers of great alpine region (GAR). Input data required to GDM were recovered from the SDI (IDB2) previously developed and ASTER GDEMv2 was used as DEM input source. Results of GDM on GAR was used to populate IDB2 in an iterative way and used to calibrate the MGM to assess glaciers response to climatic fluctuations. Geomorphological data coming from the spatial analysis on glaciers was also used to compare the glaciers and find some behaviour useful to evaluate the glacier distribution along the GAR.

At the end, to disseminate the entire dataset and to offer at the scientific community a user-friendly instruments to search and download the proxy data and glaciers data, a geoportal with a webgis was developed.

So, in this work a system for retrieval and manage multisource and heterogeneous information has been proposed. To organize and aggregate both the ice cores proxy data (useful to evaluate climatic fluctuations on the past) and glaciers geomorphic parameters (useful to validate and calibrate glaciological model) aimed to assess the glaciers response to climatic fluctuations in the past or in the future a SDI with a dedicated geoportal and a GIS tools was developed.

This two results are addressed to a broad variety of user, from researchers in glaciology, climate change and paleoclimate up to people with less experience on ice cores or glaciers data thanks to facility of use of the instrument developed. This philosophy has driven also the choice of functionality and utilities of the geo-db, as well as the type of data format. The system developed is deliberately composed by open-source and free modules, compliant to widespread standards. In this way it results scalable, customizable to meet the requirements even of single local associations, and replicable without licensing costs.

1. INTRODUCTION

1.1 Context and Aim

Nowadays, the three main topics in climate research can be summarized in to:

- understanding the climatic response to anthropogenic forcing
- understanding climate dynamics and natural climatic variability of the past
- predictions of future climate

Obviously, these topics are intimately related each other and require interdisciplinary approach research. Reconstruction of paleo climate contributes to the whole understanding of how the climate system works and thus enhances the performance of models predicting future climate of the 21st century. The essential link between climate reconstruction and its prediction could well summarized by a famous British statesman, who probably did not have climatology in mind when he said:

"The farther backward you can look, the farther forward you are likely to see." Sir Winston Leonard Spencer Churchill (1874–1965).

In other words, in order to understand future climate variability and its response to anthropogenic forcing one has to maximize the understanding of past oscillation. Moreover, only someone who is aware of the entire range of natural fluctuations and their consequences for life on Earth and also of the rate at which changes occur, will be able to assess the impact of future change. In this direction understanding the past is essential for modelling future climate development and environmental changes (*Bolius, D., Ph.D. thesis, 2006*). The amount of analytical and measured data in any field of climate research, as proxy data for models, has reached a level where mechanisms to manage this vital resource effectively have to be found. For the interpretation of comprehensive datasets, there are paramount requirements to retrieve specific dataset quickly, to determine its relevance and to evaluate it in comparison with other data at local, regional or global scales (*Diepenbroek M., et al 2002*).

The purpose of this study is to provide a contribution to the glaciological and climate scientific community offering an instrument to:

1. analyse climate proxy coming from non polar ice cores (discussed in chapter 2 and 3)
2. evaluate ice cores position to identify new potential drillable glaciers for retrieval new proxy data (discussed in chapter 3)
3. Calculate and archive geomorphic data of glaciers body to assess their response to climatic fluctuations in the past or in the future (discussed in chapter 4).

1.2 Climate Change and Glaciers

1.2.1Climate Change

Climate change refers to a change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forcing, also in combination each other, such as modulations of the solar cycles, volcanic eruptions and persistent anthropogenic changes in the composition of the atmosphere and in land use. Note that the Framework Convention on Climate Change (*UNFCCC, 1992*), in its Article 1, defines climate change as: '*a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods*'. The UNFCCC thus makes a distinction between climate change attributable to human activities altering the atmospheric composition, and climate variability attributable to natural causes. (*IPCC 2013*).

Human influence on the climate system is clear, and recent anthropogenic emissions of greenhouse gases are the highest in human history. Recent climate changes have had widespread impacts on human and natural systems. Anthropogenic greenhouse gas emissions have increased since the pre-industrial era, driven largely by economic and population growth, and are now higher than ever. This has led to atmospheric concentrations of carbon dioxide, methane and nitrous oxide that are unprecedented in at least the last 800,000 years. Their effects, together with those of other anthropogenic drivers such as pollutant in atmosphere (particulate matter as most important), have been detected throughout the climate system and are *extremely likely* to have been the dominant cause of the observed warming since the mid-20th century. Warming of the climate system is unequivocal and since the 1850s, many of the observed changes are unprecedented over decades to millennia. The atmosphere and ocean have warmed, the amounts of snow and ice have diminished, and sea level has risen. Each of the last three decades has been successively warmer at the Earth's surface than any preceding decade since 1850 (fig. 1). The period from 1983 to 2012 was *likely* the warmest 30-year period of the last 1400 years in the Northern Hemisphere, where such assessment is possible. (*IPCC, 2013*).

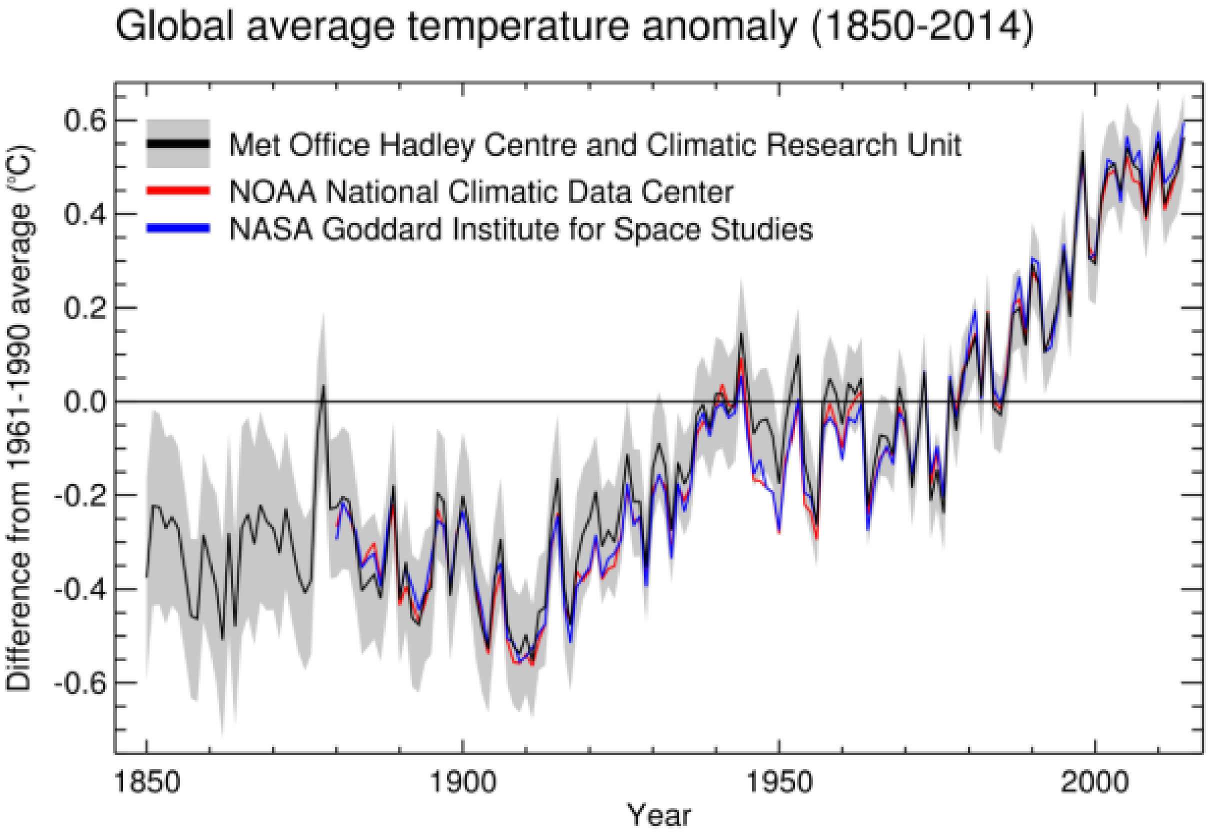


Figure 1 Global average temperature anomaly from 1850 to 2014 (World Meteorological Organization)

1.2.2Glacier

Glacier is a persistent mass of ice, snow at various stages, water and sediments that originates on land which moves along the gravity force. The glacier is formed where snow persists for many consecutive years without melting completely and is a dynamic system where the mass from an upper zone where prevail accumulation processes (accumulation zone), moves towards a lower zone where prevail fusion processes (ablation zone)

(*Benn & Evans, 2014*). The boundary between these two zones is called *equilibrium line* and it represent that area where the accumulation is equals to ablation for a year taken in account. Its altitude defines the *equilibrium line altitude*, or ELA (fig. 2). Often, the equilibrium line is not a distinct "line" but a transition zone where the glacier surface grades from snow, to snow patches, to bare ice. (*Cuffey & Paterson, 2010*).

As previously said, the glacier is formed where snow persists for many consecutive years without melting completely. After many years, layers of snow accumulate in accumulation zone and the deeper layers due to a process of metamorphism turn first in firn and then to ice glacier through the gradual reduction of porosity and increase in density (*Benn & Evans, 2014; IPCC, 2013*). This process form the ice glacier as we known it.

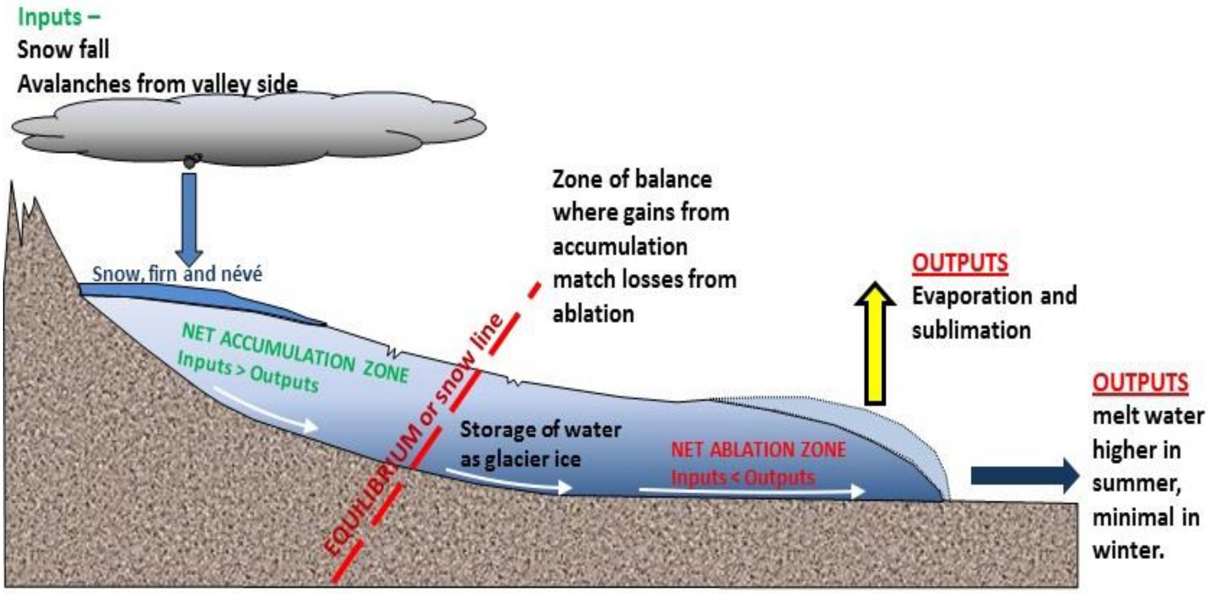


Figure 2 Cross section of a typical alpine glacier showing the two major zones of a glacier and ice flow within the glacier. The white arrows show the direction and speed of the moving ice.

Glaciers can be classified in several ways following their shape, their position on the mountain, their dimension etc. In this dissertation I'm focused on Mountain glaciers. These glaciers develop in high mountainous regions, often flowing out of ice fields that span several peaks or even a mountain range. The mountain glaciers are found in Canada, Alaska, Himalaya, Karakorum, Andes and Alps.

Mountain glaciers are key indicators and unique demonstration objects of global climate change (*Haeberli et al.*, 2007), and observing their systems it is possible detection trends potentially related to the greenhouse effect (*IPCC*, 2013). Due to their proximity to the melting point, glaciers are among the best natural indicators of global climate change (*Zemp*, 2006) and therefore must be considered as a key element in discussions about Earth evolution (*Haeberli*, 2004). Also if the ice volume of the non-polar glacier is only a small fraction of the entire ice in the world, we are well justified in studying non-polar glaciers and in particular the Alpine glaciers because in the Alpine region it has possible find the best data in term of space and temporal coverage of all mountain regions (*Braithwaite et al.*, 2013).

In high mountain regions, especially in the Alps, glaciers are a relevant component of the landscape and the environment as well as the culture. They store a relevant portion of fresh-water which is indispensable for domestic, agricultural and industrial use, and they are a relevant economic component for tourism and hydro-electric power production. Modifications in the glacier storage capacity related to climate change can therefore have relevant impact, as glacier melt often supports the water supply during summer (*Casassa et al.*, 2009). In the last decades, retreat of glaciers in the Alps has been extremely evident (fig. 3), owing also to the higher temperature rise in this region when compared to the global average (*Ciccarelli et al.*, 2008; *Gobiet et al.*, 2014). Knowledge about past, ongoing and future changes in glacier mass balance is so crucial for assessing global impacts of glacier wastage (*Huss*, 2012). Best estimates for volume changes show that glaciers in the European Alps lost about half their total volume (roughly 0.5%yr^{-1}) between 1850 and around 1975, another 25% (1%yr$^{-1)}$ of the remaining amount be- tween 1975 and 2000, and an additional 10–15% (2–3% yr^{-1}) in the first 5 years of this century (*Haeberli et al.*, 2007). Glacier around the world show a widespread retreat during the 19th century (*Oerlemans and Fortuin*, 1992; *Oerlemans*, 1994; *IPCC*, 2013). This behaviour is generally linked to climate change, and it is observed worldwide with few exceptions (e.g. Karakoram glaciers are expanding since the 90s in contrast to a worldwide decline). Glaciers in the Alps are in agreement with this global tendency, showing a diffuse retreat that started in the second half of the 19th century (*Thibert et al.*, 2013; *IPCC*, 2013). The retreat of glaciers is documented by different measurements ranging from glacier snout fluctuations (*Oerlemans*, 2005), to ELA shifts (*Vincent C., et al.,* 2014), to mass balance data (*Huss*, 2012). The Intergovernmental Panel for Climate Change (IPCC), reports highly significant correlation between the increase of land temperature and the decrease in land-ice extent in northern hemisphere (IPPC, 2007).

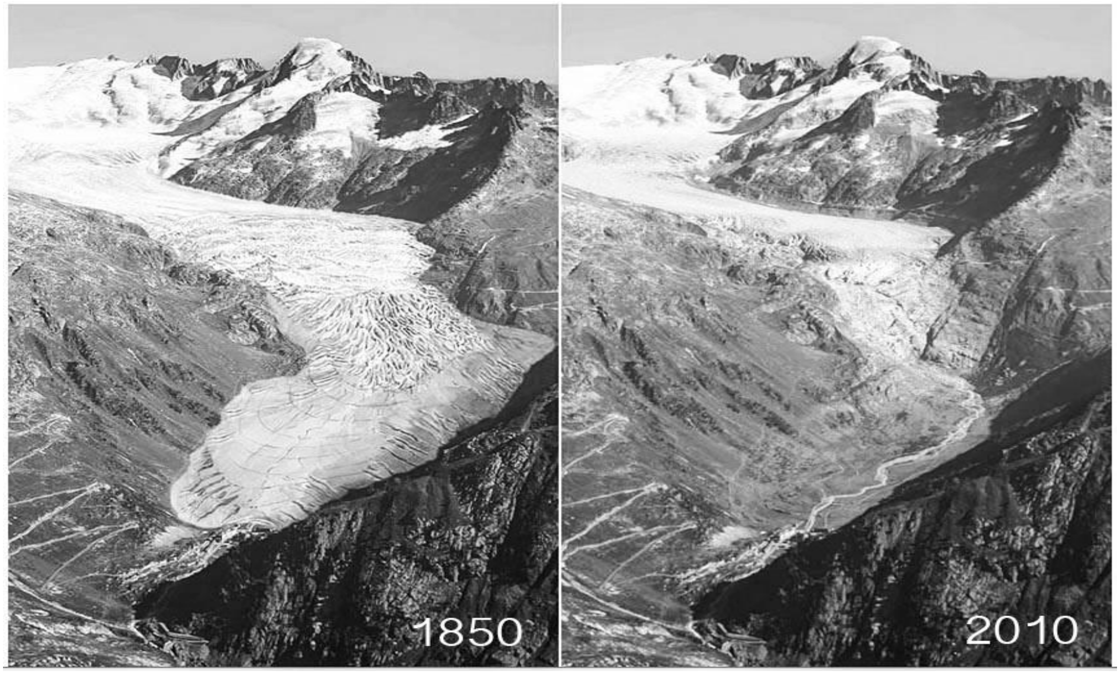
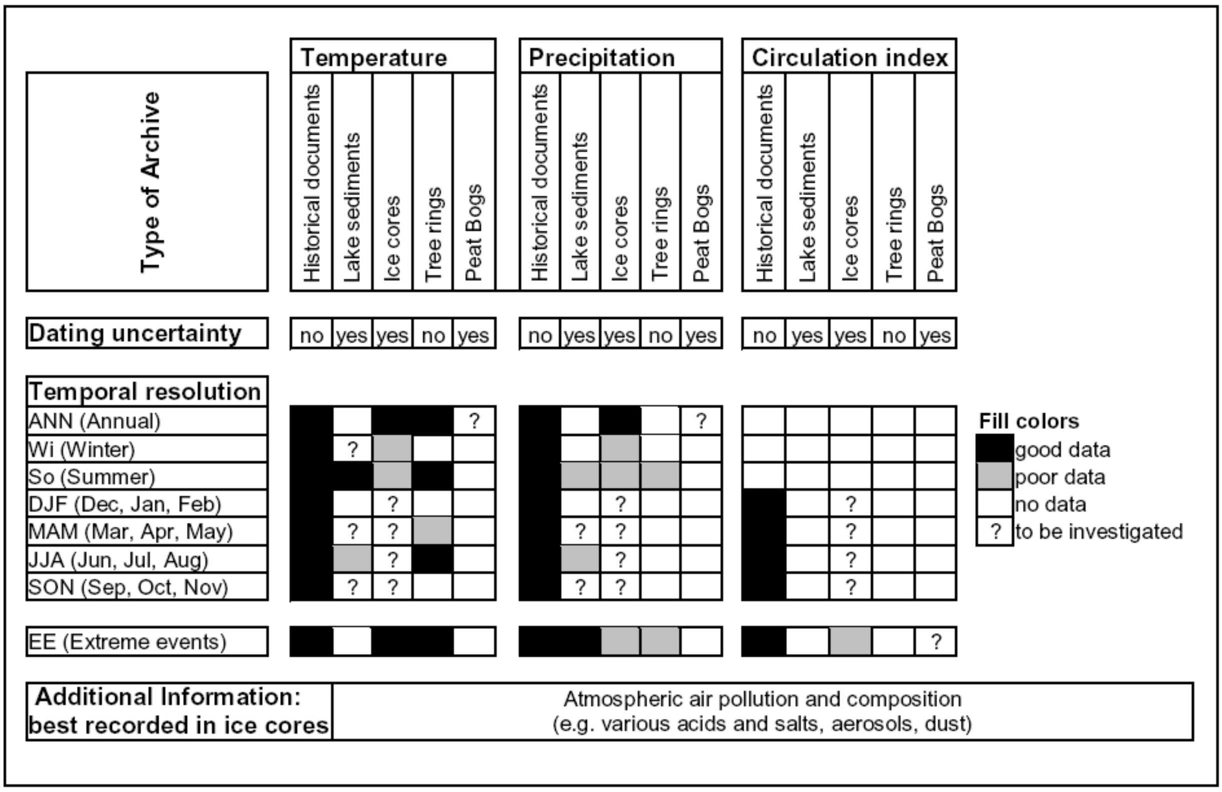


Figure 3 Picture showing the retreat of Rhone glacier, Swiss Alps, since 1850. Source: http://www.ethlife.ethz.ch/

Glacier as source of proxy data

In paleoclimatology, that branch of the science that study the past climate of the Earth, scientists use what is known as *proxy* data to reconstruct past climate conditions. These proxy data are preserved physical or chemical characteristics of the environment that can stand in for direct measurements. Paleo-climatologists gather proxy data from natural recorders of climate variability such as tree rings, ice cores, fossil pollen, ocean sediments, corals and historical data. By analysing records taken from these and other proxy sources, scientists can extend our understanding of climate far beyond the instrumental record. As instrumental records of climate related parameters (e.g. temperature or precipitation) exist only for the last ~150 years, natural archives with preserved information of such parameters are the basis of climate research. Historical documentary data such as chronicles, letters reports to authorities or novel that report extreme events, disasters impacts, loss perception, risk management and so on are valuable sources of information about past climate (*Pfister et al., 1992; Brázdil et al., 2005*) However, as the existence of historical documents is strongly decreasing going further back in time and only limited to certain areas, natural archive that are proxies providers such as ice cores, tree, corals etc., may going back several centuries or millennia, acquire major importance. Different natural archives with individual strengths and weaknesses in memorizing e.g. temperature, precipitation, atmospheric circulation or the atmospheric composition exist (fig. 4). Ice cores proxy in particular have the potential to provide climate information reaching further back even more than 800'000 years B.P. (*EPICA Community Members, 2004*).



Type of Archive	Temperature					Precipitation					Circulation index				
	Historical documents	Lake sediments	Ice cores	Tree rings	Peat Bogs	Historical documents	Lake sediments	Ice cores	Tree rings	Peat Bogs	Historical documents	Lake sediments	Ice cores	Tree rings	Peat Bogs
Dating uncertainty	no	yes	yes	no	yes	no	yes	yes	no	yes	no	yes	yes	no	yes
Temporal resolution															
ANN (Annual)	■		■	■	?	■		■		?					
Wi (Winter)	■	?	▨			■		▨							
So (Summer)	■	■	▨	■		■	▨	▨	▨						
DJF (Dec, Jan, Feb)	■		?			■		?			■		?		
MAM (Mar, Apr, May)	■	?	?	▨		■	?	?			■		?		
JJA (Jun, Jul, Aug)	■	▨	?	■		■	▨	?			■		?		
SON (Sep, Oct, Nov)	■	?	?			■	?	?			■		?		
EE (Extreme events)	■		■	■		■	■	▨	▨		■		▨		?

Additional Information: best recorded in ice cores	Atmospheric air pollution and composition (e.g. various acids and salts, aerosols, dust)

Fill colors
■ good data
▨ poor data
☐ no data
? to be investigated

Figure 4 Different archives sources with the expected quality of proxy data, the achievable temporal resolution and the dating uncertainty (time window ~1500- 2000 AD). From: NCCR- Climate internal scientific report 2002.

In this study, we focused on proxies obtaining from ice cores drilled from mid-latitude regions (+60°/-60° of latitude) and high-altitude glaciers, excluding ice caps and ice sheets because glaciers in mid-latitude, tropical and sub-tropical regions are natural archives of past precipitation, preserving paleo-climatic and paleo-atmospheric conditions (*Thompson R.S., et al.,1996*). In fact, the climate of a region can be reconstructed thanks to the accumulated snow, which contains atmospheric trace substances incorporated into the precipitation by in-cloud and below-cloud scavenging (*Baltensperger U., et al.,1998*) (fig. 5).

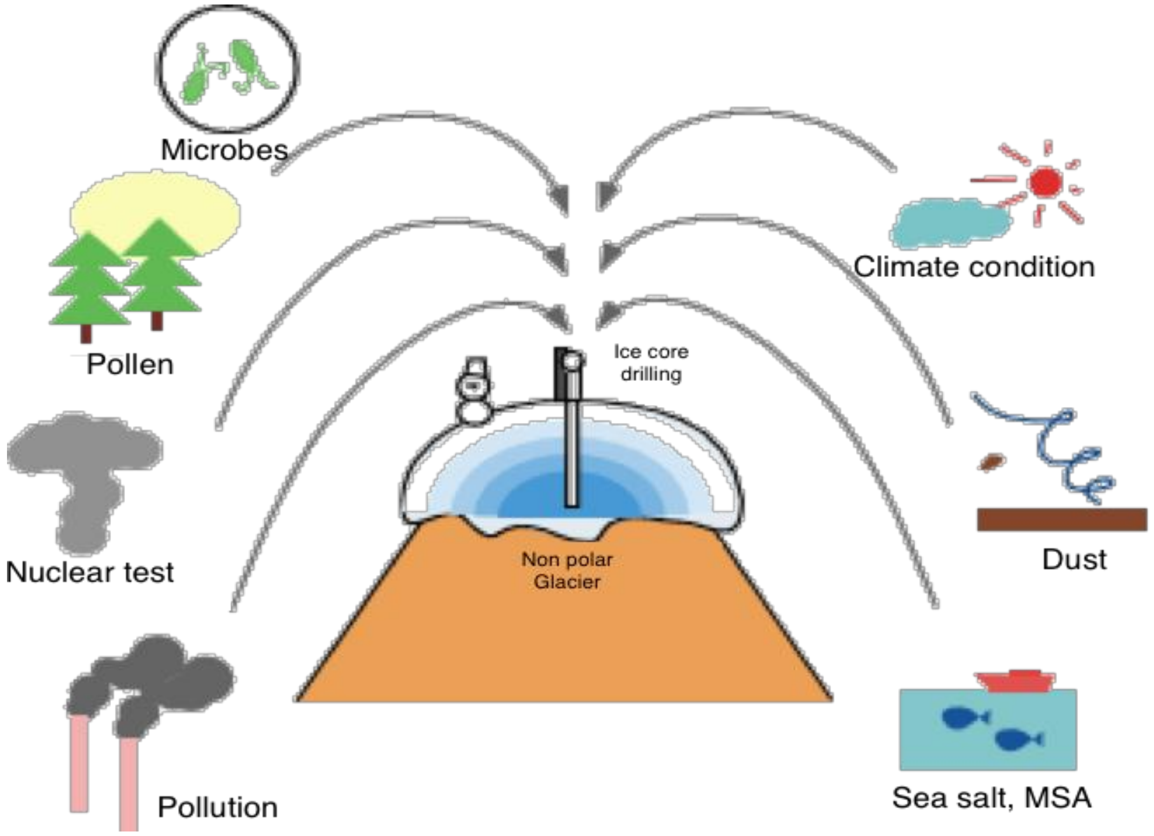


Figure 5 Example of trace substances that can be incorporated in to the precipitation.

This snow is transformed to firn and ice through snow metamorphosis, building a regularly layered archive (fig.6) that preserve information can vary from the isotopic composition of the air, the dust amount that was deposited on glacier during the year, the pollutant coming from industrial or human activities and so on.

The preserved information, such as the isotopic composition of the deposited water molecules (e.g., $\delta^{18}O$ and δD, which are proxies of temperature), can be accessed from recovered ice cores using some specifically drilling devices (*Ginot P., et al.,* 2002).

We focus on the non-polar glacier because they have some particularity that polar glacier or ice caps do not present such as the quite easily accessibility, their proximity to developed area with a huge influence of pollutant but the major strength of non-polar glacier archives is their high temporal resolution, which can be annual or even seasonal if accumulation rates are sufficiently high. For these reason and also because until now, aware of the writer after an accurate literature review there are not a comprehensive non-polar ice core and glacier data archive.

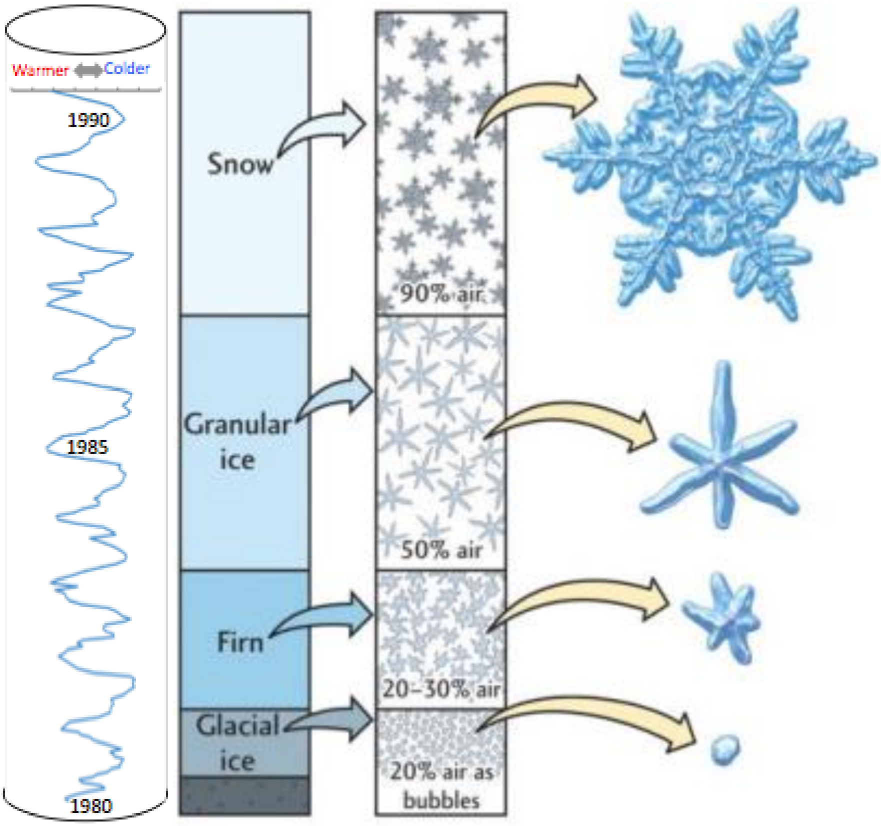


Figure 6 Snow metamorphism and % of air entrapped between the snow or ice crystal.

Non-polar Ice cores

For the past 30 years, the international scientific community has studied non-polar ice cores as indicators of climate variability and environmental changes. These ice cores were extracted from several glaciers located in tropical, subtropical and mid-latitude regions: South America, Africa, Hindu Kush - Karakorum - Himalaya (HKKH) region, Alaska, Russia and Europe (*Jones P.D., et al., 2009*). The ice cores drilled in these glaciers conserve essential information about the temporal resolution of recent climate variability, the evolution of anthropogenic pollution and information about the middle troposphere in relation to climate change on a planetary scale (*Duan K., et al 2007*) (fig. 7).

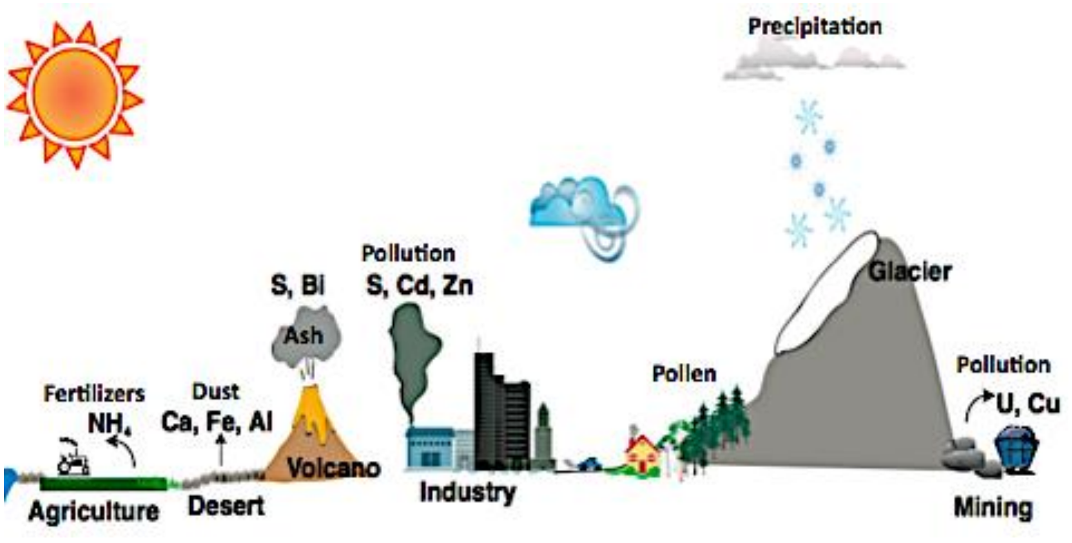


Figure 7 Examples of aerosols and chemical elements that are transported and deposited on ice sheets and glaciers.

The analyses performed on these ice cores produces a wealth of chemical and physical data that are used to reconstruct the paleoclimate of a certain area. Cores from drill sites of non-polar glaciers have been widely used as environmental archives to reconstruct the depositional history of aerosol-related species over the 20th century (*Preunkert, 2000; Schwikowski, 2004; Wagenbach, 1988*).

What is ice core and which information can we obtain from it?

An ice core is a cylinder-shaped sample of ice drilled from a glacier (fig. 8). Ice core records provide the most direct and detailed way to investigate past climate and atmospheric conditions.

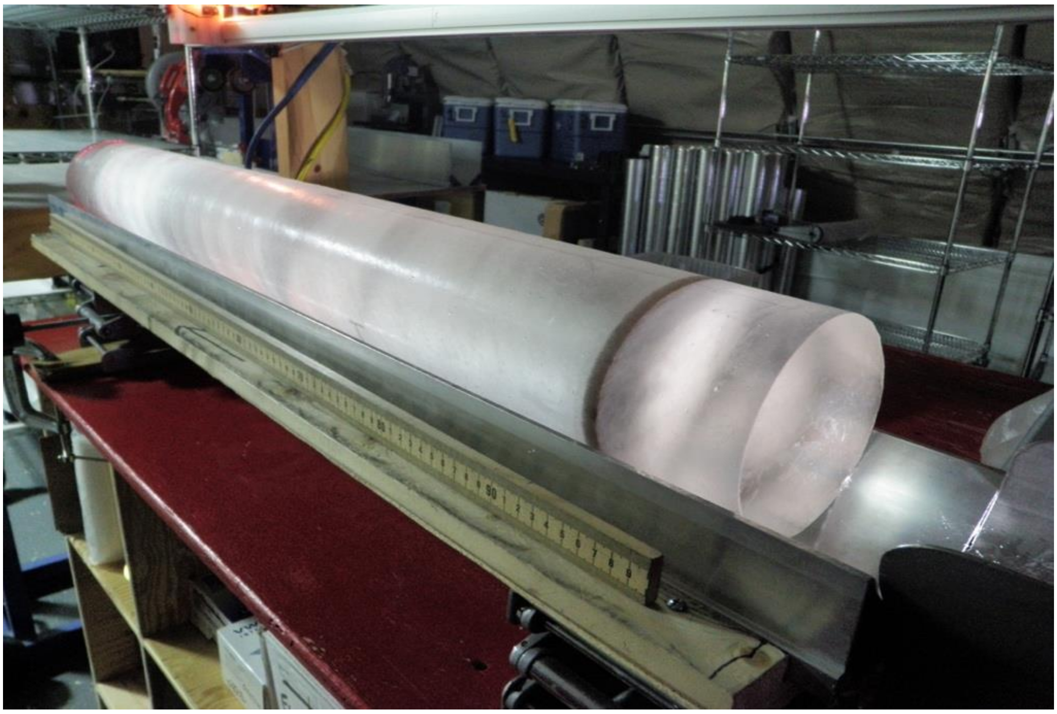


Figure 8 An example of just drilled Ice core.

Snowfall that are collects on glaciers each year, captures atmospheric concentrations of dust, sea-salts, ash, gas bubbles and human pollutants. Analysis of the physical and chemical properties of an ice core can reveal past variations in climate ranging from seasons to hundreds of thousands of years (*Haeberli W., et al., 2012, Brunetti M., et al 2009, Bolius D., 2006, Schwikowski M., et al., 2004, Thompson L.G., et al., 1995*).

In particular Ice cores may contain trace amounts of various constituents. These include:

- Trapped air bubbles, which can be analysed to find out how much carbon dioxide or methane was in the atmosphere thousands of years ago;
- Mineral glass particles from volcanic eruptions (called "tephra");
- Plants and trees pollen grains;
- Ash from forest fires;
- Dust blown from deserts or from micro-meteors entering the atmosphere
- Particles produced by cosmic rays in the upper atmosphere;

- Sea spray;
- Soot and metal particles from coal-burning power plants, metallurgical smelters and vehicle exhaust;
- Radioactive particles from surface nuclear tests and accidental emissions from nuclear power plants;
- bacteria.

After scientists procure the cores, they slice them up into various portions each allotted to a specific analytical or archival purpose. Once the samples have been prepared, the scientists run a variety of physical and chemical analyses on the cores. Some of these procedures are ice consumptive, meaning their analysis requires destruction of the ice, while others have no effect on the ice. Scientists study the gas composition of the bubbles in the ice by crushing a sample of the core in a vacuum. Overall, most of the core is reserved for archival purposes, preserving a long record of Earth history for future research (fig. 9).

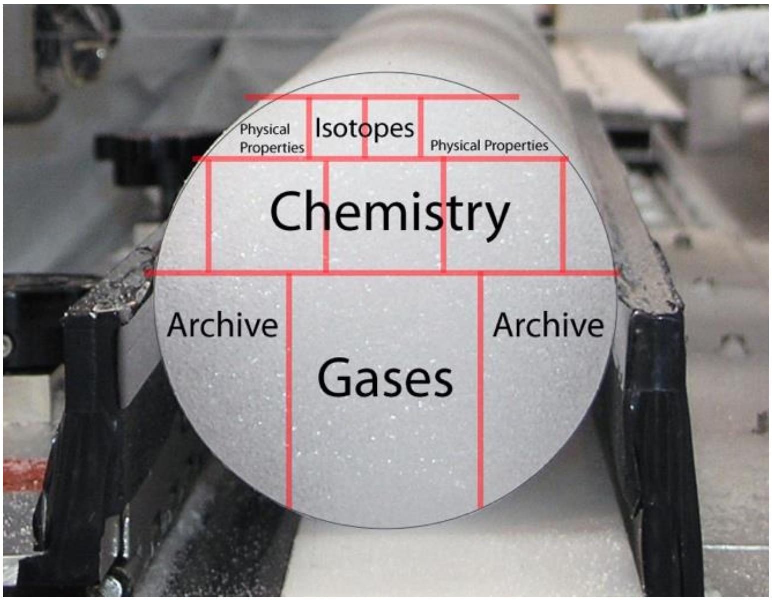


Figure 9 Typical cut plan for a multi-investigator ice coring project.

Dating the ice core

Ice core records can be used to reconstruct temperature, atmospheric circulation strength, precipitation, ocean volume, atmospheric dust, volcanic eruptions, solar variability, marine biological productivity, sea ice and desert extent, and forest fires (fig. 10) as previously explain. Furthermore, ice cores provide excellent seasonal markers that allowing a very accurate dating. Seasonal markers such as stable isotope ratios of water depending on temperature and can may used to reveal warmer and colder periods during a year, so, evaluating and counting the succession of the markers it possible underline the annual seasonal variation of the ice core layers or for the longest ice cores, underline the climatic variability along the centuries or millennia. These markers can be used to dating the ice cores, so, starting from the upper samples, scientist it is possible to count the "colder" or the "hottest" layers to date every layer of the ice core until markers are visible.

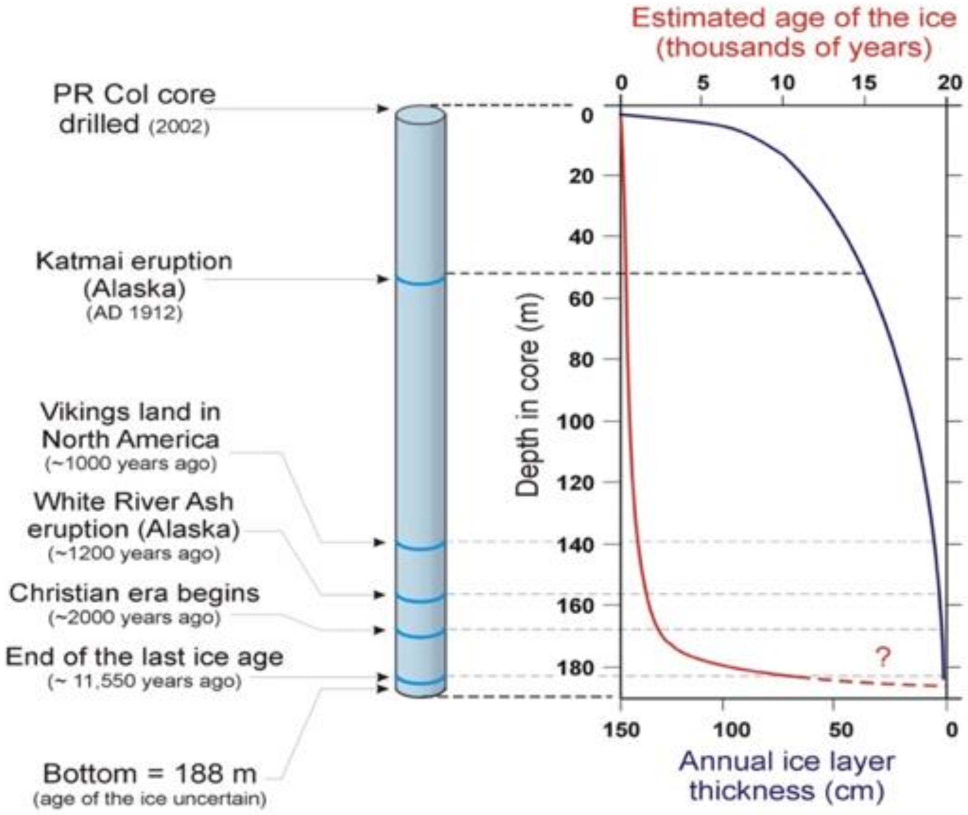


Figure 10 Example of ice core dating going back 11550 years before present.

Other seasonal markers may include dust; certain regions have seasonal dust storms (as e.g. the Saharan event in Europe), dust falls on glaciers body and a thin layer is deposed on glacier and here it is trapped. Some times dust may be thick enough to become visible in the ice. Therefore, measuring the dust concentration in the ice and knowing when the typical dust event happened in the study area, it is possible dating the layers containing the dust years. Annual dating can be linked by "dating horizons" such as well-known volcanic eruptions (fig. 11). In addition, "dating horizons" include the measure of that particles that increase the atmospheric radioactivity (e.g. 36Cl-, Tritium, and beta activity) that reflect the nuclear bomb tests that began in the 1940s and peaked in the early 1960s (fig. 12).

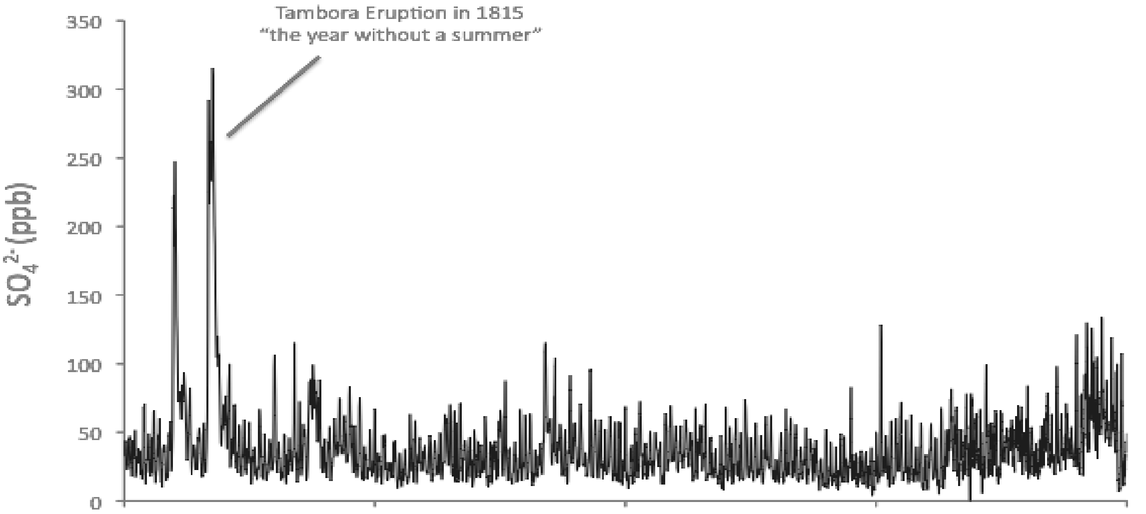


Figure 11 *Large peaks in sulfate (SO42-) can be used to identify input from volcanic sources. The 1815 Tambora Eruption, responsible for the "year without a summer", Is a commonly used "dating horizon" that has been found in ice cores around the Earth. Source http://climatechange.umaine.edu*

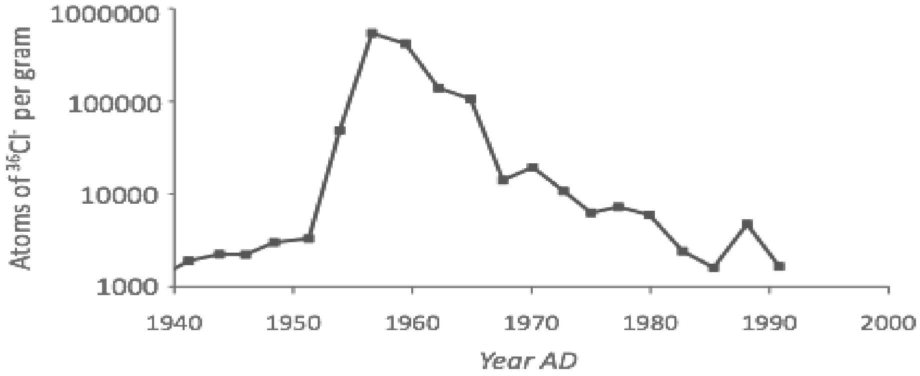


Figure 12 Chlorine-36 concentrations in samples from the Gulya ice cap. From: Green et al.,2004.

In the past 30 years, ice cores have become very important sources for informing and guiding the environmental policy in international affairs. Ice cores provide critical evidence of the human influence on the Earth's climate and atmospheric composition. For example, air extracted from Antarctic ice cores show that the present rise of CO2 levels in the Earth's atmosphere far exceeded levels experienced for thousands of years. Likewise, ice cores from Colle del Lys (Italy) have been used to verify if legislation on air pollution have effectively reduced pollution (fig. 13). Thanks to all this factor, ice cores became one of the most used proxy to evaluate and reconstruct the climate of the past.

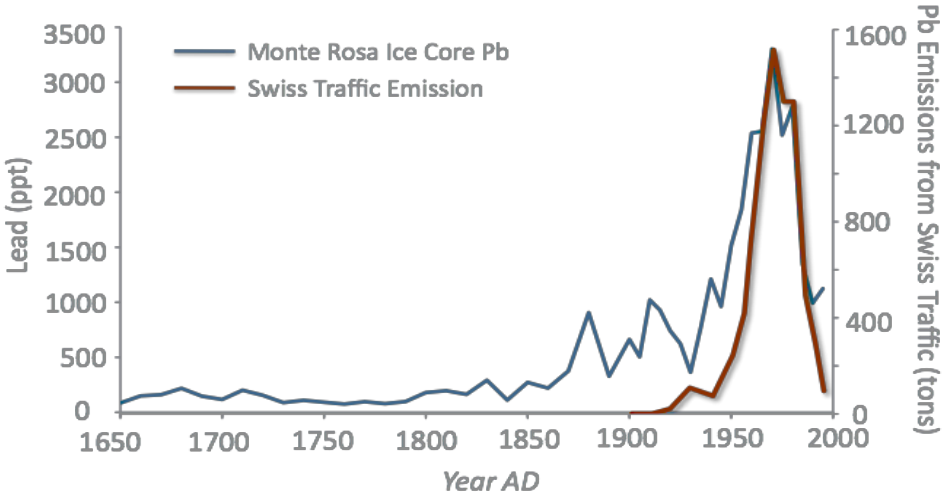


Figure 13 Lead concentration (ppt) measured in Monte Rosa ice core and lead emission from Swiss traffic. The increase and the decrease are given by the lead or un-lead fuel usage (Schwikowski M., et al., 2004).

Another important factor that allowed ice cores to became one of the most used proxy is the quality and the resolution of the temporal information which can be measured in ice. The resolution of temporal information in ice core is quite high, in some cases in non-polar ice cores it is possible observe the seasonal variability of the layers. Seasonal differences in the snow properties create layers, just like rings in trees, fortunately, ice cores preserve annual layers of accumulated snow (fig. 14).

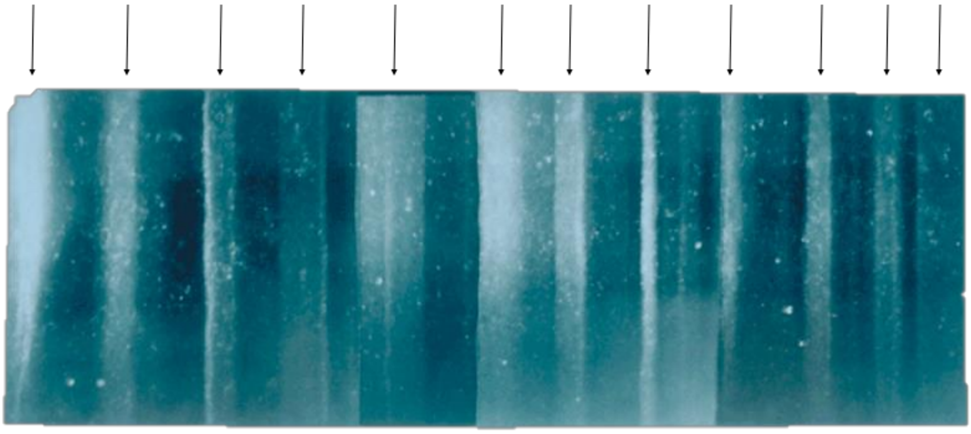


Figure 14 19 cm long section of GISP 2 ice core from 1855 m showing annual layer structure illuminated from below by a fiber optic source. Section contains 11 annual layers with summer layers (arrowed) sandwiched between darker winter layers.

Seasonal variations in isotopic composition and impurity content of the snowfall provide the basis for a distinct annual signal in the snowpack, which may be preserved in the ice under favourable conditions. The ability of an ice core to provide (sub-)annual information depends on the accumulation rate. It typically ranges from a few centimetres of ice per year in high-elevation areas of Antarctica to several meters at on low latitude glaciers. In the accumulation area of a glacier, snow slowly compacts into incompressible ice. Due to the continuous accumulation of snow, annual layers become buried in the glacier over time. Gravity causes the compression of ice in the lowermost section of an ice core causing a stratigraphic disturbance that can complicate precise dating (*Rasmussen S.O., et al., 2014*). So, as with any annually laminated record dated by layer counting, the uncertainty accumulates with increasing age

(*Delmas R.J., 1992*). Consequently, the determination of absolute ages is very accurate for recent periods, while the accumulated uncertainty often becomes large (i.e. low accuracy) compared to e.g. radiometric dating uncertainties in the last glacial period. However, even when the absolute accuracy is relatively low, layer counting still provides the possibility to determine event durations as recorded in the ice cores very precisely (*Steffensen J.P., et al.,2008*). Quality and resolution of the temporal information contained in an ice cores are influenced by different surface and subsurface process (*Thompson L.G., 2000*) (fig. 15):

- Accumulation rate: greater is the accumulation rate, more accurate temporal information it is possible obtain but less will be the temporal coverage of the ice cores,
- phenomena occurring during the formation of ice as: thawing, percolation, refreezing,
- Glacial transport phenomena with destruction of the annual layers.

Ice cores from different sites can be synchronized using common time marker horizons of, for example, volcanic origin (*Rasmussen S.O., et al.,2008*; *Severi M., et al.,2007*; *Parrenin F., et al.,2012*).

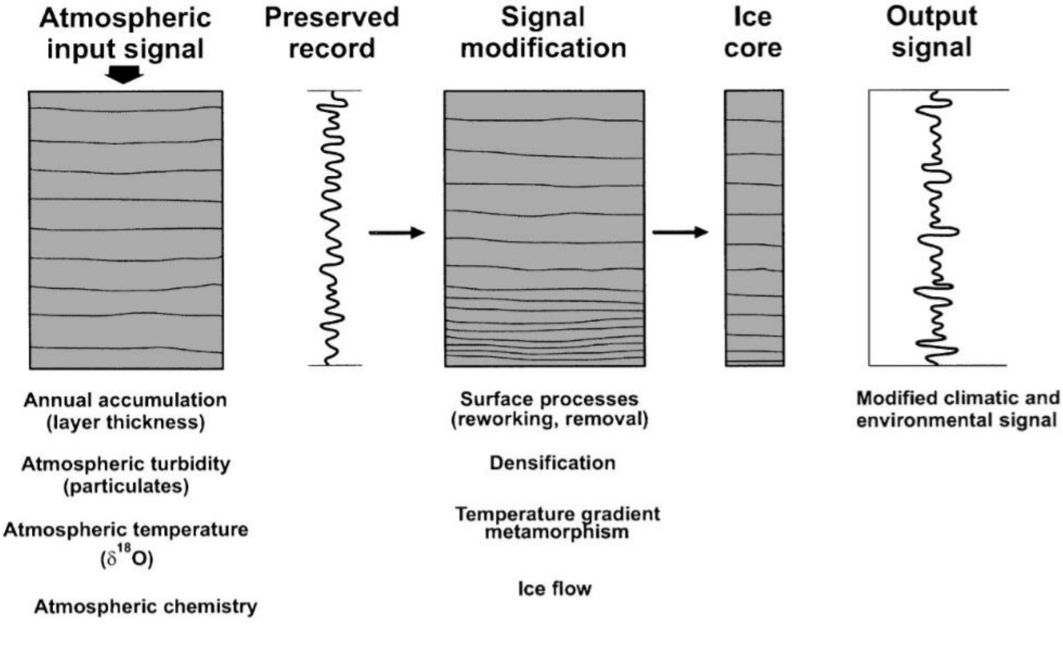


Figure 15 Schematic indicating how atmospheric climate and environmental signal can be modified through surface processes (Thompson L.G. 2000)

1.3 Spatial Data Infrastructure and NEXTDATA project

This research is a part of “*The NextData Project*” (www.nextdataproject.it), that aims to create an infrastructure of measurement networks in remote mountain and marine areas. The main goal of the NextData project is to create a system of archives and portals, connected through a General Portal, to access measured data, simulations, reanalysis results and scientific findings in an open-access, integrated and easy-to-use manner in order to fulfil the grand challenge of these project that is to provide information on the climatology and climate variability in Italy over the last two thousand years through a blend of paleoclimatic data information and numerical simulations. In this context, my research was target to development a spatial data infrastructure (SDI) to disseminate ice cores proxy data and to assess glacier response to climatic fluctuation by modelling. The working proposal presented in my thesis goes beyond the requirements of the NextData, in fact it far exceeds the only methodology to storage the paleoclimate proxies derived from ice cores by offering tools in an integrated system, a *Spatial Data Infrastructure (SDI)*, to retrieve, access and analyse glaciological proxies and offer also a GIS tool to retrieval and conduct geomorphic analysis on large scale dataset of glaciers.

The term *spatial data infrastructure* was coined in 1993 by the U.S. National Research Council to denote a framework of technologies, policies, and institutional arrangements that together facilitate the creation, exchange, and use of geospatial data and related information resources across an information-sharing community. Such a framework can be implemented narrowly to enable the sharing of geospatial information within an organization or more broadly for use at a national, regional, or global level. In all cases, an SDI will provide an institutionally sanctioned, automated means for posting, discovering, evaluating, and exchanging geospatial information by participating information producers and users. A more comprehensive view of SDI is offered by this definition (The White House - Office of Management and Budget 2002): “the technology, policies, standards, human resources, and related activities necessary to acquire, process, distribute, use, maintain, and preserve spatial data”. SDIs enable the discovery and delivery of spatial data from a data repository, via a spatial service provider, to a user, following a SOA (Service Oriented Architecture) approach. Further operations on data can then be offered to users (for instance updating, map composing, ...), even working from off-centre positions (*Criscuolo 2015*).

The basic software components of SDIs are according to *Steiniger and Hunter (2012)*:

- a software client - to display, query, and analyse spatial data (this could be a web browser or a GIS),
- a catalogue service - for the discovery, browsing, and querying of metadata or spatial services, spatial data-sets and other resources,
- a spatial data service - allowing the delivery of the data via the Internet,
- a spatial data repository - to store data (typically a Spatial database),
- a GIS software (client or desktop) - to create and update spatial data.

All these components were developed during my Ph.D. research activity (fig. 16). In particular, as software client and spatial data services, a geoportal was generating and made available (cap. 2.4 and 3.3.) As catalogue service the NextData metadata portal was used to upload and sharing metadata (cap. 2.4). A spatial database was implemented using the open source advanced-object-relational database management system, PostgreSQL using its spatial extension PostGIS.

Figure 16 The components of a Glaciological SDI developed. (modify from Criscuolo 2015)

1.4 Research workflow

The work that I conducted during my Ph.D. research embrace all the glaciological aspect cited in the previous paragraph Specific aim of this thesis is to develop a methodology for recovery, storage, access and disseminate glaciological data (ice cores characterization) to support climatic reconstruction and to assess glacier response to climatic fluctuations. So, I created a SDI that contains all glaciological data coming from ice cores characterization and glaciers geomorphic analysis to reconstruct the paleoclimate of the Earth and to evaluate the glacier behaviour in a climate change scenario.

Ice cores and glaciers are the two entities that are taken to account in my Ph.D. research, obviously ice cores and glaciers are two different entities that show different characteristics with different spatial and temporal information. As previously define, ice cores can be described as a punctual entity with an ensemble of chemical and physical parameters (the characterization of a specific ice core). Ice core can be considered a proxy of climatic condition, with high temporal resolution information that can going back several centuries or millennia. Glaciers in opposite show a complex geometry (representable as a non-regular polygon) that offer a physical and geomorphic information that can be used to validate and set mathematical model to predict their future behaviour in a climate change scenario. Moreover, they can offer seasonal information of the last 150-200 years, useful to evaluate the human impact on climate system.

By the creation of an advanced-object-relational database I was able to adsorb their diversity and their complexity both in factors and temporal scale grouping they in a single Spatial Data Infrastructure that embrace 4 dimension: the 3 spatial dimension, latitude, longitude, elevation of ice cores and glacier body, and the 4th, the temporal dimension of ice cores data and of the geomorphic parameters of the glaciers evaluable in the past and in the future.The 4th dimension, temporal factor, is a key parameter in this context; both, for the past with the ice core proxy and the paleoclimate reconstruction, then for the future with the most recent and past geomorphic parameters used to calibrate and validate glaciological models. The work that I conducted could be split in three parts. In the first year a geodatabase for glaciological data was built. A structure that can contain data about world non polar ice core characterization (IDB1) was implemented in order to offer at the scientific community and in particular at the NextData project a spatial database for retrieval ice core chemical and physical data.This first structure was related only to the ice cores and showed some weaknesses so, to overtake the critical issues showed in former phase a new structure IDB2 was set-up with this improvements during the second year:

- A repositioning methodology was developed and applied to increase the accuracy of coordinates of the ice cores find in literature or in other archives,
- Different entities with information about project of perforation, drilling-site, references of data and additional information about ice core were added to the IDB1 structure,
- A geoportal where it’s possible visualize and download data was realized.

During my third year of Ph.D. the IDB2 database was linked with glaciological databases of glaciers containing spatial and geomorphic information of glaciers and a new part was developed to store data coming from geomorphic analysis. To provide detailed information to calibrate 1D deterministic model to assess glaciers response to climatic fluctuations and to linkage the geomorphological parameters with climate variability a GIS module called *GlacierDataModule* (GDM) was also developed.

The workflow in the next page (fig. 17) should be a help for the reader to understand the logical scheme of the research and the interaction between different parts of the work.

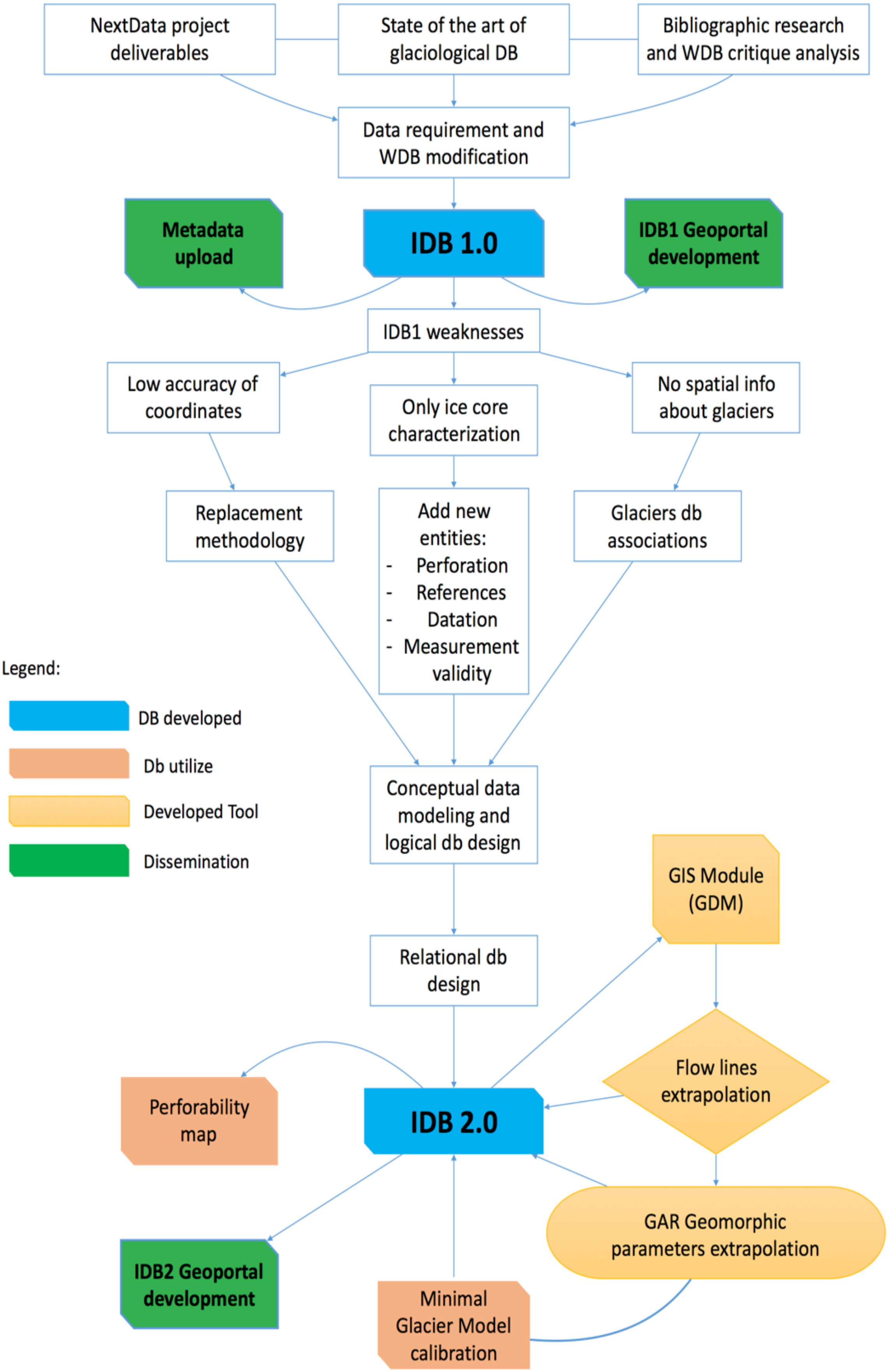


Figure 17 Workflow of the Ph.D. research activity

2 ICE CORE DATABASE V.1 (IDB1)

During the first year a geodatabase containing ice cores characterization was set-up. This geodatabase was called Ice Core Data Base v.1.

2.1 Non-polar ice cores data repository, a review

As the first part of the work, a comprehensive literature review about database and repository that can contain ice cores data was made.

Data from non-polar ice cores and non-polar ice core analysis are archived in three principal repositories:

- PANGAEA Data Publisher for Earth & Environmental Science (PANGAEA 2014, www.pangaea.de),
- the NOAA National Climatic Data Center (NCDC NOAA 2013, www.ncdc.noaa.gov/paleo/icecore)
- the National Ice Core Laboratory (NICL 2009, www.icecores.org).

1) PANGAEA Data Publisher for Earth & Environmental Science is a digital data library and a data publisher for Earth system science (*Diepenbroek, M 2002*). Data can be georeferenced in time (by date/time or geological age) and space (latitude, longitude, and depth/height). Scientific data are archived with related metadata in a relational database (Sybase) through an editorial system. Data are open-access and are distributed through web services in standard formats through various Internet search engines and web portals. Dataset descriptions (metadata) conform to the ISO 19115 standard and are also serve in various further formats (e.g., Directory Interchange Format, Dublin Core). They include a bibliographic citation and are consistently identified using digital object identifiers (DOIs). Identifier provision and long-term availability of datasets via library catalogues are ensured through cooperation with the German National Library of Science and Technology (TIB). The user can choose

datasets related to the characterization of ice cores. A single parameter of a particular ice core can be searched, but the name of the ice core and principal investigator must be known and entered. It is not possible to download a single parameter; one must download the entire dataset related to that specific ice core. A usable Webgis for identifying the location of the ice cores and their spatial coverage has not yet been implemented.

2) The NOAA-NCDC database stores ice-core data from the NOAA Paleoclimatology Program. These ice cores are divided in 5 subgroups: Antarctica, Greenland, Other Polar Ice Cores, Tropical and Temperate Cores, and Sea Ice Cores. The entire dataset of a single ice core can be downloaded, and a well-structured and user-friendly WebGIS has been implemented. However, the spatial position of the ice core has low precision, which causes most of the non-polar ice cores to locate in rocky areas, at the perforated top of the mountain, etc. It is only possible download the entire data of ice core analysis in ASCII or tabular format. Commonly, these files are simply structured in two formats: the first is a metadata repository that supplies the principal investigator of the research and a reference to the paper wherein the data are published; the second are records of the chemical and physical analysis of the ice core, which is a limitation for scientists who require specific data.

3) The U.S. National Ice Core Laboratory (NICL) is a National Science Foundation (NSF) facility for storing, curating, and studying meteoric ice cores recovered from the glaciated regions of the world. The NICL provides scientists with the capability to conduct examinations and measurements on ice cores. It preserves the integrity of these ice cores in a long-term repository for future investigations. This repository is not structured as a geodatabase in which the spatial information is one of the

principal keys to enable spatial queries. Furthermore, the NICL repository is not structured to archive each single numeric value from the analysis of the ice; thus, these data cannot be queried by the data provider, parameter of interest or ice core name. This repository also does not include chemical-physical characterization archives; instead, there is only a table with information about the ice cores stored at NICL.

These repositories store 57 non-polar ice cores located prevalently in America and some in Indo-Kush-Karakorum-Himalaya (HKKH). They do not contain Italian ice cores and only 3 European ice cores (Vernagtferner core I, II, III). So a huge literature review about scientific paper, Ph.D. thesis and technical reports was made to find European (and of course the world) ice cores never census. I review papers publishing from the 1976 (*L. Liboutry 1976*) to 2013 (*H. Konrand, 2013*).

2.2 Proposal and database implementation

To overcome the cited limitations especially of the NOAA and NICL databases; to assemble the non-polar ice cores spread in different archives; to make available ice cores never census and to georeferencing all the non-polar ice cores, a new geodatabase structure, called the IDB1, has been designed and produces. Regroup and harmonize a great number of the non-polar ice cores adding spatial and temporal information (when they are available) together with data derived from chemical and physical characterizations, is primary to offer a useful instrument to the glaciological and paleo-climatological community. In this direction, IDB1 is the first database that offers to the stakeholders the opportunity to do spatial data mining of the characterization and the dating of a non-polar ice cores. The IDB1 is structured as a spatial database wherein the spatial information is defined by a couple of coordinates that identify a point in a non-polar glacier where ice cores were drilled. An existing database scheme has been adopted as a technical solution because one of the NextData project deliverables is to increase the interoperability between different paleoclimatic proxy data and meteorological data. The adopted DB scheme was created by the Norwegian Meteorological Institute, which designed an open database to store meteorological, hydrological and oceanographic data. This database, called the WDB (Water and Weather Database System, TNM 2012, http://wdb.met.no), has previously been used to improve the quality and effectiveness of IT systems for those types of data. The WDB architecture was selected also because the ice cores may be compared with weather stations. From a conceptual standpoint, these two entities can be represented by the same two principal aspects (fig. 18):

- *Geometry*: ice cores and weather stations may both geographically represented by a couple of coordinates, a punctual geometry in a GIS environment;

- *Data type*: Weather station and ice cores store the same type of data which is characterized by a numerical value with a parameter related to temporal information. Data from ice cores provide information about the past, whereas data from weather stations provide information about the current climatic system. They

WDB has been released according to the GNU General Public License and is completely configurable, customizable and sharable. According to these features and following the NextData policy about open and interoperability of data, the IDB1 is so structured from the WDB.

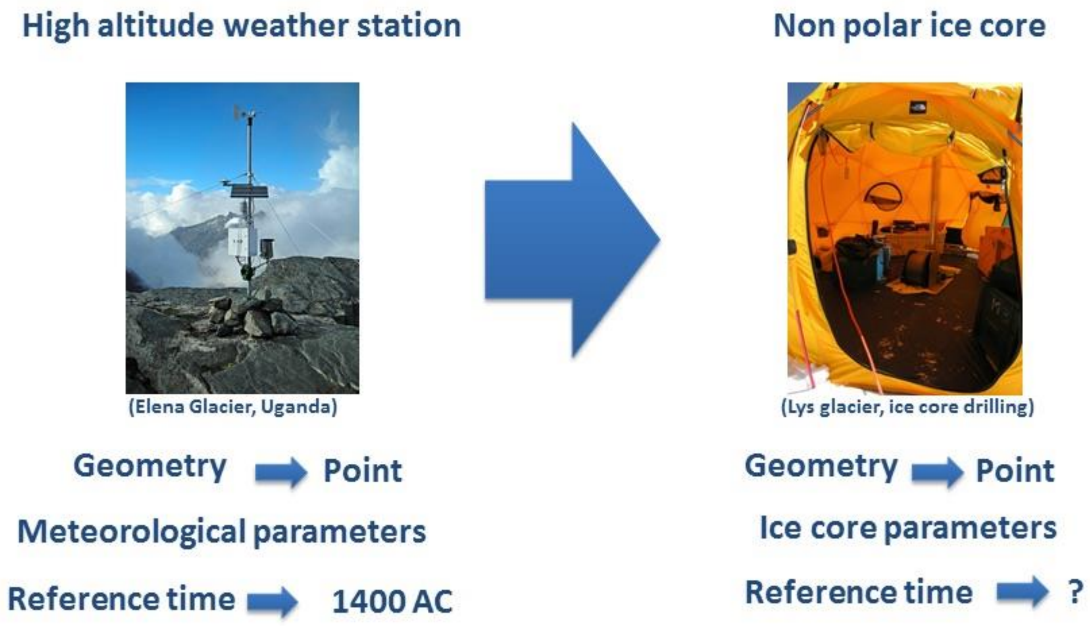


Figure 18 Comparison between weather station and non-polar ice core.

2.3 Ice core data structuration: the IDB1

An accurate study of WDB architecture was performed to identify the best method to archive information regarding data providers, ice core data and parameters. Three main areas of WDB were selected as central core of the IDB1: the first area comprises tables of parameters derived from chemical and physical ice core measurements. All the results of analysis accomplished on ice core can be archived in this area. It's the core area for paleoclimatology researcher and where the temporal information about the ice core dating is stored. The second area is tables to archived data providers' information, name of principal investigator of the ice cores. The third area is ice core tables, where some accessory data like ice core name, place name of drilling site and altitude were stored. The interaction between these table are represented by the '*floatvaluegroup*' table that is the place where unique combinations of ice cores, parameters and data providers ID were archived to retrieve information more quickly. In particular, IDB1 is composed by 5 tables (fig. 19):

- *Floatvalue*: ID of the 4 principal table of IDB,
- Ice Core: coordinates, drilling site name, ice core ID,
- *Dataprovider*: principal investigator or person who write the reference papers.
- *Parameter*: Name and measurement unit of all the parameter stored in IDB1,
- *Value*: raw numeric value end reference time of parameter.

The created geo-database is based on a relational model that allowed to identify main entities with their attributes and relationships between them. The peculiarity of this relational model is given by the interpretation of the numerical values, derived from chemical and physical characterization of ice cores. The observance of entities independence principles allows a better description of stored information and reducing redundancy (Mannino, M. V., 2007).

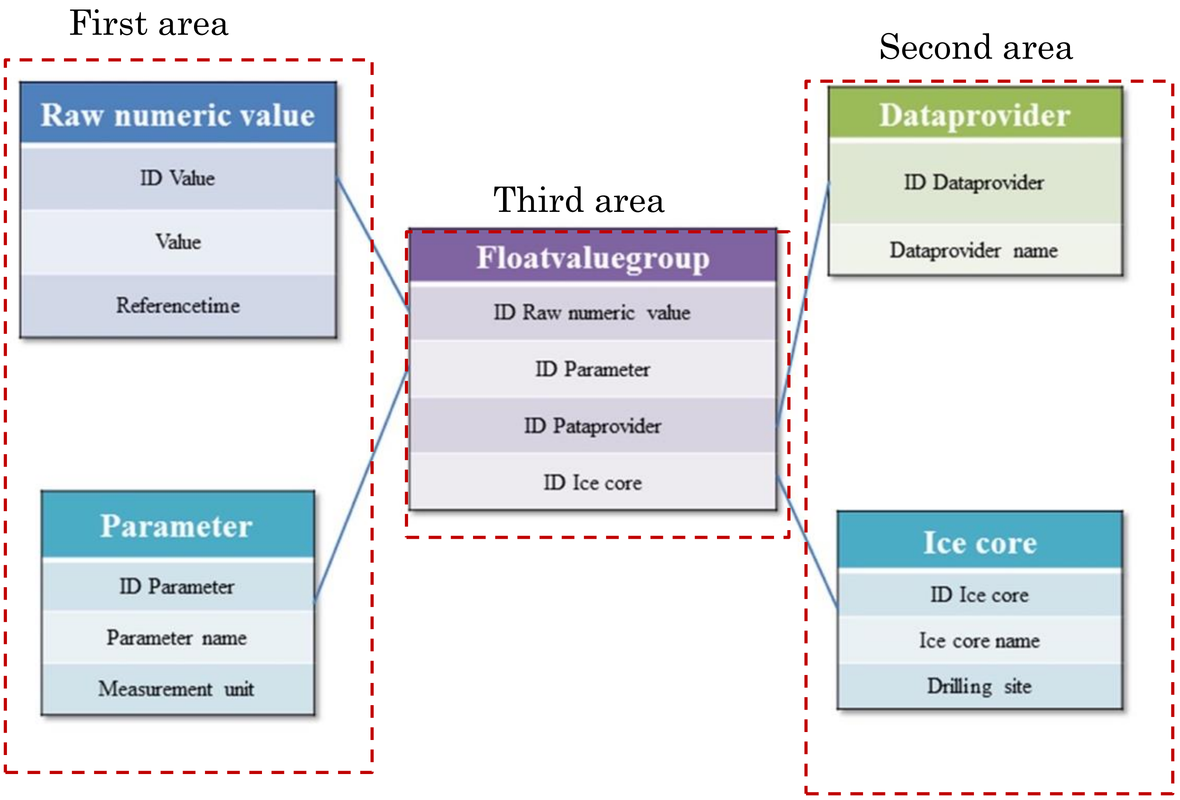


Figure 19 IDB1 conceptual scheme

WDB Structural adaptations

In general, the WDB have a very good initial structure for the development of an ice core archive, as described in the above paragraph. However, some adaptations were made to the open-source WDB code to increase its suitability for paleoclimatic ice core proxies.

Whereas chemical and physical parameters are considered identical in data from meteorological stations, paleoclimate data are completely different from weather data if the temporal factor is considered. In fact, the first network of meteorological measurements began in the second part of the XVIIth century thanks to the Medici family (*Camuffo D., et al., 2012*). Therefore, no weather data series starting before 1600 exist. Normally ice cores in our research domain, especially in HKKH region provide data at least for the last 2 kyr, in particularly in the Tibetan Plateau (*Delmas et al., 1992, Thompson et al.,1995*). For example, the Guliya ice core, which was drilled on the western side of the Tibetan Plateau, has a length of 309 m and data that extend back more than 120 kyr (*Yalcin K., 2003*). In the WDB, this structure was limited; data before 1400 AD cannot be inserted due to the informatics libraries used. The problem was fixed by managing the WDB source code to enable the storage of raw value of time. The code was modify changing the typology of the field in "*real*" where a very high value of character (number in our case) can be written.

A second important adaptation provide to the user to do a better data search experience. The capability to archive the geographic area where ice cores were drilled was added. Thus, a useful indexing can be performed to create a webpage with keywords that are useful for retrieving specific data.

Data

A total of 178 non-polar ice cores have been collected from 4 different sources. Amongst these cores, 52 are from the NOAA and NICL databases, 2 coming from the DISAT archive and 124 ice cores have been collected from the literature, georeferenced and stored in a geodatabase for the first time. The three ice cores from Pangaea were found after the compilation of IDB1 and so added in the IDB2 (cap.3). For 34 ice cores was found chemical and physical characterization that was upload in IDB1 (tab. 1). Before this work, no geodatabase with geographic and chemical/physical information on European ice cores was set-up. All coordinates for each ice core were obtained after a careful literature search and stored in the database according to the EPSG geodetic parameter registry 4326 (WGS 84) (http://spatialreference.org/ref/epsg/wgs-84/). However, several problems were found related to the accuracy of the spatial positions of the ice cores. For this reason, the geocoding of the spatial information of the ice cores are not always linked to the references where the ice core characterizations were found for two main reasons:

- Some coordinates found in the literature have poor accuracy, sometimes only the coordinates of the mountains summit where drilled glaciers are being found, just a dot in a topographic map drawn on paper at scale of 1:50.000 or worst 1:100.000;
- In some cases, no spatial coordinates were stored in the available databases.

This problem was resolve during the second year, developing and applying a reposition methodology for the non-polar ice cores (see paragraph 3.1).

Table 1 The 34 ice cores for which chemical and physical analyses are available. The first and second columns indicate the ice core name and drilling site, respectively. The last column contains the reference or the paper wherein the geographic positions were obtained.

Ice core name	Drilling site	Reference for spatial position
Bl2001 1	Belukha Glacier	Henderson K., 2006
Hsc1/Hsc2 huascaran	Col of Nevado Huascaran	Thompson L.G., 1995
Cdl03/1	Colle del Lys	DISAT database
Cdl96	Colle del Lys	DISAT database
Dasuopo c3	Dasuopu Glacier	Thompson L.G., 2000
Dasuopo c2	Dasuopu Glacier	Duan K., 2007
Dasuopo c1	Dasuopu Glacier	Thompson L.G., 2000
D-1/D-3 dunde	Dunde Ice Cap	Thompson L.G., 1990
Eric2002a/c	East Rongbuk Glacier	Xu J., 2009; Ming J., 2008;
Fedchenko c1/c2	Fedchenko	Aizen V., 2009
Fremont glacier 98-4	Fremont Glacier	Naftz D.L., 2002
Fremont glacier 91-1	Fremont Glacier	Schuster P.F., 2000, 2002
Guliya c7	Guliya Ice Cap	Yang M., 2006, 2000;
Guoqu c2	Guoqu Glacier	Grigholm B., 2009;
Lg1/lg2 kenya ice core	Kenya Lewis Glacier	Thompson L.G., 1979
Fwg kilimanjaro ice core	Kilimanjaro Furtwangler	Thompson L.G., 1979
Nif2/nif3 kilimanjaro	Kilim. Northern Ice Field	Thompson L.G., 2002
Sif1/sif2 kilimanjaro	Kilim. Southern Ice Field	Thompson L.G., 2002
Mount logan ice core	Mount Logan	NOAA database
Puruogangri c1/c2	Puruogangri Ice Cap	Thompson L.G., 2006
Quelccaya core 1	Quelccaya Ice Cap	Thompson L.G., 2013
Quelccaya core 2	Quelccaya Ice Cap	Thompson L.G., 1993
Sc-1	Sajama Ice Cap	Ginot P., 2010
Sc-2	Sajama Ice Cap	Ginot P., 2010
Inilchek c1	South Inilchek Glacier	Kreutz K.J., 2000
Eclipse icefield icecore 1	St. Elias Mountains	Yalcin k., 2007, 2003,2002

Loading data

The IDB1 is composed by three main areas in which the data about ice cores, data providers and parameters are archived.

Prior to loading the physical and chemical characterizations, so called the “raw numeric value” other data must be upload to configure the database. These data include information about the ice cores, data provider, and ice cores parameters. Then, the results of physical and chemical ice core analyses can be uploaded.

The uploaded data are described in the next sections:

- *“Ice core”*:

  The first data to be loaded in the IDB1 are the spatial position of the ice cores. In most cases, spatial information is obtained from the literature and reported as a set of coordinates for each ice core drilled in the same glacier because coordinates are often measured with poor precision and often refer to the drilling site rather than the specific location of a single ice core. Quality control was run on the coordinates using information retrieved from maps and images found in the literature. Some ice core locations or perforation sites that locate in rocky areas or off the glacier were repositioned with estimates of the most probable locations (flat area, ice covered area, not crevasses area). To respect topological rules while inserting the geographic data of ice cores into IDB1, the GIS operation *shift points* was applied. This function moves collocated points into a circle with a given radius (1 meter). A total of 178 points with ice core name and drilling site attributes have been stored.

  - *Data provider*:

    The data provider field identifies the person in charge of ice core drilling or the principal investigator who performed the analysis.

Twelve data providers are stored in the IDB1 (tab. 2). The data provider name in table 2 includes the corresponding authors of the paper wherein the ice cores characterization were published or the principal investigator of the ice core project.

Table 2 Data providers stored in the IDB1.

Data provider name	Ice core investigated
Aizen, V.B.	Fedchenko C1; C2
Eichler, A.	Bl2001-1
Grigholm, B.	Guoqu C2
Kaspari, S.	ERIC 2002 A
Kreutz, K.J.	Inilchek C1
Maggi, V.	Cdl03/1; Cdl96
Ming, J.	ERIC 2002 C
Osterberg, E.	Mount Logan PR Col Ice Core
Shuster, P.F.	Fremont 91-1; 98-4
Thompson, L.G.	Dunde D1; D3; Dasuopo C1; C2; C3; Fwg Kilimanjaro; Guliya C7; HSC1; HSC2; LG1; LG2; Nif2; Nif3; Puruogangri C1; C2; Quelccaya C1; C2; SC1, SC2; Sif1; Sif2
Yalcin, K.	Eclipse Icefield IceCore 1

- *Parameters*

The variable "*Parameter*" in the IDB1 identifies the characteristic or measurable factors of the values being parameterized. Parameters provide a definitive description of what the data represent, including chemical and physical properties. Ice cores contain many proxy parameters that help scientists to reconstruct past climate. For example, in the chemical analysis, the concentrations of atmospheric trace gases, such as nitrous oxide (N_2O), methane (CH_4) and carbon dioxide (CO_2), provide information about natural variations and manmade changes in atmospheric composition (*IPCC, 2007*). After an accurate investigation into the main physical and chemical factors, 80 parameters with their corresponding units of measurement were selected (tab.3, the complete list is reported in Appendix A). To standardize data, a JUPAC name for chemical value and SI (International System of Units) units for physical parameters was assigned. However, the same parameters for different ice cores are occasionally expressed in different measurement units to avoid conversion from the published data values. At the end of this investigation, the data were stored in the IDB "parameter name" table (tab. 3).

Table 3 List of some parameters and measurement units in the IDB.

Parameter name	Measurement unit
$\delta^{18}O$	per mil
Calcium	Ppb
Chloride	Ppb
Ammonium	Ueq/L
Cerium	Ppb
Conductivity	µS per cm
Fluoride	Ppb

- *Raw numeric value:*

  To upload all the 300000 numeric value founded for the 34 ice cores that have the chemical-physical characterization, an automatic procedure was developed using SQL language. Functions were built to control the data that will be inserted into the database to avoid redundancy and other errors. After the data were specified, a descriptive statistic about the type of data upload was performed. $\delta^{18}O$ is the most common parameters (4%) in our database, furthermore 52% are related to the physical variables and 45% are chemical parameters. In the near future, further measurements taken from continuous flow analysis (CFA) systems, mass spectrometry systems, ion chromatography and Coulter counters, made in the EuroCOLD Laboratory of the University of Milano-Bicocca, will be added to IDB1.

2.4 Dissemination

Sharing data via web by the Open Geospatial Consortium

To easily sharing data, it was chosen to archive and disseminate metadata in the NextData Geonetwork portal (http://geonetwork.nextdataproject.it/), a system for climate and paleoclimate metadata sharing (*Melis M.T., et al., 2014*) (fig. 21).

Metadata have been archived following a Parent/Child hierarchical structure (fig. 20). Metadata were structured as follow:

- *Project domain* (first parent) contains information about the perforation project such as: scope-work of the project, geographic region and point of contact of principal investigator.
- C*ampaign domain* (first child - second parents) contains information about Drilling campaign. This entity has to contain the name of the campaign of perforation, the reference time, the drill methods and the ice cores number taken from each extraction.
- *Ice Core domain*. It contains: ID of the Core, abstract of the principal paper wrote about the ice core, information about the point of contact and the spatial information.

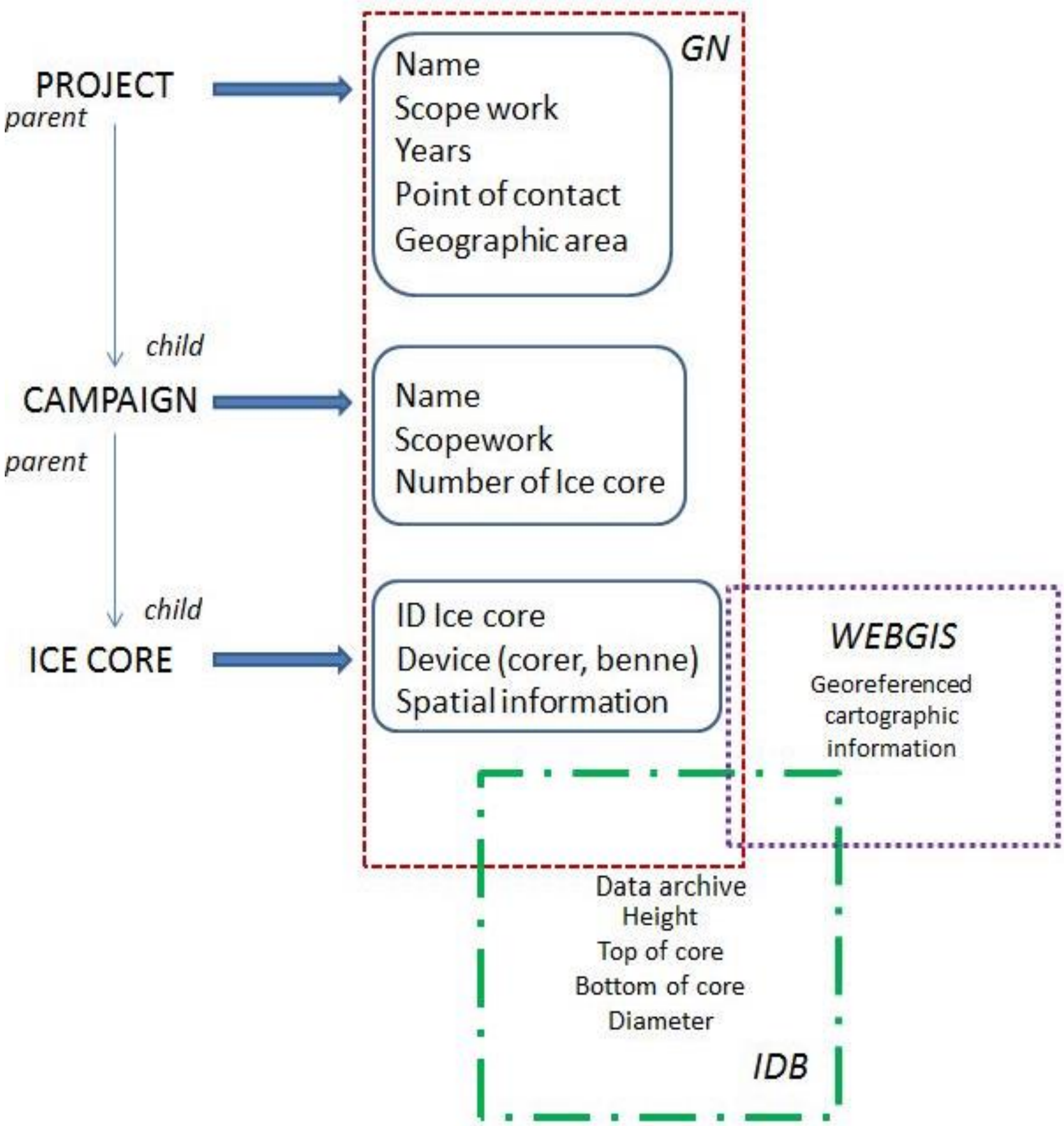


Figure 20 Hierarchical structure for data/metadata archived in Geonetwork (GN) NextData portal and interaction between GN and the IDB database and the webgis developed.

AGGREGATE RESULTS MATCHING SEARCH CRITERIA : 9

ECLIPSE ICEFIELD PERFORATION PROJECT
Abstract A 160 m ice core (Core 1) was recovered from Eclipse Icefield, St. Elias Mountains, Yukon, Canada, (60.51°N, 139.47°W, 3017 m elevation) in 1996. Two additional cores, 345m (Core 2) and 130m (Core 3) ...more...
Keywords Icecore;, Eclipse Icefield; St. Elias Mountains; Canada

ECLIPSE ICEFIELD FIRST PERFORATION
Abstract A 160 m firn and ice core was recovered from Eclipse Icefield (60.510 N, 139.470 W, 3017 m elevation) in the summer of 1996. Visible stratigraphy (location and thickness of ice layers) and density me ...more...
Keywords Perforation, Eclipse Icefield,, Eclipse Icefield; Perforation; St. Elias Mountains; Canada

ECLIPSE ICEFIELD SECOND PERFORATION
Abstract Two Icecores (345 m and 130 m) were recovered in 2002, 100 m up the flow line from the 1996 drill site. All two cores were sampled continuously at high resolution for major ions and stable isotopes t ...more...
Keywords Icecore; Eclipse Icefield; Second perforation, Eclipse Icefield; St. Elias Mountains; Canada

ECLIPSE ICEFIELD FIRST ICECORE
Abstract A 160 m ice core was recovered in June 1996 from Eclipse Icefield (60.51 degrees N, 139.47 degrees W, 3017 m elevation). Visible stratigraphy (location and thickness of ice layers) and density measu ...more...
Keywords Eclipse Icefield Ice Core; Core Accumulation; Stable Isotope; Major Ion Data, Eclipse Icefield; Ice Core; St. Elias Mountains; Canada

ECLIPSE ICEFIELD SECOND ICE CORE
Abstract Icecore 345 m was recovered in 2002, core was sampled continuously at high resolution for major ions and stable isotopes to establish a detailed chronology for the core. Sample resolution ranged from ...more...
Keywords Icecore; Eclipse Icefield; Second perforation, Eclipse Icefield; St. Elias Mountains; Canada

ECLIPSE ICEFIELD THIRD ICE CORE
Abstract Icecore of 130 m was recovered in 2002, 100 m up the flow line from the 1996 drill site. The core was sampled continuously at high resolution for major ions and stable isotopes to establish a detaile ...more...
Keywords Icecore; Eclipse Icefield; Third Ice core, Eclipse Icefield; St. Elias Mountains; Canada

Figure 21 Example of metadata available for ice cores archived in geonetwork NextData portal.

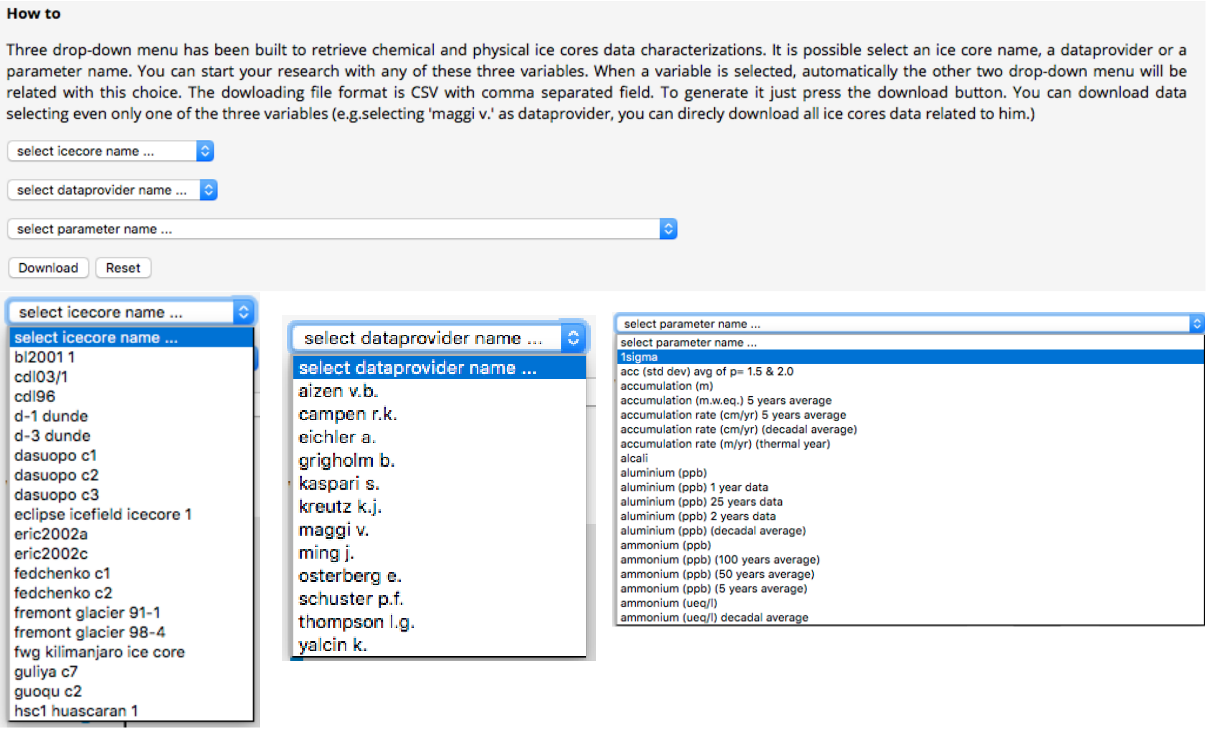
To enable ice cores data sharing, a web platform was also developed on the Geomatic Laboratory server of the Environmental and Earth Sciences Department of the University of Milano-Bicocca. The working environment is based on open-source structures in accordance with the NextData policy.

A web map service (WMS) and web feature service (WFS) based on Open Geospatial Consortium (OGC) services was created using Geoserver software (http://geoserver.org/). The OGC standards offer a method to share geospatial information and metadata, with multiple applications increasing their interoperability. The web portal is equipped with a webGIS built with Leaflet (http://leafletjs.com/), in which ice cores are visualized spatially with their attributes. A visual interface for downloading data was developed inside the web portal. To achieve this goal, two different access keys have been implemented:

I) A query system realized in the web page (fig. 23): A form was built to retrieve chemical and physical characteristics of ice cores. Data can be searched through three main keys*: ice core name, data provider* and *parameter name*.

II)Searching ice core from its spatial position (fig. 22);

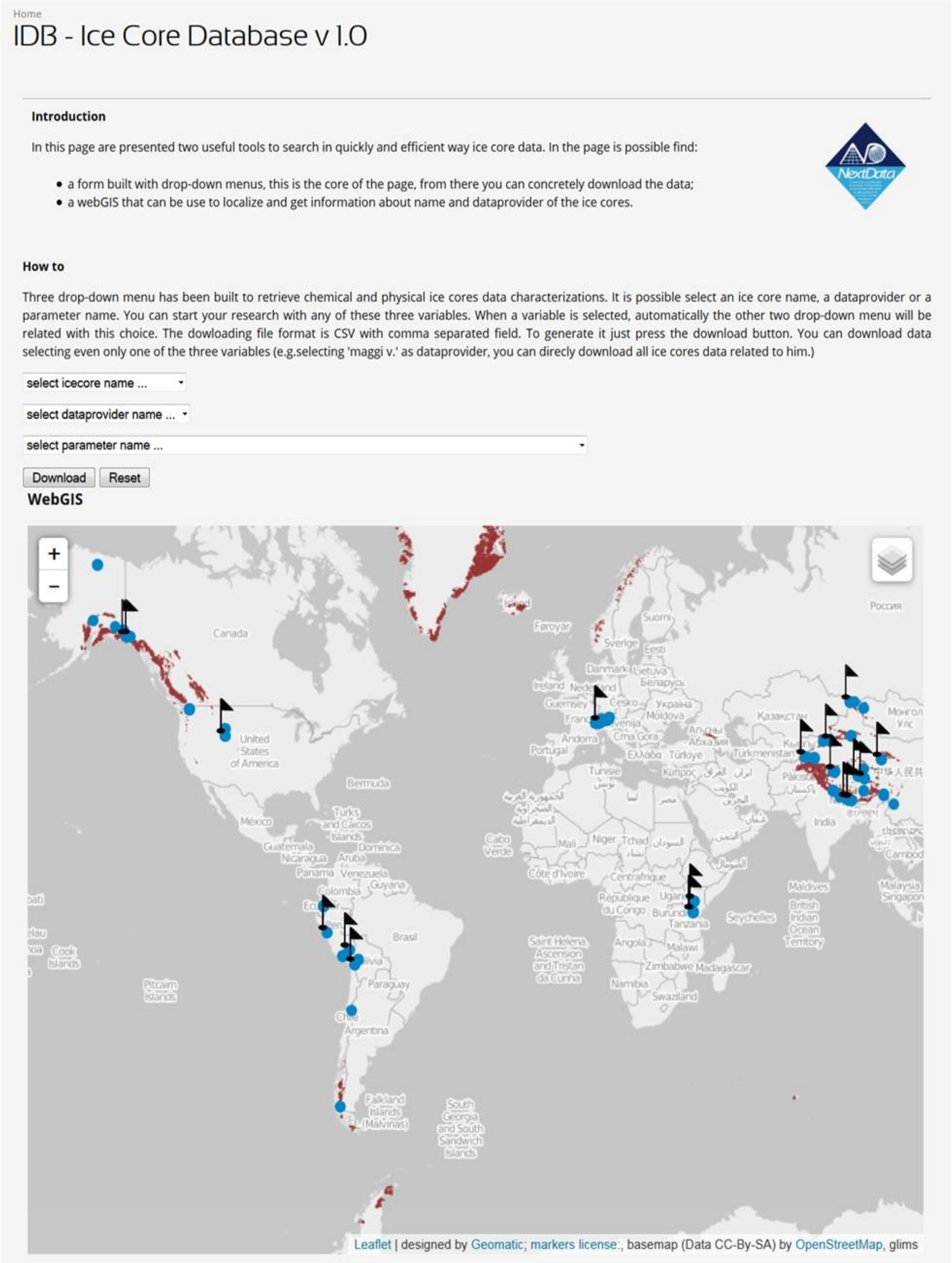
In addition, the connection to PostGIS layers from a GIS client (Quantum GIS) allows expert users to execute spatial queries, such as geoprocessing operations. All this work was done with the technical support of dr. Strigaro.



How to

Three drop-down menu has been built to retrieve chemical and physical ice cores data characterizations. It is possible select an ice core name, a dataprovider or a parameter name. You can start your research with any of these three variables. When a variable is selected, automatically the other two drop-down menu will be related with this choice. The dowloading file format is CSV with comma separated field. To generate it just press the download button. You can download data selecting even only one of the three variables (e.g.selecting 'maggi v.' as dataprovider, you can direcly download all ice cores data related to him.)

Figure 22 Form built to retrieve chemical and physical characteristics of ice cores. Data can be searched through three main keys: ice core name, data provider and parameter name.



IDB - Ice Core Database v 1.0

Introduction

In this page are presented two useful tools to search in quickly and efficient way ice core data. In the page is possible find:

- a form built with drop-down menus, this is the core of the page, from there you can concretely download the data;
- a webGIS that can be use to localize and get information about name and dataprovider of the ice cores.

How to

Three drop-down menu has been built to retrieve chemical and physical ice cores data characterizations. It is possible select an ice core name, a dataprovider or a parameter name. You can start your research with any of these three variables. When a variable is selected, automatically the other two drop-down menu will be related with this choice. The dowloading file format is CSV with comma separated field. To generate it just press the download button. You can download data selecting even only one of the three variables (e.g.selecting 'maggi v.' as dataprovider, you can direcly download all ice cores data related to him.)

WebGIS

Leaflet | designed by Geomatic; markers license:, basemap (Data CC-By-SA) by OpenStreetMap, glims

Figure 23. The IDB1 query system and webgis used in http://geomatic.disat.unimib.it/idb. Blue points are the locations of the ice cores, black flags indicate the ice cores with characterizations available, and red indicates the GLIMS polygons upload. Clicking on ice core a pop-up with ice core name and other info will be open. By using that information it will be possible search and download the ice core characterization.

2.5 Conclusions

A database structure to store and share data from chemical and physical analyses of ice cores is proposed. This database is the first attempt to build up a geodatabase in which raw numeric values, derived from measurements of ice core samples, are stored at least at knowledge of writer. Unlike other databases or repository such as: Pangaea, NICL, NCDC, the IDB1 allow user to search a specific chemical or physical value starting from the name of the data provider, the name of parameter wanted or from the name of the ice core. This approach is essential to enable rapid data searching and quick comparisons between different ice cores. The spatial information of ice cores archived in the IDB1 will also be used to determine the location of glaciers suitable for ice-core drilling. By using different statistical and probabilistic methods, such as the Weight of evidence (WoE) modelling technique or spatial multi-criteria evaluation, the spatial distribution of the ice cores can be related to the spatial distribution of geological and morphometric variables (lithology, slope, aspect, internal relief, etc.) of drilled glaciers. The combination of this information could be used to estimate the probability of finding potential new drill sites. To make this challenge possible, the highest possible accuracy of geographical information is required. To obtain that accuracy, a repositioning methodology of already drilled ice cores will be developed to overcome the problems associated with the poor accuracy of geocoding highlighted before. The data storing and sharing structure from the database to the webgis application are released under a GNU license; thus, this structure can be customized and shared without limitations. In particular, through the development of the webgis application, it is possible to share environmental datasets and provide easy access for users lacking GIS knowledge. This database is a first step towards a more complete geodatabase containing not only missing data from other non-polar ice cores but also the spatial distribution of the glaciers and other parameters useful in evaluating glacier dynamics and glacier response to climate change. Another NextData goal is to use the IDB1 to investigate climate variability over the last 2 kyr over northern Italy through multi-proxies' analysis so, IDB1 could be also the first step toward building a larger paleoproxy database to store and share data from ice cores, marine cores, pollen and tree rings.

3 FROM ICE CORE DATABASE TO GLACIOLOGICAL SPATIAL DATA INFRASTRUCTURE

3.1 ICE CORE AND GLACIERS DATABASE (IDB2)

IDB1, as describe before, is an adequate structure to satisfy the NextData requirements: to create a system of archives and portals, connected through a General Portal, to access and disseminate environmental measured data and, in particular for me, to create a structure to access and disseminate ice cores proxy data. IDB1 is suitable to archive chemical-physical raw data usable as proxy data and to conduct paleoclimatic analysis, but, it does not satisfy all the requirements that a glaciological spatial data infrastructure must have to assess the glaciers response to the climatic fluctuations such as stored different level of territorial data e.g. location of perforation site, geomorphic parameters about perforated glaciers and so on.

In general, IDB1 shows weaknesses to archive all the necessary data due to the constraint of use an existing structure (WDB) designed for store meteorological data.

In particular:

- Is not suitable to store information such as validation of measurements and spatial and temporal distribution as indicate by Bradley (*1999*) to evaluate the spatial validity of a proxy.
- Is not suitable to store different level of territorial data and accessory data for each ice cores.
- Is not possible relate the Ice core to any glacier nor as a simple association, nor by territorial point of view.
- Low accuracy of spatial positioning due to the low precision of found or supplied data.

To overtake the previous critical issues, a new structure called *Ice core and glacier database* (IDB2) with some improvements was set-up.

In particular:

- Different entities with information about project of perforation, drilling-site, references of data and additional information about ice core were added.
- The accuracy of coordinates of the ice cores was increased by applying repositioning methodology developed during the second year of Ph.D.
- Ice cores were linked with glaciological databases containing spatial information about glaciers such as geomorphometric data and other several information about the drilling site.
- New entities were added to store data coming from geomorphological analysis carried out on glaciers and in particular to archive the flow lines of the glaciers.

Last, the Creative commons licenses (Creative Commons, 2001) was chosen to determine the copyrights of data.

All these improvements are described in detail in the next section of this chapter.

3.1.1. Ice core and glacier database (IDB2) structure

About the general structure: IDB2 is composed of seven logical entities; project, drilling, ice core, ice core data, references, glacier code and glacier data. These are linked each other and some of them are primary linked with the Ice core tab (fig. 24).

In this structure definitions of project, drilling respectively are (fig. 25):

- Project: union of administrative, financials, technical and scientific components for study one or several sites.
- Drilling: campaign suitable for the collection of one or more cores in the same site or in a different site a short period of time (seasonality dependences).

In particular, the entities are:

1. *Ice core*: Is the principal entity, the spatial information and the accessories parameters (tab. 4) about ice cores are archived.
2. *Project:* Is the parent entities in which are stored all data about perforation project such as the founding institution, the year of reference and the project name.
3. *Drilling:* Contains the geographical information about the drilling site and offers the possibility to link the drilling location with other geodb related to glaciers such as GLIMS, WGI, WGMS, RGI or any vectorial geodb useful to archive and share glaciological data.
4. *References:* stores all the references for papers were data or metadata about ice cores comes from.
5. *Ice core data:* Is the entity that stores the parameter and the raw numeric value of the chemical-physical characterization of each ice core.
6. *Glacier code* and 7. *Glacier data* will be described in the section 3.1.4.

Every one of these entities are composed by different numbers of tables to respond at the technical requirements to build a spatial database structure. Different table are linked each other with primary or foreign keys that allows a quickly answer at the query submitted by researcher or experts. The complete scheme of the structure of the database is reported in Appendix B. As examples of data stored in IDB2, the most significant tables and parameters with examples for some European ice cores are reported in Appendix C.

This geodb was built on PostgreSQL. PostgreSQL, is an open source object-relational database management system (ORDBMS) with an emphasis on extensibility and standards compliance. It is released under the PostgreSQL License, a free/open source software license. PostgreSQL have a spatial tool called PostGIS. PostGIS is an open source software program that adds support for geographic objects in PostgreSQL.

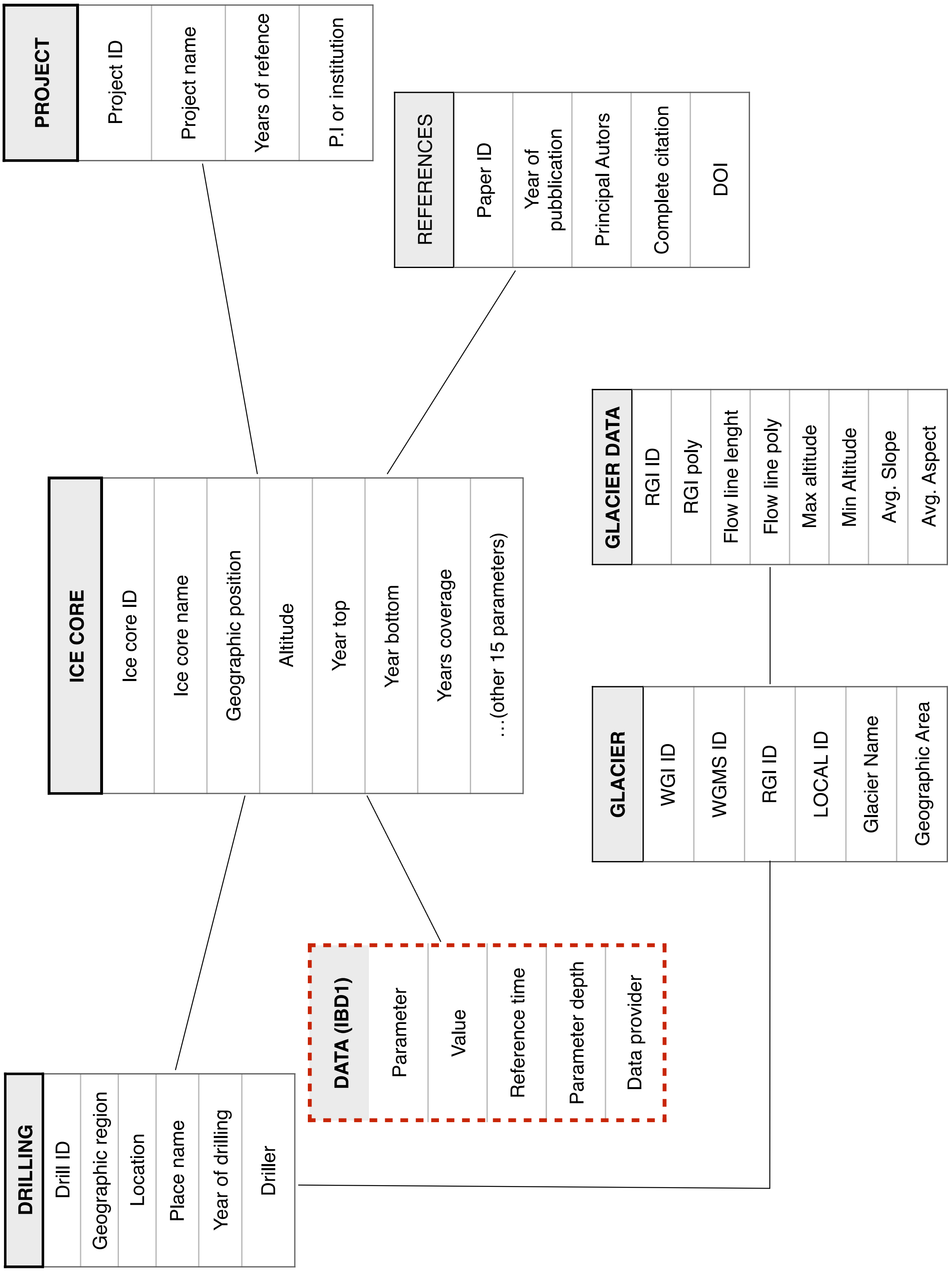
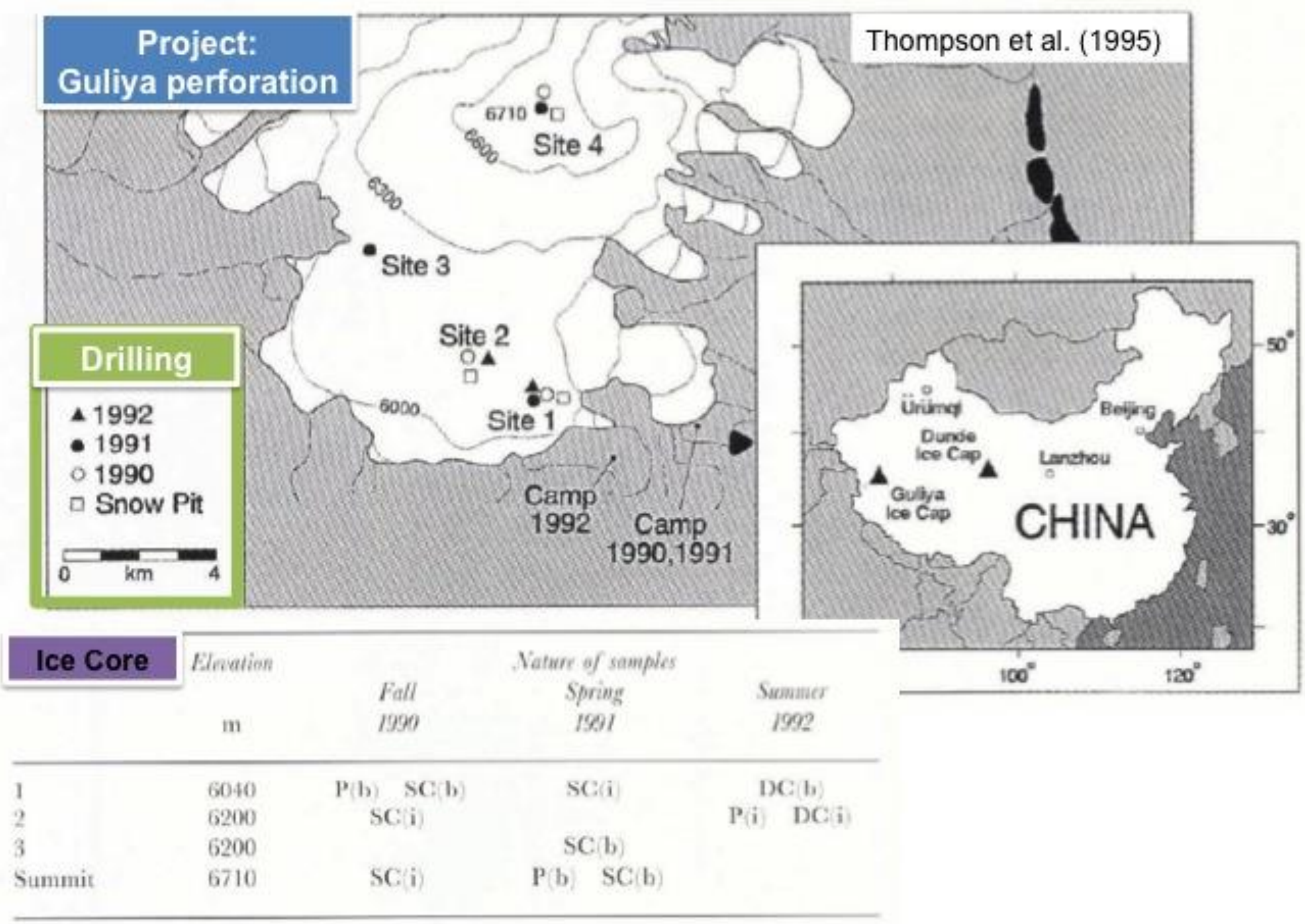


Figure 24 IDB2 conceptual scheme. With dotted contour the table DATA (the oldest IDB1) is highlighted.



	Elevation m	*Nature of samples* *Fall* *1990*	*Spring* *1991*	*Summer* *1992*
1	6040	P(b) SC(b)	SC(i)	DC(b)
2	6200	SC(i)		P(i) DC(i)
3	6200		SC(b)	
Summit	6710	SC(i)	P(b) SC(b)	

Figure 25 Example of definition of project, drilling and ice cores from Guliya glacier Himalaya: one project (Guliya perforation) with three different drilling, 1990-1991-1992 in three different locations of the Guliya glacier taken a total of 8 ice cores. Modified from Thompson L.G., et al., 1995

Ice core additional information

For every census ice core some additional spatial and characterizing data and metadata were searched, as well as coordinates and references paper. Geographic area of drilling site, altitude of drilling site, year of drilling, length of the core and core diameter, method of drilling, drill fluid, principal investigator, affiliation research centre or university are the principal parameters searched for every core and archived in the dedicated entity (*Ice core*) IDB2 (tab. 4).

Table 4 A complete dataset for an ice core data and metadata searched in literature, 20 unique parameters filled with data and metadata create a complete identification for all the 182 ice cores. E.g.: Ice core of Colle del LYS.

Ice Core ID	CL0300751E04555NC31
Ice Core Name	CdL 03/1
Geographic Area	Alps Monte Rosa, Swiss Alps
Place name of Drilling site	Colle del Lys
Longitude in literature	7°51'32.73"E
Latitude in literature	45°55'7.78"N
Repositioned longitude	7,859091670
Repositioned latitude	45,918800000
Reposition class	4
Altitude (m. a.s.l.)	4248
Year Drilled	2003
Bottom of Core (m)	102,38
Top of Core (m)	0
Core Diameter (cm)	9,8
Samples Taken to Date	No value
Source	DISAT
Method of drilling	Electromechanical
Drill Fluid	Dry
Original Principal Investigator	V. Maggi
University or Affiliation	DISAT, UNIMIB, Milano

3.1.2. Repositioning methodology

IDB2 was thought as a spatial database where the geographical information is defined by a couple of georeferenced coordinates that identify the exact point inside a non-polar glacier where the ice cores were taken. All coordinates for every single ice core have been obtained after careful literature research and are stored in the database in longitude/latitude with WGS84 datum (EPSG 4326). Due to the precision of the coordinates found in literature, an accuracy problem is emerged. Sometimes only the coordinates of the mountain summit where drilled glacier is, were found. Some time was found just a dot in a topographic map drawn on paper at scale of 1:50.000 or worst 1:100.000. This problem has been evaluated and a reposition methodology has been created. The reposition methodology is based on DEMs, orthophoto and figures find in papers and work was done in GIS environment.

As said in papers or in official reports a map or morphological information that show the location of perforation or the exact point where ice cores were taken can be found. Using the contour line tracks on maps, if available, the altitude reported on papers or some particular elements of the drilled glacier such as, peaks, ridge, depression and so, it was possible, by DEMs and orthophoto GIS analysis to extract the most probable point or drilling area. Five different repositioning class were set-up in accordance with the accuracy that can be reach by the repositioned coordinates (tab. 5). For ice core that was not repositioned (class 0), the coordinates find in literature was reported in the geodb. To repositioning ice cores for class 1,2 and 3, a ASTER-GDEM-Ver.2 was used in association with maps and information recovered by papers and official reports. ASTER-GDEM-Ver.2 was chosen as global DEM because it is suitable for the compilation of topographic parameters in a glacier inventory thanks to the average differences from the elevation values from different global DEM (STRM, GLSdem, GLOBE) that are not larger than

±7 m which is in the same order of magnitude than the vertical accuracy of these DEMs (*Frey P., et al., 2012*).

Table 5 Description of the four repositioning class identify and number of ice cores for every class.

Reposition accuracy	***Reposition based on***	***Number of repositioned ice cores***
0	*No repositioning.*	***25***
1	*No map, no topography of the area, repositioning made with altitude or choosing most probably point.*	***26***
2	*Location map of the perforation found in a paper, map is not detailed, there is one point for several ice core.*	***38***
3	*Detailed map of the location of the cores found in papers.*	***73***
4	*Found GPS coordinates*	***23***

Two example of reposition class 2 (fig. 26) and 3 (fig. 27) are reported below. The reposition methodology allowed an increase of accuracy useful for the spatial analysis based on ice core or drilling site position such as the determination of the suitability of mountain glaciers for ice core drilling (Garzonio R, 2016). This methodology permitted also to increase the ice cores which may be spatially associated with their perforated glaciers as shown in the next paragraph.

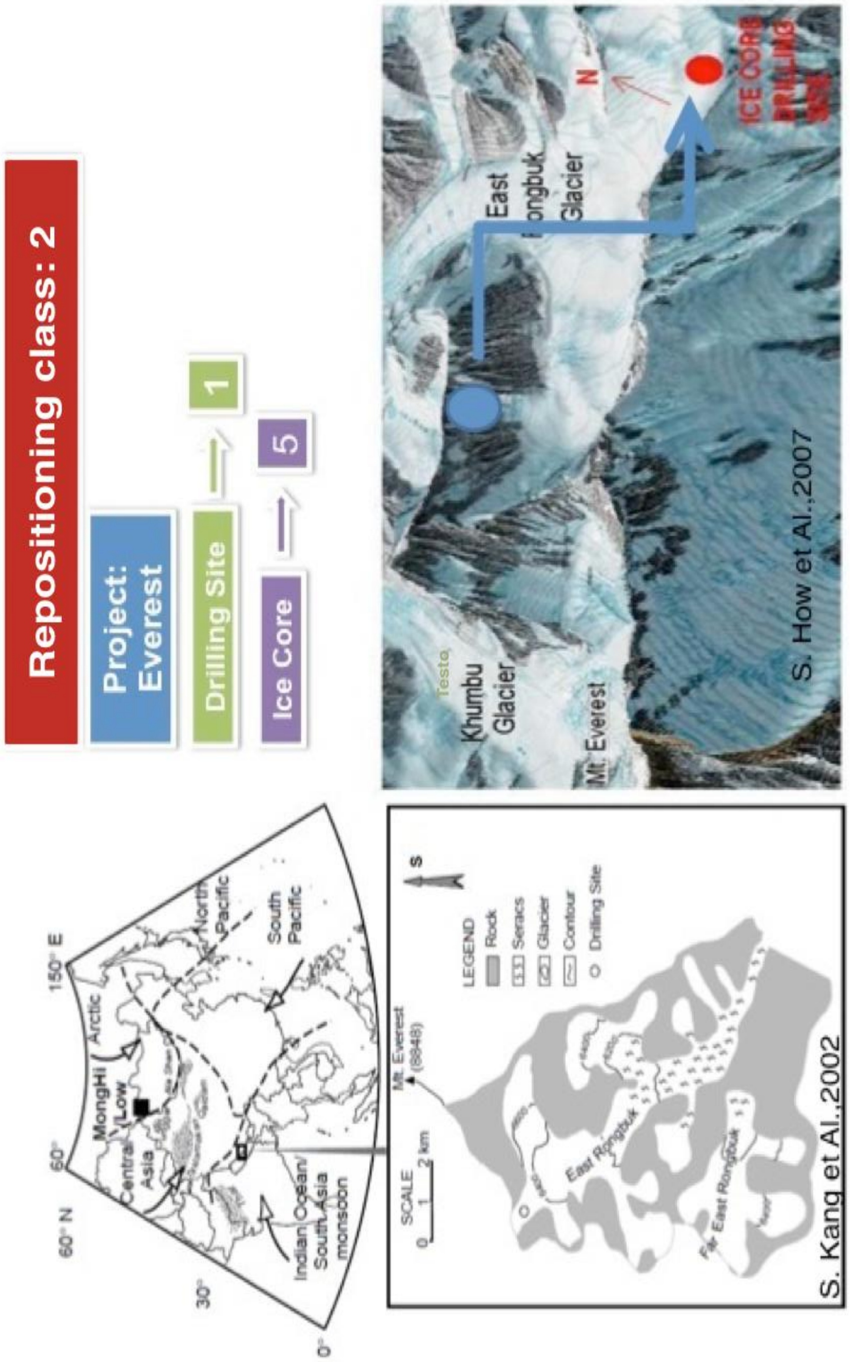
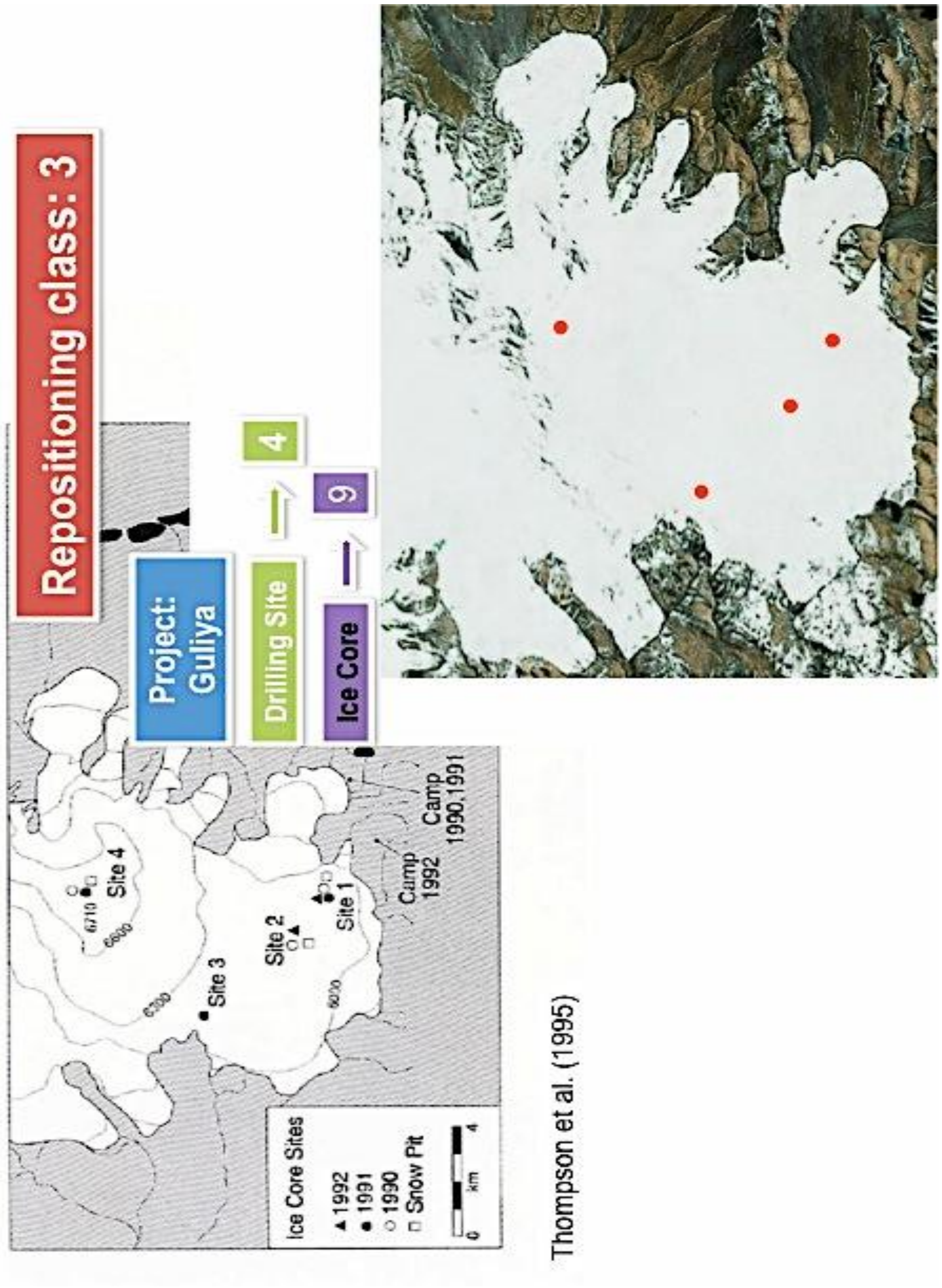


Figure 26 Reposition class 2: From one point falling on the rocks, the blue dot derived from literature (Kang et Al.,2002), to one point, red dot, in the exacting drilling site. Repositioning was possible using maps found in the same and other paper (Hou et Al. 2007).



Thompson et al. (1995)

Figure 27 Reposition class 3: For 9 ice core drilled in Guliya glacier (Himalaya), was possible find only a couple of coordinates. Using maps find in Thompson et al., 1995, was possible identify each single location to the 9 ice core and repositioned their position.

3.1.3 Ice core and Glacier association

To permit a better classification of the ice cores, to offer the possibility to recover data such as area, perimeter, slope, orientation of the glaciers body where ice cores were taken or to execute analysis on the entire glacier body, a spatial association between ice cores stored in IDB2 and glaciological geodatabase were accomplished. The association between ice cores and glaciers was made by a spatial join between the geometries of different databases. The spatial join algorithm computes the distance between the ice cores (point) and the glaciers (polygons). Ice core were considered drilled in a glacier when the distance between point and the nearest polygon is less then 200 m. This threshold was chosen after an accurate evaluation. The 200 m of threshold is due to the temporal acquisition discrepancy between ice cores point and glaciers polygon, in general ice cores were draw some year or decades before the acquisition of glaciers boundary by the inventory which are used for this purpose.

Geodatabase chosen for the application of proposed methodology store mainly geomorphological data about glaciers. The geodb used are:

- World Glacier Inventory (WGI, *updated 2012*): contains information for over 133000 glaciers. Inventory parameters include geographic location, area, length, orientation, elevation, and classification. The WGI is based primarily on aerial photographs and maps with most glaciers having one data entry only. Hence, the data set can be viewed as a snapshot of the glacier distribution in the second half of the 20th century. It has a punctual geometry.

- Randolph Glacier Inventory (RGI 5.0, *updated 2015*): is a global inventory of glacier outlines (polygonal geometry). It is supplemental to the Global Land Ice Measurements from Space initiative (GLIMS). Production of the RGI was motivated by the forthcoming Fifth Assessment Report of the Intergovernmental Panel on Climate Change (*IPCC, 2013*). In version 5 there are 176091 glaciers polygon archived.

- Global Land Ice Measurements from Space GLIMS (*GLIMS, updated 2015*): is an international collaborative project that includes more than sixty institutions world-wide: its goal is to create this globally comprehensive inventory of land ice including measurements of glacier area, geometry, surface velocity, and snow line elevation (polygonal geometry). To perform these analyses, the GLIMS project uses satellite data, primarily from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) and the Landsat Enhanced Thematic Mapper Plus (ETM+) as well as historical information derived from maps and aerial photographs. In the latest version of GLIMS (07/28/2015 there are 136135 glaciers polygon archived).

- World Glacier Monitoring System WGMS (*WGMS, updated 2014*) provides standardized observations on changes in mass, volume, area and length of glaciers with time (Fluctuations of Glaciers), as well as statistical information on the distribution of perennial surface ice in space (World Glacier Inventory). It has a punctual geometry and stored data of 3538 glaciers. In addition, information on special events (e.g., surges, calving instabilities, ice avalanches, lake outbursts) is available. All data and information is freely available for scientific and educational purposes. The use requires acknowledgement to the WGMS and/or the original investigators and sponsoring agencies according to the available meta-information.

In the entity of the database that stores the union (tab. 6) it was also decided to insert the local id (coming from WGI dataset), the glacier name and the geographic area of the glacier. This table will be linked to the *DrillingTab* where the information about the perforation site are archived.

Table 6 : Id association between ice cores and glacier

Ice core	Ice core id	wgi_id	rgi id	glims_id	wgms	Glacier Name
Muztagat 1	MN0107506E03817NIC1	CN5Y663E0009	RGI3213.05994	G075079E38288N	5Y663E0008	Kematulejia
PZ02/1	PZ0200956E04622NPZ1	CH4J14322004	RGI3211.01946	G009927E46382N	None	Morteratsch

Thanks to repositioning methodology developed and described, it was possible find a spatial correlation with the perforated glacier for 176 ice cores of 185 ice cores upload in the infrastructure. Before that, only for 124 ice cores was possible find a spatial correlation with the perforated glaciers.

3.1.4 Glacier association

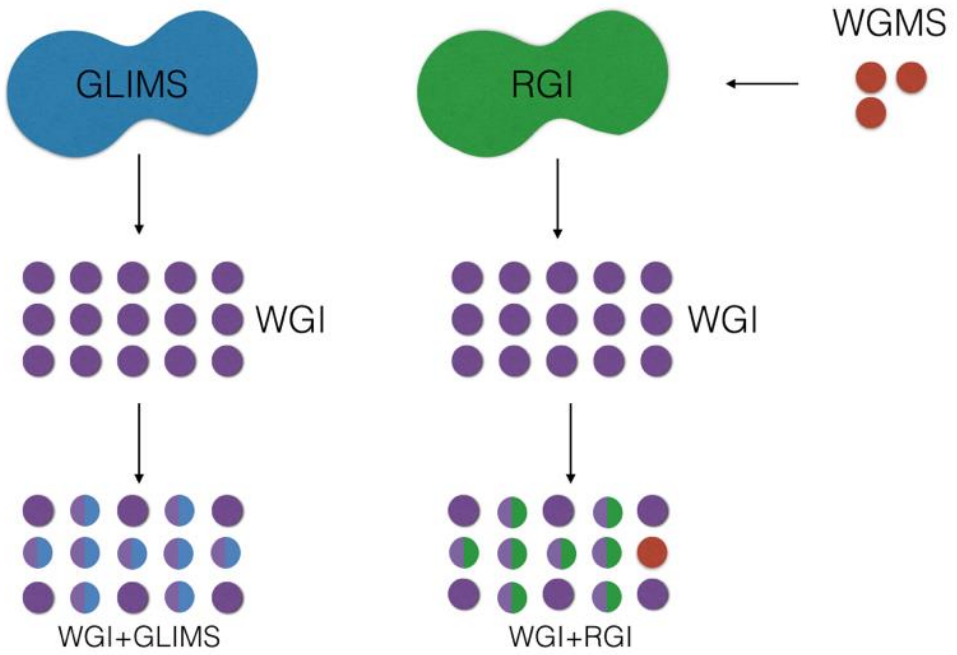
To increase the strength of IDB2 two entities about glaciers called *Glacier Code* and *Glacier Data* were added.

- *Glacier Code:* stores the union between the different glaciers databases. WGI, RGI, GLIMS, WGMS identification code for each perforated or not perforated glaciers were joined with a spatial analysis. The results were added to the IDB2 in a dedicated entity that contains 132890 glaciers. At the beginning it was decided to use a normal association between the different databases based on the name of the glaciers but several problems occurred due to the different name by archive used for the same glaciers, name is not a unique element and it can change State by State or archive by archive. So it was evaluated that the best procedure was join the same glacier contained in different archive using a spatial association by a spatial join tool available in QGIS software. Spatial join operation is used to combine two or more datasets with respect to a spatial predicate. The predicate can be a combination of directional, distance, and topological spatial relations. In the case of non-spatial joins, the joining attributes must be of the same type, but for spatial joins they can be of different types. Usually each spatial attribute is represented by its minimum bounding rectangles (MBR). To conduct the spatial join, the WGI was choose as reference layer for the main reason that is the one that contains the greatest number of geometries. First operation was check how many RGI polygons include the WGI points. With this operation it was possible join the RGI ID of glaciers at the WGI parameters. GLIMS was associated with the WGI with the same analysis of RGI. Different was for WGMS. WGMS is also a punctual database such as WGI and it is not possible conduct a spatial join between two punctual geometries. So it was decided to join WGMS at RGI already join at WGI. At the end two different table was created, the first one contains the join between WGI and (RGI +WGMS) and the second table that contain the join between WGI and GLIMS. From this two tables a third table was created to obtain the association between WGI, RGI GLIMS and WGMS.

The WGI, RGI, GLIMS and WGMS databases take in account data coming from different source and different years, so it was impossible join all the glaciers of one database with the others. (fig. 28).

- *Glacier Data entity* contains the geomorphological parameters such as Flow line length, min and max elevation, average slope and aspect calculate using the GlaciersDataModule (explain in the chapter 4). This entity will be better explained in the paragraph 4.4.

These two entities, the *Glacier code* and the *Glacier data* just explained were used to obtain data to create a suitability map of drillable glacier *(Garzonio R., 2016*) and data from glacial modelling to predict a retreatment curve for glaciers of the Greater Alpine Region (GAR) in the next century (*Moretti* M., 2016) (two goals of NextData project).



wgi_id	glims_id	rgi id	wgms id	Glac name
CN5Y663E0009	G075079E38288N	RGI3213.05994	5Y663E0008	Kematulejia
CH4J14322004	G009927E46382N	RGI3211.01946	None	Morteratsch

Figure 28 Glaciers association, methodology and results.

3.2 Results

A total of 185 different ice cores were found (fig. 29) from 5 different sources, NOAA-NIDC database, NICL table, PANGEA database, DISAT repository and scientific literature. Of these 185, 52 ice cores come from NOAA and NICL, 3 from PANGEA, 2 from DISAT repository and 128 are new georeferenced and first time stored ice cores (fig. 30). To identify this ice cores a total of 56 project and 98 drilling site table were compiled (tab. 7) with requested information and a list of 116 papers were added and linked as references. The ice cores characterization values are the same already uploaded in IDB1.

Table 7: Summary of Project, Perforation and Ice cores found. Numbers in parentheses shown new ice cores never censed for each geographic region.

	Project	***Perforations***	***Ice cores***
America	20	27	61 (35)
Europe	9	29	44 (41)
Africa	2	2	8(0)
Asia	24	39	69 (51)
Oceania	1	1	3(3)
TOT	***56***	***98***	***185***

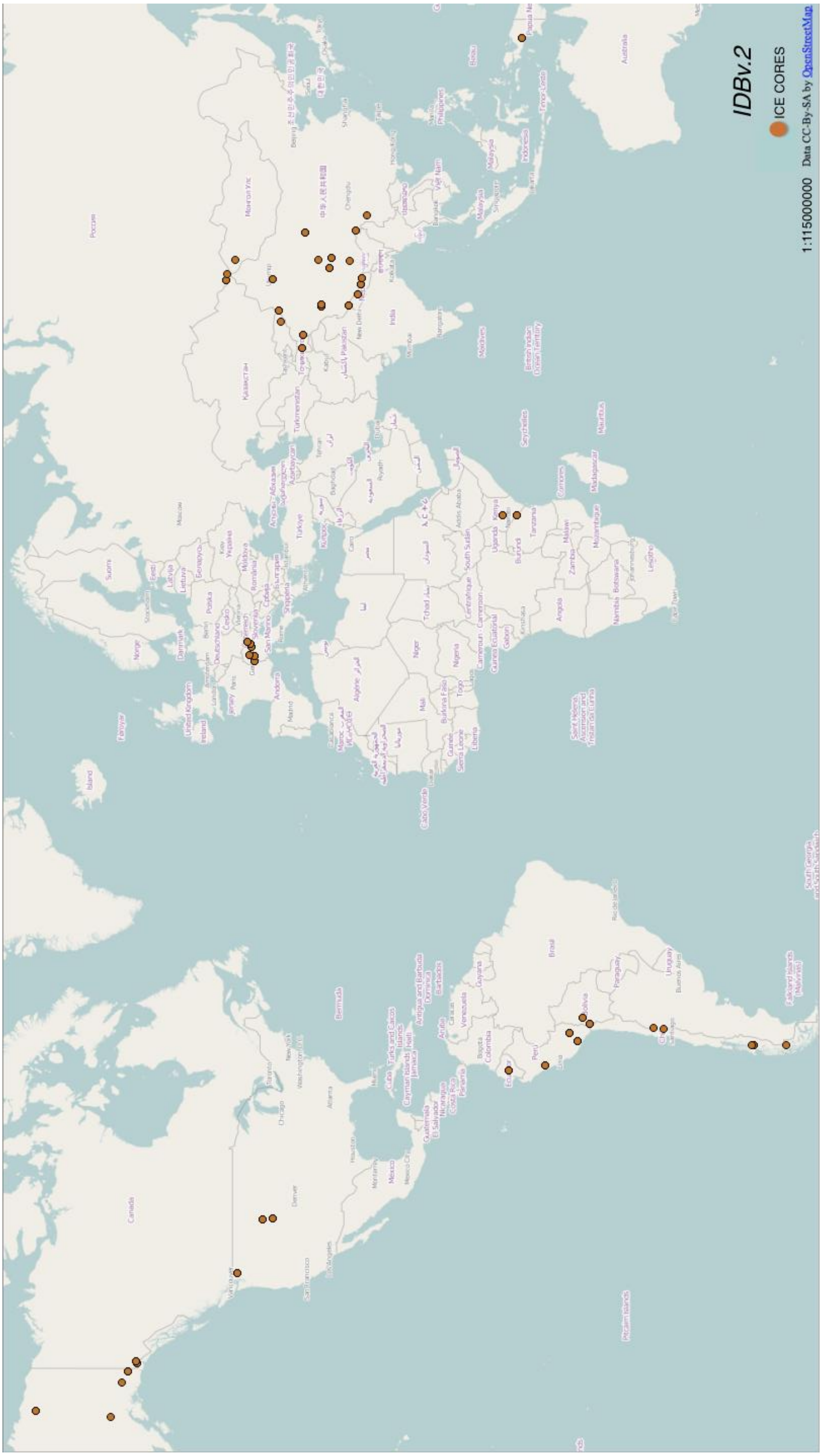


Figure 29: Spatial distribution of ice cores contained in IDB2

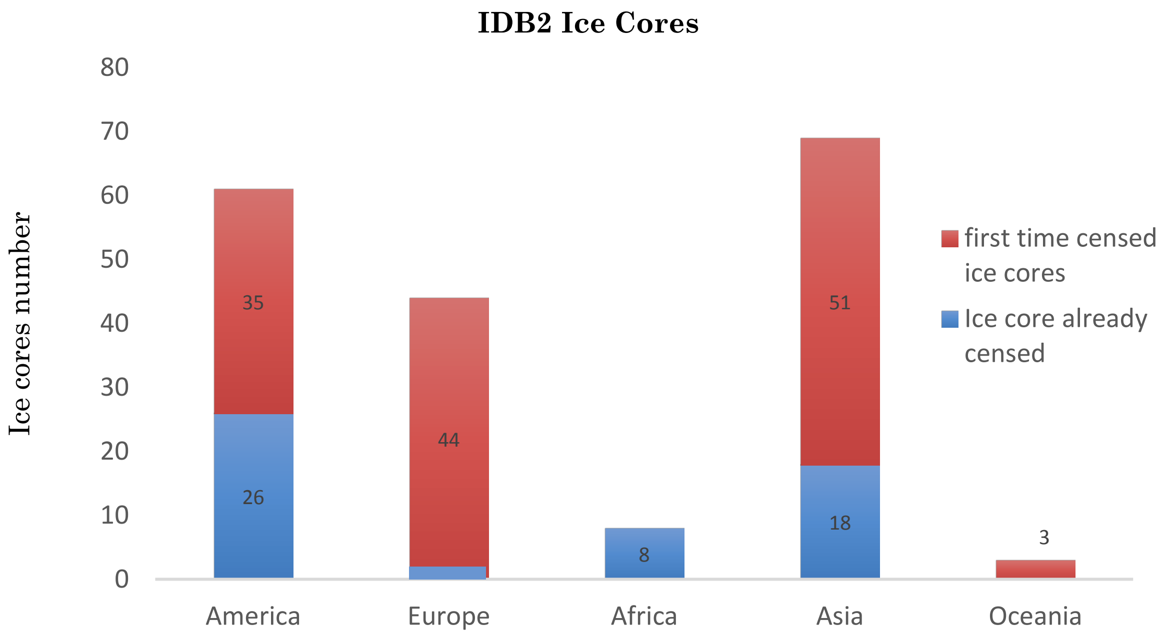


Figure 30 distribution of the 185 archived ice cores.

132890 glaciers with unique identification come from 4 different databases after an accurate spatial join analysis was add in a dedicated entity of the infrastructure. In particular, there are 132890 ID of glaciers contained in WGI, 30260 contained in RGI, 22493 contained in GLIMS and 761 contained in WGMS.

This last entity has been the starting point to develop a GIS algorithm to evaluate and draw the glaciers flow lines and to calculate geomorphic parameters to assess their response to climatic fluctuations.

3.3 Data dissemination

To enable data sharing, a web platform was also developed on the Geomatic Laboratory server of the Environmental and Earth Sciences Department of the University of Milano-Bicocca. The working environment is based on open-source structures.

A web map service (WMS) and web feature service (WFS) based on Open Geospatial Consortium (OGC) services was created using Geoserver software (http://geoserver.org/). The OGC standards offer a method to share geospatial information and metadata, with multiple applications increasing their interoperability. The web portal is equipped with a webgis (fig. 31) built with Leaflet (http://leafletjs.com/), in which ice cores are visualized spatially with their attributes (fig. 32). For every characterized ice cores, a webpage with info and graphs about the selected parameter is shown (fig. 33). A visual interface for downloading the data was developed inside the web portal. All this work was done with the technical support of dr. Strigaro.

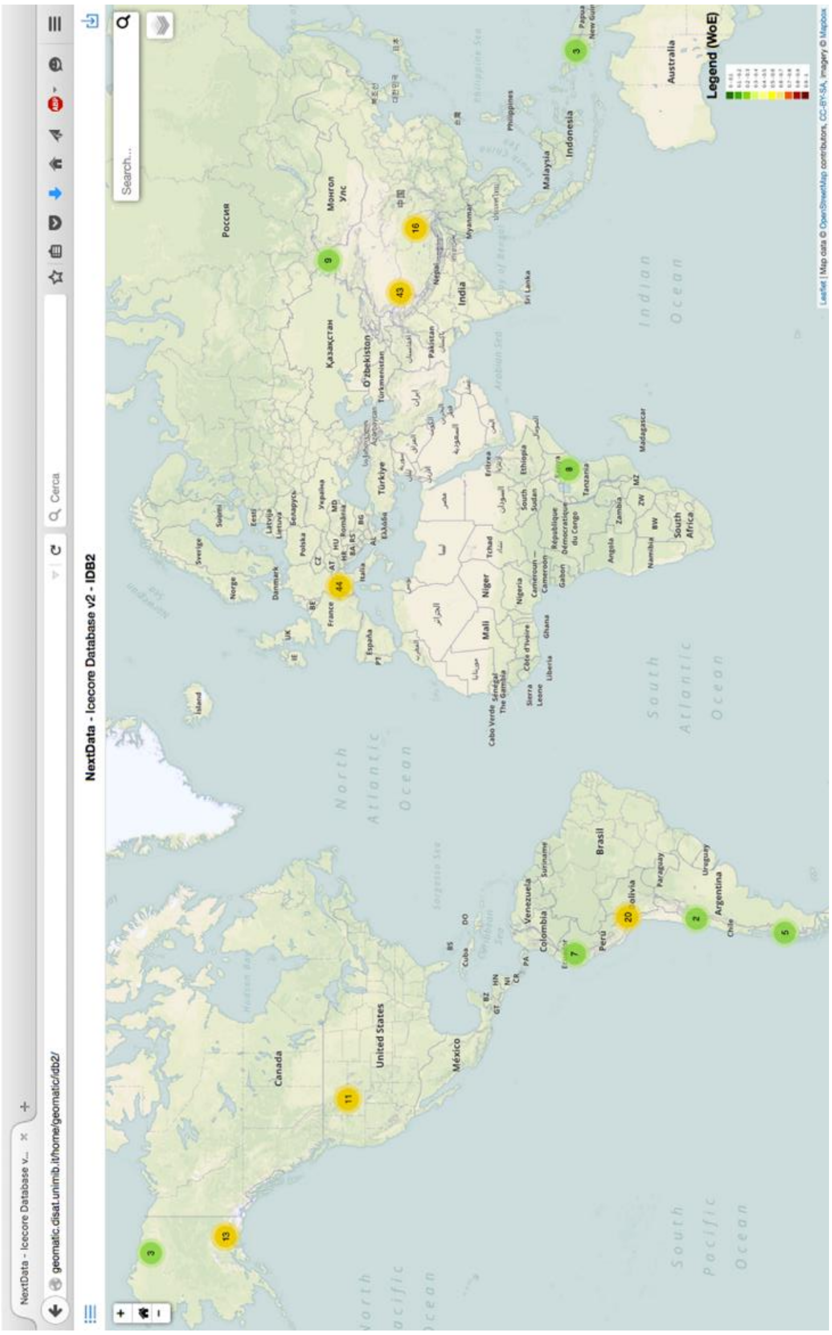
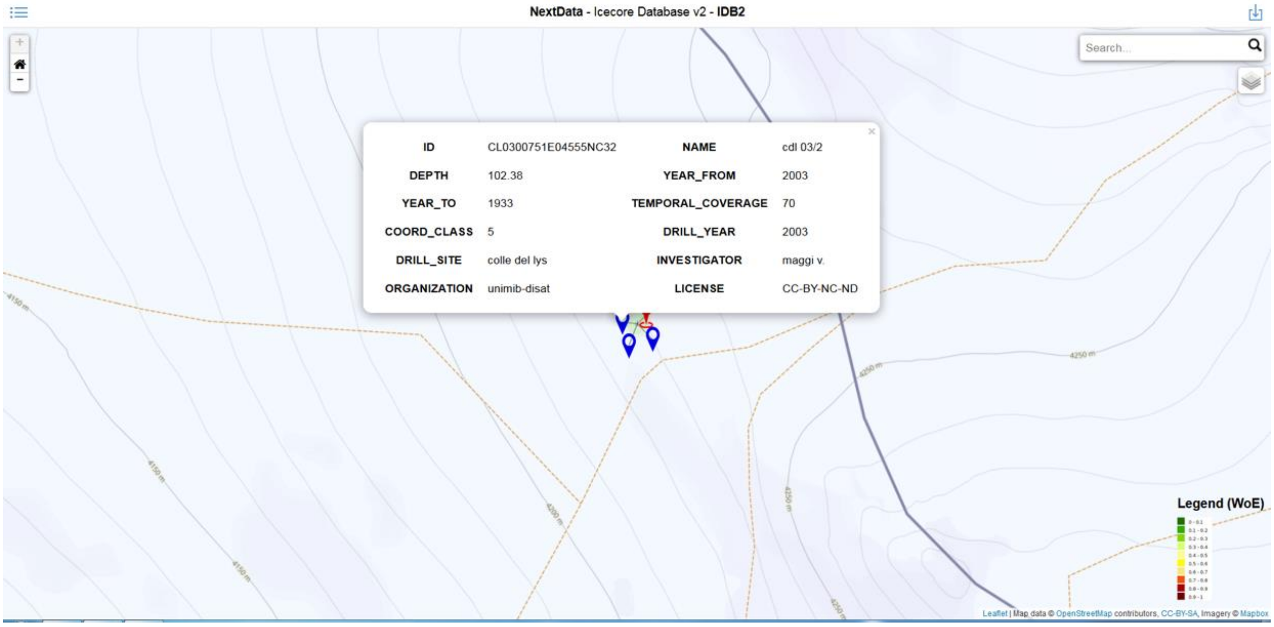
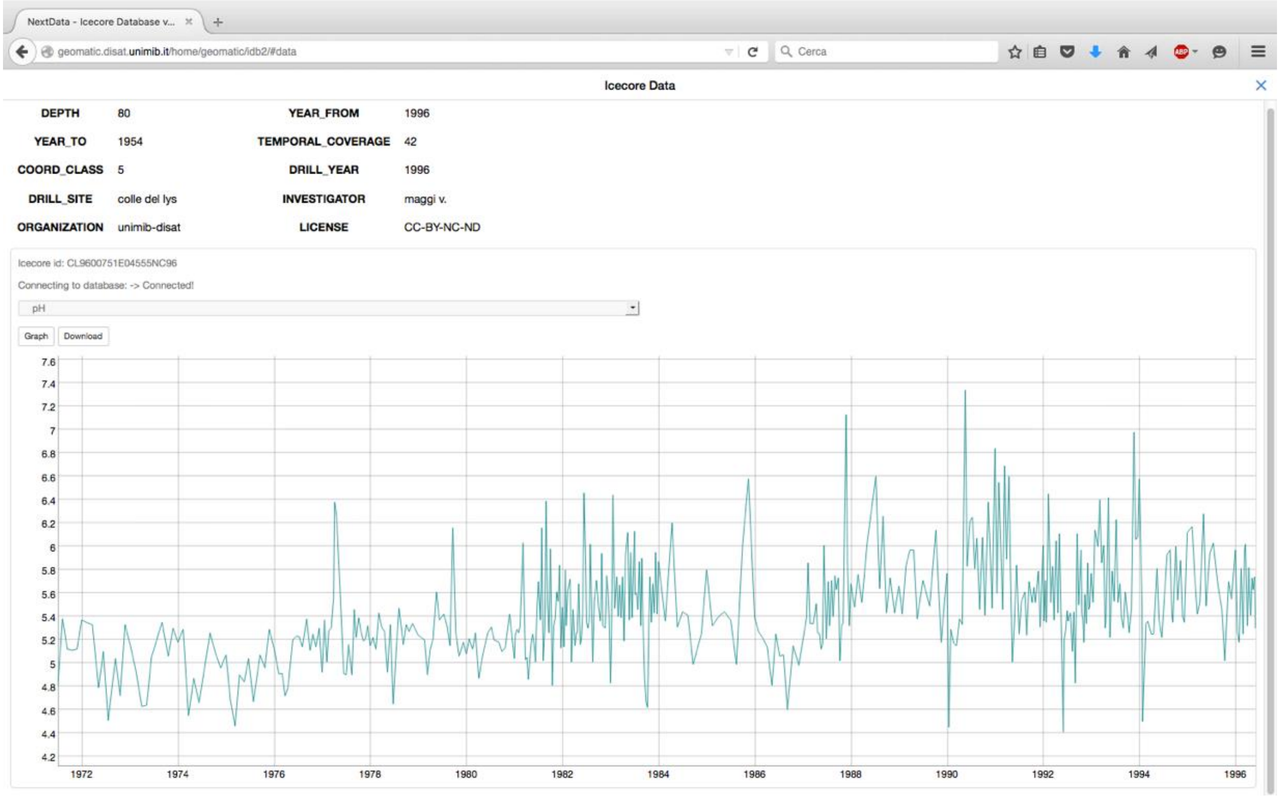


Figure 31 IDB2 webgis with ice cores distribution for each mountain range.



ID	CL0300751E04555NC32	NAME	cdl 03/2
DEPTH	102.38	YEAR_FROM	2003
YEAR_TO	1933	TEMPORAL_COVERAGE	70
COORD_CLASS	5	DRILL_YEAR	2003
DRILL_SITE	colle del lys	INVESTIGATOR	maggi v.
ORGANIZATION	unimib-disat	LICENSE	CC-BY-NC-ND

Figure 32 Ice core attributes shows as pop-up in IDB2 webgis



DEPTH	80	YEAR_FROM	1996
YEAR_TO	1954	TEMPORAL_COVERAGE	42
COORD_CLASS	5	DRILL_YEAR	1996
DRILL_SITE	colle del lys	INVESTIGATOR	maggi v.
ORGANIZATION	unimib-disat	LICENSE	CC-BY-NC-ND

Icecore id: CL9600751E04555NC96

Connecting to database: -> Connected!

pH

Figure 33 IDB2 Ice core characterization visualization and download page.

3.4 Conclusion

The aim of the infrastructure that I have developed is to store spatial and temporal information about glaciers and ice cores and data derived from chemical and physical ice cores characterization in an orderly structure (IDB2) that do not contain a redundancy data and allows to search and analysing data in a quickly way. This spatial database is addressed to a broad variety of users, from researchers in glaciology, climate change and paleoclimate field up to people with less experience thanks to its simplicity of use.

In particular, this structure (IDB2) permits to extrapolate proxy data ($\delta^{18}O$, greenhouse gasses, and so on) or ice cores chronology and compare them to search anomaly or harmony in their signal. The comparison of ice cores signal can currently be applied to all main ice cores to allow analysis of the climatic information from all cores in a consistent chronological framework. Recent studies also have employed a set of global event markers to synchronize ice cores from both hemispheres (*Raisbeck et al.,2007; Svensson et al., 2013; Sigl et al., 2013*) and they are also looking for a strategy consists of obtaining a reference chronology for a given ice core, which is then wiggle matched to several other cores in order to construct a consistent multi-ice-core chronology *(Lemieux-Dudon et al.,2010, Veres et al., 2013; Bazin et al., 2013*). Starting from the information archived in the IDB2 it is also possible through web-crawling to search other sources of proxy data comparable and temporally overlap with the ice cores record to build the best probable scenario of climatic evolution of the Earth. This approach is in direction and in agreement with the recent evolution of the paleoclimatic research and in particular with the *climatic field reconstruction methodology* (*Jones P.D., et al., 2009; McShane W.B., et al., 2011)* that use several sources of signal to reconstruct the climatic evolution using a system of methods called multi-proxy reconstruction (*Birks H.H., et al., 2006, Kaufman D.S., et al 2012;*

Fissinger W., et al., 2014). These methods are the best to quantify and evaluate the climatic trajectory of the last centuries or even better, the last millennia. In this direction a preliminary analysis on data contained on the developed infrastructure was done evaluating how far it is possible going back with the ice cores archived in the IDB2 (fig. 34). This approach is also useful to identify which glaciers are formed by the oldest ice so, the first glacier to study, to model, to drill to avoid the loss of precious information that can be retrieved and archived from their hidden layer.

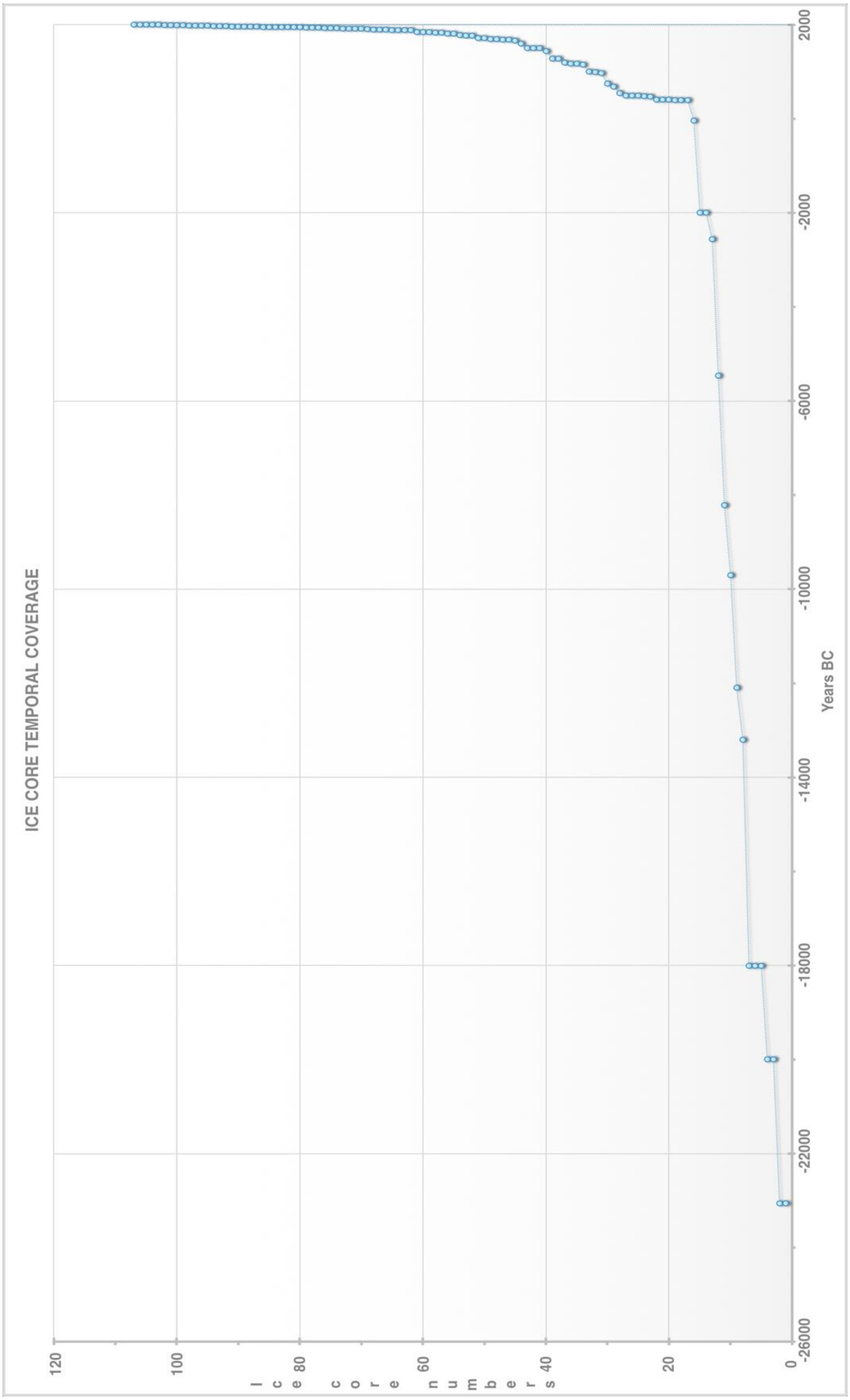


Figure 34 IDB2 ice cores temporal coverage.

Regard to the glaciers entities and their data, they were already used to retrieve the spatial position of the drilling site of the ice cores to build a methodology to evaluate the suitability for ice core drilling for a non-polar glacier as developed by Garzonio in his Ph.D. research (*Garzonio R., 2016)*. Furthermore, in the next chapter (cap 4) the interaction between this structure and the calibration of the Minimal Glacier Model (*Oerlemans J., 2008)* modify by Moretti in his Ph.D. research (*Moretti M., 2016)* will be shown. Data obtained from the results of the MGM modelling will be uploaded in the IDB2 dedicated entity (*glacier data*).

In general, IDB2 was evaluated strong enough for recovery other proxy data such as; peatbogs; lake sediments; marine sediments and pollen. In this way a comprehensive geodatabase of proxy data could be set and used to reconstruct the paleoclimate history (*Strigaro D., et al., 2014*).
Future upgrade of the IDB2 geoportal will be to create a query system to search and retrieval ice cores by their age, or their dating and plotting together different signals from different ice cores or different proxy. But up to date, the goal was to create a structure useful to comparison and extrapolation of data.

4 A GIS TOOL TO EVALUATE GLACIER RESPONSE TO CLIMATIC FLUCTUATIONS

4.1 Introduction

The final step of this work is aimed to design, develop and verify a GIS tool called *Glacier Data Module (GDM)* for evaluate the glaciers response to climatic fluctuation. Data obtained from the GDM application were uploaded in the IDB2 in the *GlacierData* entity that was expressly created.

Data obtained were also used to calibrate a Minimal Glacier Model, a particular family of glaciological model developed by J. Oerlemans (*Oerlemans J., 2008)* and modify and apply on glaciers of the Greater Alpine Region by Moretti (*Moretti M., 2016*) in his Ph.D. research. The term Minimal Glacier Model specifies a class of models that do not explicitly describe the spatial dependence of the dynamical variables and develop a bulk description of the glacier in terms of glacier-averaged dynamical quantities that depend only on time (*Oerlemans J., 2011*). In such approach, the main state variable is glacier length, L, while the other variables such as the average ice thickness are expressed as a function of L using a perfect plasticity assumption. As in more complex models, the evolution of the glacier length is obtained from an integrated continuity equation driven by the glacier mass balance.

In this chapter I disclose the design, the development and the verify process of a GIS tool called the *GlacierDataModule* useful to calibrate and to obtain geomorphological data for evaluate the glacier response to the climate fluctuation and also useful to increase the accuracy of the MGM. The integration of the Minimal Glacier Model with the

GlacierDataModule is useful also to move from a non-spatial deterministic approach, MGM, to a spatial deterministic one, MGM coupled with GDM. In particular, the resulting data of GIS analysis carried out with the developed procedure were used to calibrate the boundary condition of the Minimal Glacier Models as applied by Moretti on a subset of glaciers in the Greater Alpine Region (GAR).

The methodology used to create the GIS tool, its validation and the first test of MGM calibrate with GDM and the application of GDM to obtain data of Greater Alpine Region glaciers are described in the next sections of this chapter.

4.2 THE "*GLACIER DATA MODULE*"

Mapping and modelling the changes in glacier extent through GIS using data from field and remote-sensing techniques are a well know methods *(Paul F., et al., 2012; Napieralski J., et al., 2007; Bamber J.L., et al., 2007)*. Today, a quantity of morphometric and morphologic parameters like glacier boundary, elevation, aspect, slope, rock covered surface, existence of crevasses, flow speed, mass balance of several glaciers are collected by different remote sensing instruments, as well as by in-situ measurements. Such morphometric parameters provide detailed information about glaciers dynamics and their evolution and response to climatic fluctuations *(Bamber J.L., et al., 2007, Napieralsky J., et al., 2007, Linsbauer A, et al., 2012)*. These data are also useful to calibrate and validate glaciological models used to predict the future behaviour of the glaciers. To analyse data coming from in-situ and remote sensing measurements, to create a dataset of useful but not redundant information already presents in other spatial infrastructure such as WGI, RGI, GLIMS, WGMS, and also because in the MGM applied by Moretti the main state variable and the final results is the glacier length variation along the flow line, it was decided to create a GIS tool that evaluates glaciers morphometric parameters along their flow lines. In particular, GDM tool was created to:

- evaluate the geospatial fluctuations of glaciers along their flow lines (multitemporal analysis in batch process) by a complete and user-friendly GIS tool;
- development of an easy way to apply Minimal Glacier Models on large scale.

GIS tool *"Glacier Data Module" (GDM)* was created to obtain glaciers morphometric parameters such as length, max and min elevation, max and min slope and orientation, along their flow lines, using QGIS (http://www.qgis.org) an open source software,

This tool has been developed following the main international standards for geo-spatial information (OGC) with QGIS processing tools, using several libraries such as GDAL and the interoperability of different open source software such as, GRASS-GIS (*Neteler M., et al., 2012*) and SAGA GIS (the entire module workflow is reported in in appendix D). The algorithm requires, as inputs, the principal FLOW LINE of glacier (in glaciology the flow line is the vector which describes the flow of mass between the accumulation area at the top of glacier and the ablation area at the bottom, *Le Bris R., et al., 2013*), the glacier digital elevation model, DEM, and the POLYGON that represent the contour line of the glacier body. It is applied on a hundred meters' neighbourhood zone from the flow lines and the outputs are these geomorphic parameters (fig. 35):

- Flow line length
- maximum, averaged and minimum elevation, along the flow lines.
- maximum, averaged and minimum slope along the flow lines.
- maximum, averaged and minimum aspect along the flow lines.

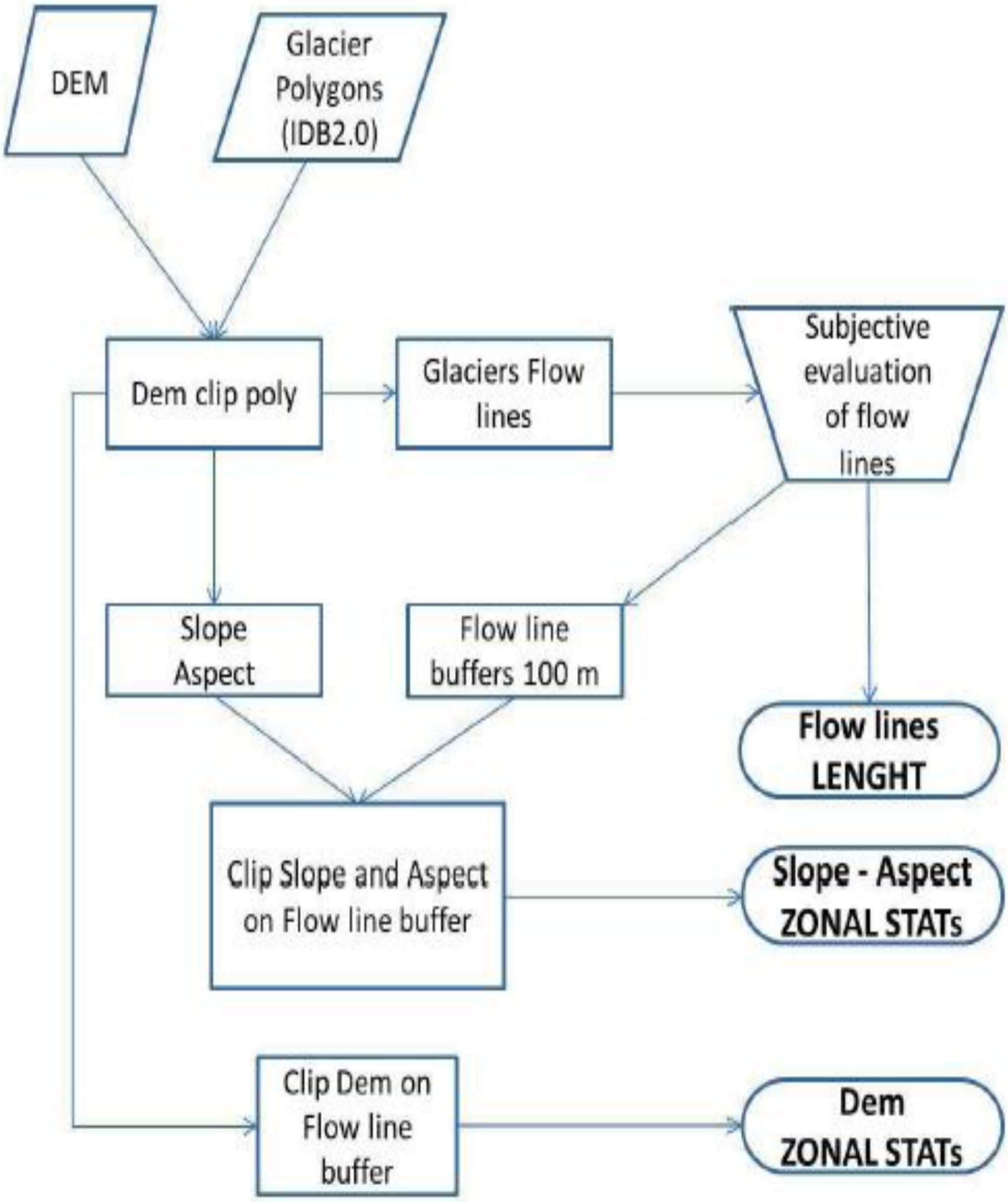


Figure 35 Glacier Data Module conceptual scheme

4.2.1 INPUT description

4.2.1.1. Flow Lines

Understanding water movement through a glacier is fundamental to several critical issues in glaciology, including glacier dynamics *(Fountain. A. G., 1998*). In general, the superficial water movement in a complex morphology such as mountain environment is described by the principals' flow lines. The flow line is the vector which describes the flow of water from the top to the bottom of the valley. The flow line reconstruction is usually used in addition to a basic topographic analysis, in particular to model the erosion and the deposition in complex terrain. The general pattern of the ice flow is determined by the net budget between accumulation and ablation of the ice mass driven by the morphology of bed rock and the gravity force. The balance velocity is a parameter that describes this behaviour (*Bahr D.B., et al., 1998*) and can be calculated from directions of ice flow using ice thickness and slope map (*Huybrechts P., et al., 2000*).

In this context, the flow line can be estimated by various algorithms that are based on morphological factors from which the flow depends. Some of these parameters are: slope angle, slope length, aspect and the upslope contributing area (*Mitasova et al., 1996*). Exporting these concepts in glaciology, the flow line can be defined as the vector which describes the flow of mass between the accumulation area at the top of glacier and the ablation area at the bottom (*Le Bris R., et al., 2013*).

It is possible digitalize the glacier flow line as a vector line from top to bottom in a GIS environment. Different algorithm to calculate flow line in GIS were developed in the past. Three of them was evaluated by L. Maffezzoni in his thesis work (Maffezzoni L., 2015) conducted under my supervision. Goal for that work was find the best algorithm for calculate a single continuous flow line starting from the top of the glacier and finishing at the glacier front. In the GIS tool developed, flow lines are the most important input to find glaciers length and modelling future evolution in Minimal Glaciers Model. The three algorithm that were evaluated evaluated are: *r. flowmd, r. flow* and *Flow Mapper*.

The last one was discarded immediately because it works only in 2D dimensions, so was not possible extract the real length of flow line. The *r.flowmd* and the *r.flow* algorithms are very similar but the *r.flow* is faster and supports a larger data set than *r.flowmd* so, the choice was to used *r.flow*.

r.flow algorithm

The *r.flow* algorithm generates 3D flow lines using a combined raster-vector approach, from an input elevation raster map (DEM cutting on glacier boundary in our cases). The algorithm is based on the surface interpolation with bivariate function z= *f(x,y)* that is continuous up to second order derivatives. The parameters characterizing surface geometry are expressed via derivatives of this function and the results give many gradients, fundamental to interpret the topography of the area (fig. 36), reconstruct the stream and slope lines enjoying a good squareness with the isolines level (*Mitasova H., et al., 1993*).

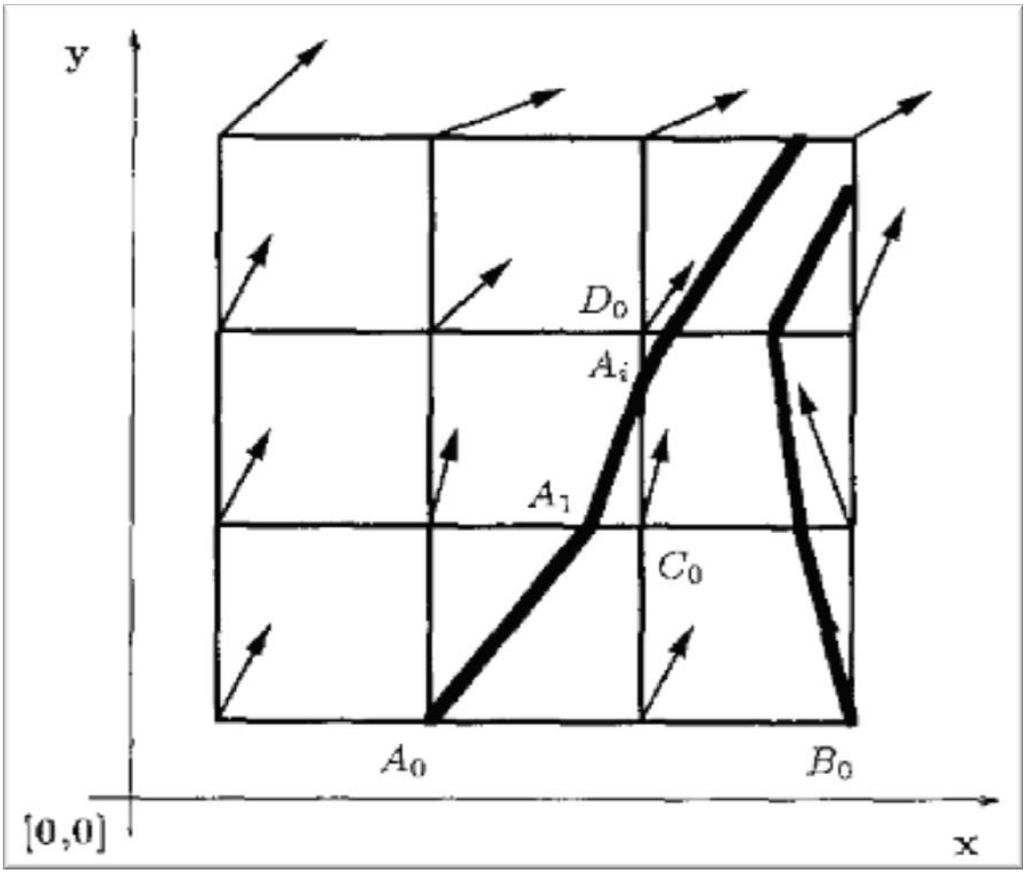


Figure 36 r.flow mathematical schematization

After introducing this following simplification, where:

$\boldsymbol{f_x = \frac{dz}{dx}}$, $\boldsymbol{f_y = \frac{dz}{dy}}$, $\boldsymbol{f_{xx} = \frac{dz^2}{dx^2}}$, $\boldsymbol{f_{yy} = \frac{dz^2}{dy^2}}$, $\boldsymbol{f_{xy} = \frac{dz^2}{dxy}}$; $\boldsymbol{p = f_x^2 + f_y^2}$; $\boldsymbol{q = p + 1}$

the algorithm derives and calculate the curvatures equations using the general equation for curvature *k* of a plane section through a point on a surface:

$$\boldsymbol{k = \frac{f_{xx}cos^2\beta_1 + 2f_{xy}cos\beta_1 cos\beta_2 + f_{yy}cos^2\beta_2}{\sqrt{q}cos\vartheta}}$$

Where ϑ is the angle between the normal to the surface at a given point and the section plane; β_1, β_2 are angles between the tangent of the given normal section at a given point and axes x, y, respectively.

This algorithm has proved largely ineffective only on flat surfaces and special points as peaks. One of the most important advantage of *r.flow* in comparison to other flow line algorithm is that it utilize an original vector-grid algorithm which uses an infinite number of directions between 0.0000 and 360.0000 where aspect angle $\alpha = arctan\frac{f_y}{f_x}$ $(\alpha = 0\ in\ west\ direction)$ and traces the flow as a line (vector) in the direction of gradient. Flow lines output is given in a vector map where the flow lines vectors have endpoints on edges of a grid formed by drawing imaginary lines through the centres of the cells in the elevation map. The flow line stops if its next segment would reverse the direction of flow (in our case from up to down) cross a barrier, or arrives at a cell with undefined elevation or aspect.

3D flow lines extraction

To extract the 3D principals flow lines of glaciers, the *r.flow* algorithm was run in GRASS-GIS. Two parameters were set-up to obtain the best results from the algorithm:

- number of cells between flow lines, = 3, for higher values the results are a small amount of flow lines and for smaller values the results are too many lines which is not possible to distinguish.
- maximum number of segments per flow-line. It was decided to assign higher value available because, for our goal, the longer are the flow lines, easily will be the next step, create a singles continues flow line from top to the bottom of the glacier.

The final result is a linear vector map formed by 3D flow lines generated (fig. 37)

As mentioned above, the slope curves created by algorithm stops at the cell edge where the next cell represent a flat terrain or a singular point (Mitášová, H.,1993). So, since glacier morphology is irregular, the results of *r.flow* is a lot of segments spread on the entire glacier surface. To obtain flow lines along the entire glacier a manually operation is required as explain in the next section.

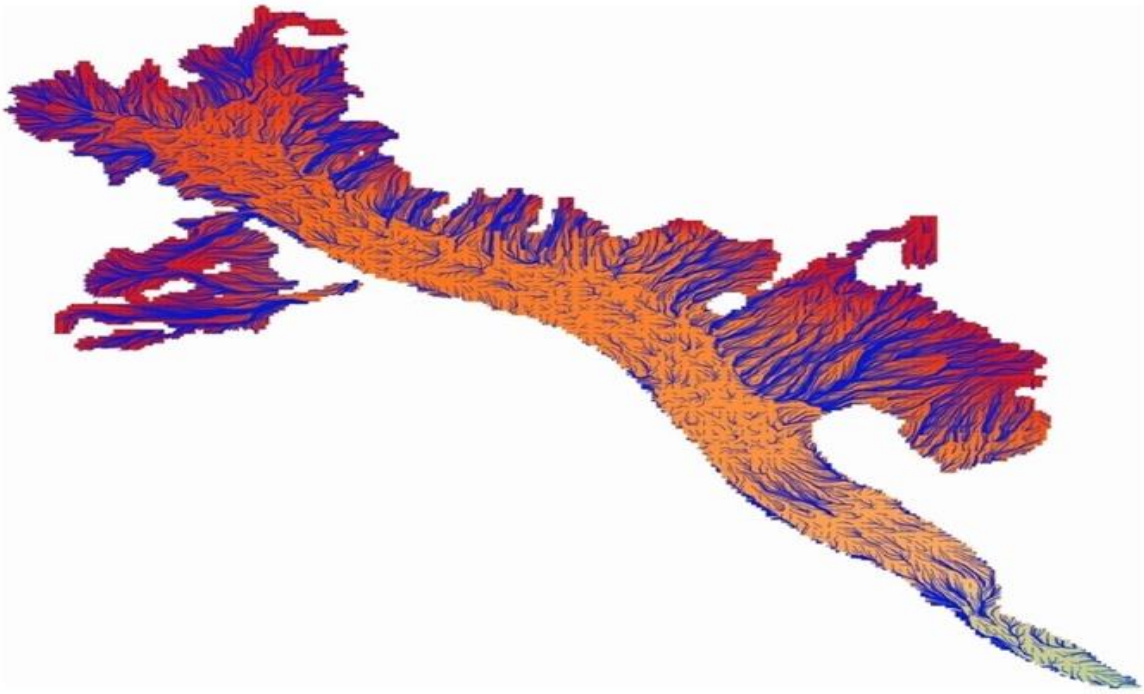


Figure 37 3D flow lines generated from r.flow algorithm for Argentiere Glacier.

R.flow results are a set of different flow lines segments that cover the entire glacier area, *Glacierdatamodule* require as input only one flow line that cover the entire glacier length. To overtake this problem, the most important glacier flow lines was manually digitized starting from the *r.flow* results. This operation was made using the elaborated flow line segments (fig. 38) superimpose at satellite images dating back to 2013 October. Starting from the *r.flow* results and following the glacier morphology, avoid the crevasses, we were able to manually draw, from top to the bottom, the path of the principal flow line(s)(fig. 39).

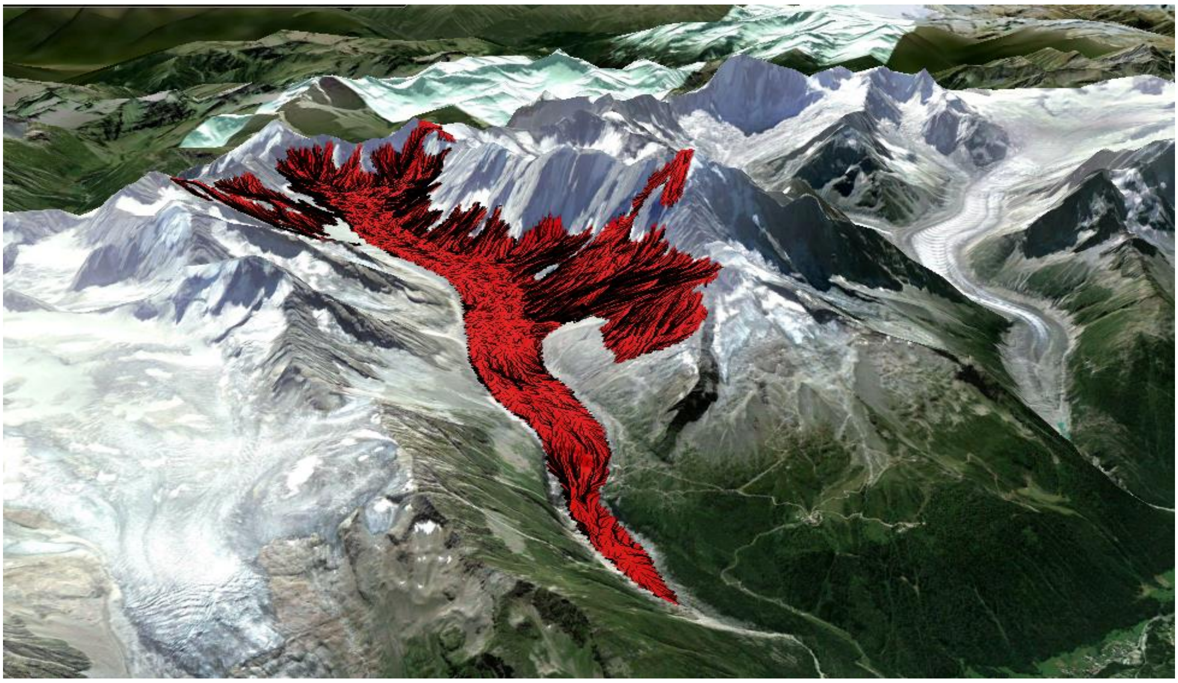


Figure 38 Argentiere Glacier polygon and flow lines from algorithm r.flow. Google Earth map on background.

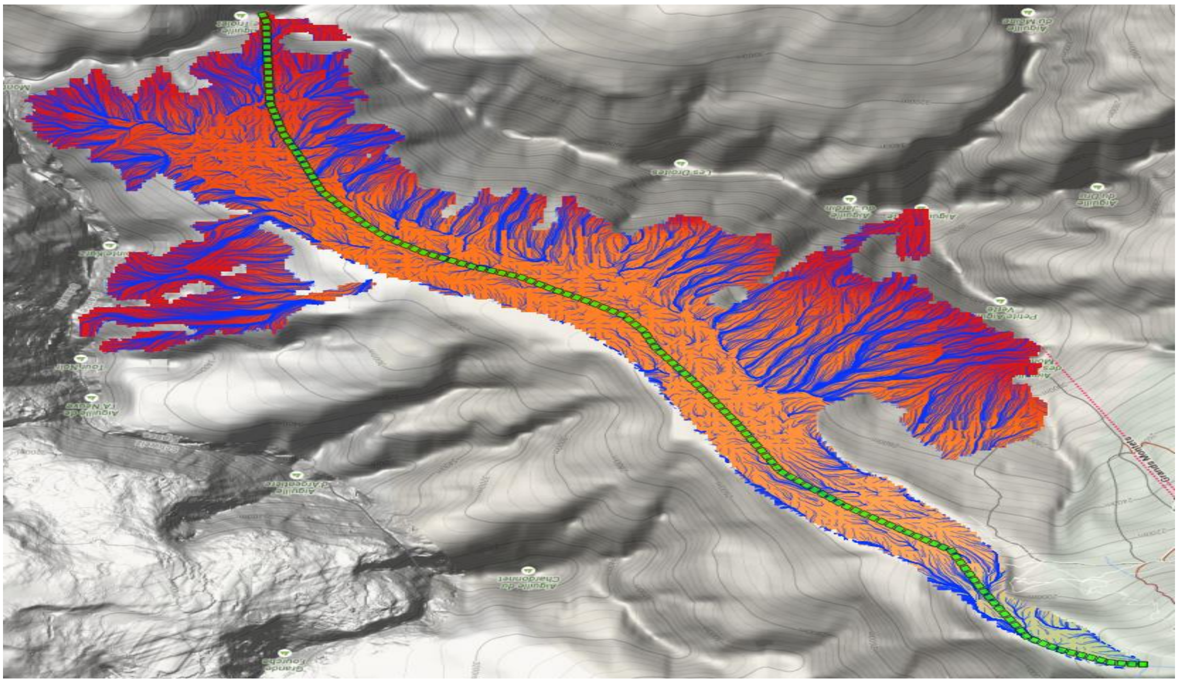


Figure 39 DEM, polygon, algorithm flow lines (blue) and the manually digitized dashed flow-line corrected by google images. On the background, physical map of the area.

For very small glaciers it was decided to consider only the most significant flow line, while as regards bigger glaciers with different tongue or with high area in accumulation zone, more than one flow lines was digitalized. For the biggest glacier or for that glaciers that have more than one flow lines, the GDM was applied on each flow line.

An example of flow lines drawn for Aletsch glacier following the above mentioned methodology are shown in figure (fig. 40).

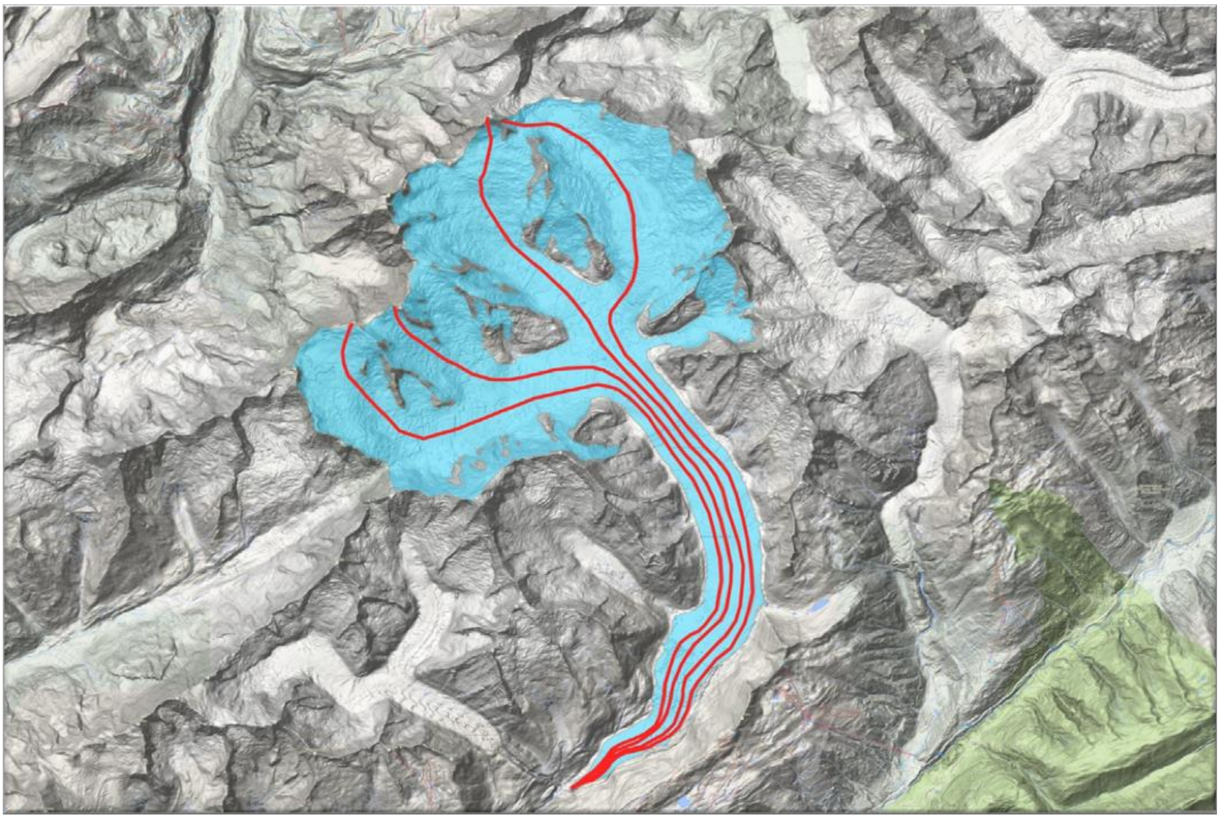


Figure 40 RGI Polygon and principals manually digitized flow lines of Aletsch Glacier. On the background, physical map of the area. four principal flow lines were extracted from Aletsch Glacier, the biggest glacier of the Greater Alpine Region (GAR).

4.2.1.2. Glacier Surface from DEM

Digital Elevation Models (DEM) are currently a fundamental instrument to study the "spatially distributed" processes affecting the physical landscape, its morphology and its evolution. Their potential lies the possibility of carrying out both qualitative and quantitative analysis of topography and morphology of the area, as well as the modelling geomorphological and hydrological processes. By using GIS tools and different algorithm it is possible compared DEM acquired by different sources and extract many parameters as slope, aspect, minimum, maximum, medium height, glaciers flow lines lengths directions and profile.

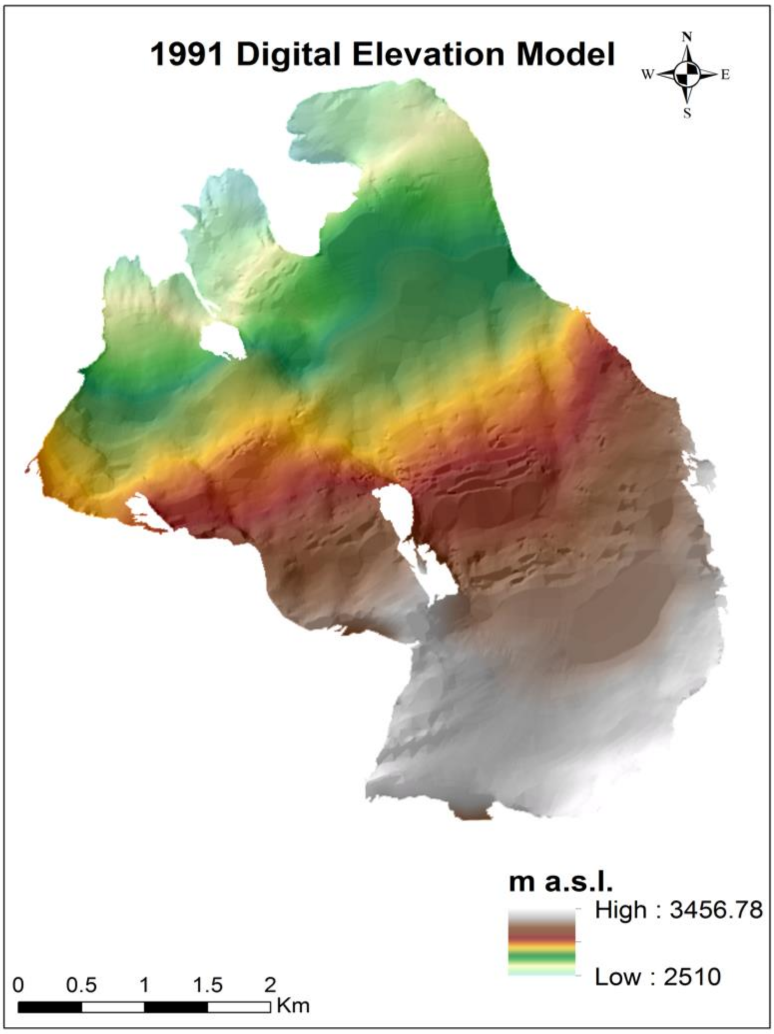


Figure 41 Rutor 1991 DEM (digitalize from CTR 1:10000) classification based on altitude.

Limits and Error evaluation in DEM

DEM is a representation of the reality by a regularly spaced grid with associated altitude data. The smaller the grid size, the more detailed the model is. This means that the altitude values in a DEM are a weighted average of the altitude of the surface area covered by every single cell. Furthermore, a DEM is usually generated by interpolation, and the result obtained by this interpolation is linked to the quality of the original data and to the grid size chosen. It derives that the use of a digital model for quantitative analysis is strongly linked to an esteem of its accuracy. (Villa. F., 2007) The quality of a DEM is normally defined by the only calculation RMSE (Root Mean Square Error, or σ) of the elevations, which is the root square of the variance statistic represented by this formula:

$$\sigma = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n} x_i}$$

where n is the number of the control points used, and x_i is the altitude difference between the i-th control point and the DEM cell in which it falls.

4.2.1.3 Glacier Boundary (polygon)

Boundary of glacier are represented in a GIS environment as polygons of glacier body. The polygons are one of three compulsory input of GDM and were used to delimiting the contour line of glaciers on DEM and to calculate the flow lines referring to a single year. For each glacier at least one polygon referred to one year has to be presents. In this study it was decide to use glacier boundaries coming from the RGI project as described in section 4.4.

4.3 Glacier Data Module validation

The GIS tool developed was tested on Rutor glacier to verify its accuracy. The Rutor glacier is one of the largest glaciers in the Italian Alps. It is located in the La Thuile valley (Val d'Aosta) (fig. 42), Rutor massif, in north-western Italy, next to the French/Italian border. The Rutor has a surface area of more than 8.5 $km2$ and its watershed faces mainly North-West. From this top elevation of about 3480 m, below the "Testa del Rutor" (3485 m), the glacier descends alternating steep parts with more flat areas up to the actual front, subdivided in three tongues. The middle front reaches the minimum altitude of about 2510 m (*Orombelli, 2005*). Many lakes are located in front of the Rutor and occupy the cavities left during its retreat that began after the LIA (Little Ice Age): Lake Santa Margherita (sadly famous for the catastrophic flood), Seracchi and another two newer lakes that are less than thirty years old (*Villa et al., 2007*).

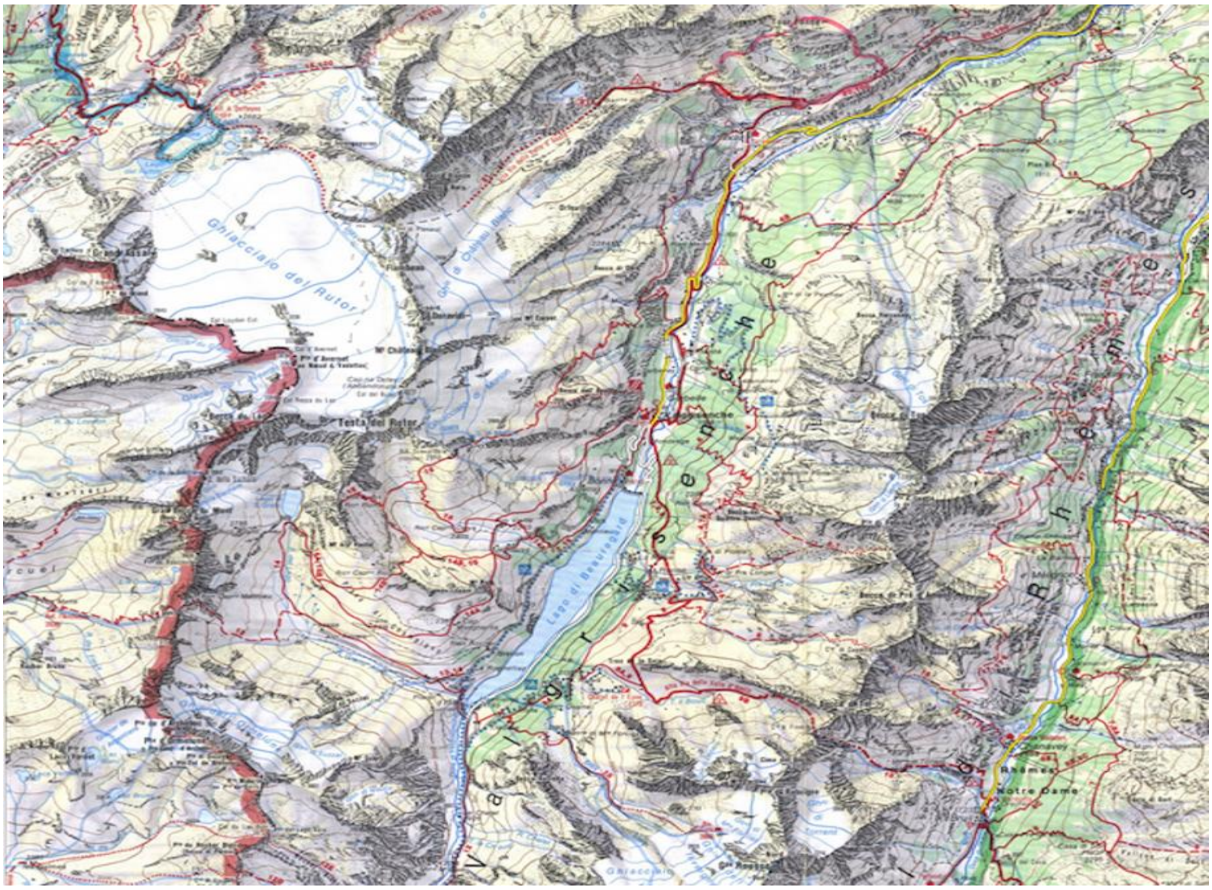


Figure 42 Rutor glacier geographical position

For the Rutor glacier, a large amount of maps and cartography/geomorphology studies were made. As a result, several DTMs were built, using data collected by land surveying and remote sensing techniques. The oldest one is referred at 1820. The last one, referred at 2008 is a DEM with 2x2m resolution. The 2008 DEM comes from LIDAR data acquired by the Valle d'Aosta Italian region.

For the GDM algorithm validation, 6 different DEM (tab. 8) and 12 polygons (fig. 43) were used as input source.

The contour line of 1820 was digitalized from reconstruction of the glaciers body during the LIA (*Orombelli G., 2005*), the boundary of 1879 and 1905 was digitalized based on *Sacco F., 1917*, and the contour lines of 1930 and 1968 was taken from the IGM 28 III SO "*La Salle*" table and IGM 41 IV NO "*Valgrisanche*" table. Glacier boundaries of 1954 and 1988 was derived from orthophoto. The 1975 boundary was based on CTR 1:10000 of Valle D'Aosta region and the 1998 comes from a topographic survey (*Parigi A., 1999*). The 2000 and 2004 and 2008 contour lines are based on orthophoto and GPS campaign.

Table 8DEM used to run Glacier Data Module on Rutor Glacier

Year	Sampling methods	DEM resolution	Source	Scale
1820	Reconstruction	25m	Orombelli	1:50000
1954	Reconstruction	25m	Orombelli	1:50000
1975	Digitalization	5m	CTR	1:10000
1991	Digitalization	5m	CTR	1:10000
2003	Reconstruction	5m	Orthophoto	1:5000
2008	Reconstruction	5m	LIDAR	1:5000

Flow lines extrapolation

The flow lines were retrieved with the procedure described before. The correct vector lines were produced by editing from the top to the end of the three tongues, so, from the accumulation area, the ablation area, the results of the *r.flow* algorithm. Three flow lines were digitized (fig. 44) the East, the centre and the West. The three flow lines follow the ice dynamics of tge Rutor glacier, highlighted also by the three different tongue of the glacier.

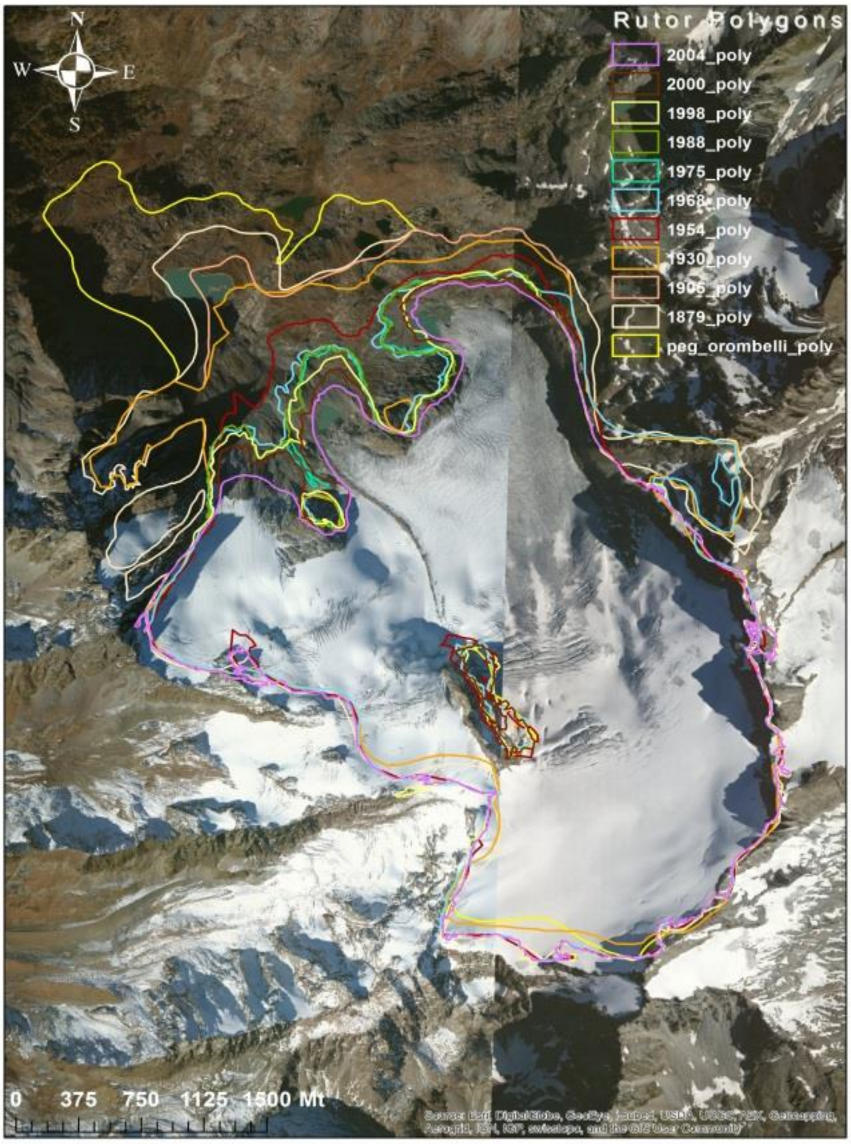


Figure 43 Rutor glacier polygons used in this study

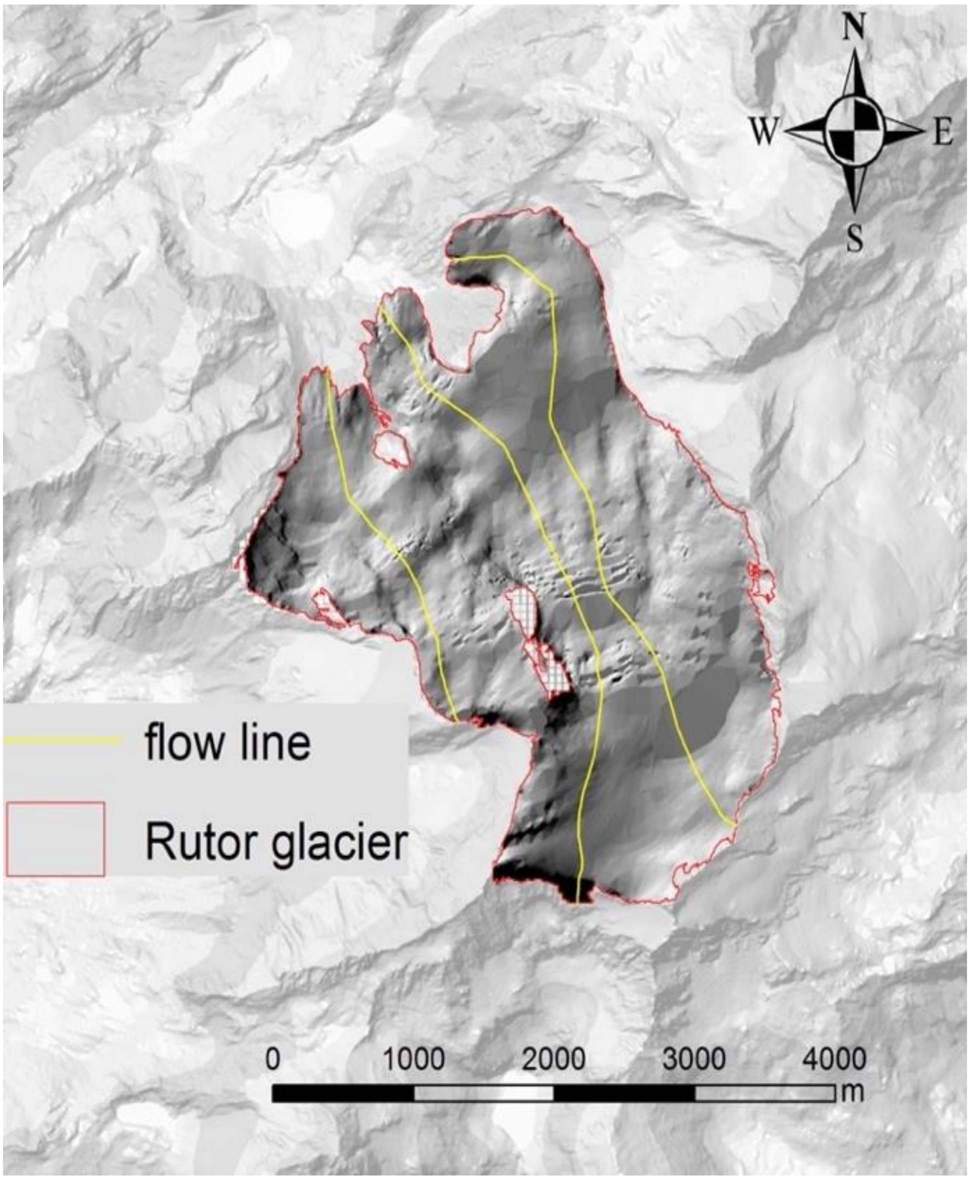


Figure 44 Identify and digitalized flow line for Rutor glacier

Results

The GDM results for Rutor glacier are, as describe before, a list of geomorphic parameter calculated in one hundred meters of buffered zone from the flow line to better evaluate the glacier body diversity along the flow line. These parameters for Rutor glacier are (tab. 9):

Table 9 Rutor glacier GDM results

	Year	.L. lenght (m)	Z max (m)	min (m)	Slope (%)	Aspect (°)
WEST	PEG	4482	3221	2147	24,83	113
	1954	2614	3215	2335	26,85	107
	1975	2439	3210	2566	27,45	102
	1991	2495	3220	2560	27,96	101
	2003	2252	3234	2539	31,44	110
	2008	2120	3223	2619	30,93	108
CENTRE	PEG	5090	3300	2425	16,91	104
	1954	4538	3300	2483	18,24	106
	1975	4126	3330	2510	21,98	107
	1991	4352	3302	2516	22,75	109
	2003	4118	3111	2547	25,58	113
	2008	4030	3295	2542	28,52	123
EST	PEG	5500	3400	2308	26,78	115
	1954	4682	3402	2335	23,48	113
	1975	4575	3403	2357	19,45	111
	1991	4592	3408	2532	19,51	111
	2003	4369	3384	2547	23,18	123
	2008	4288	3409	2540	26,78	126

GDM coupled with Minimal Glacier Model

The results obtained by the GIS analysis just presented were used to calibrate MGM applied on Rutor Glacier by Moretti (Fig. 45). To calibrate the MGM more than mass balance, temperature and precipitation data, the initial flow line length and the value of the following boundary condition are required: highest elevation, minimum elevation, mean slope.

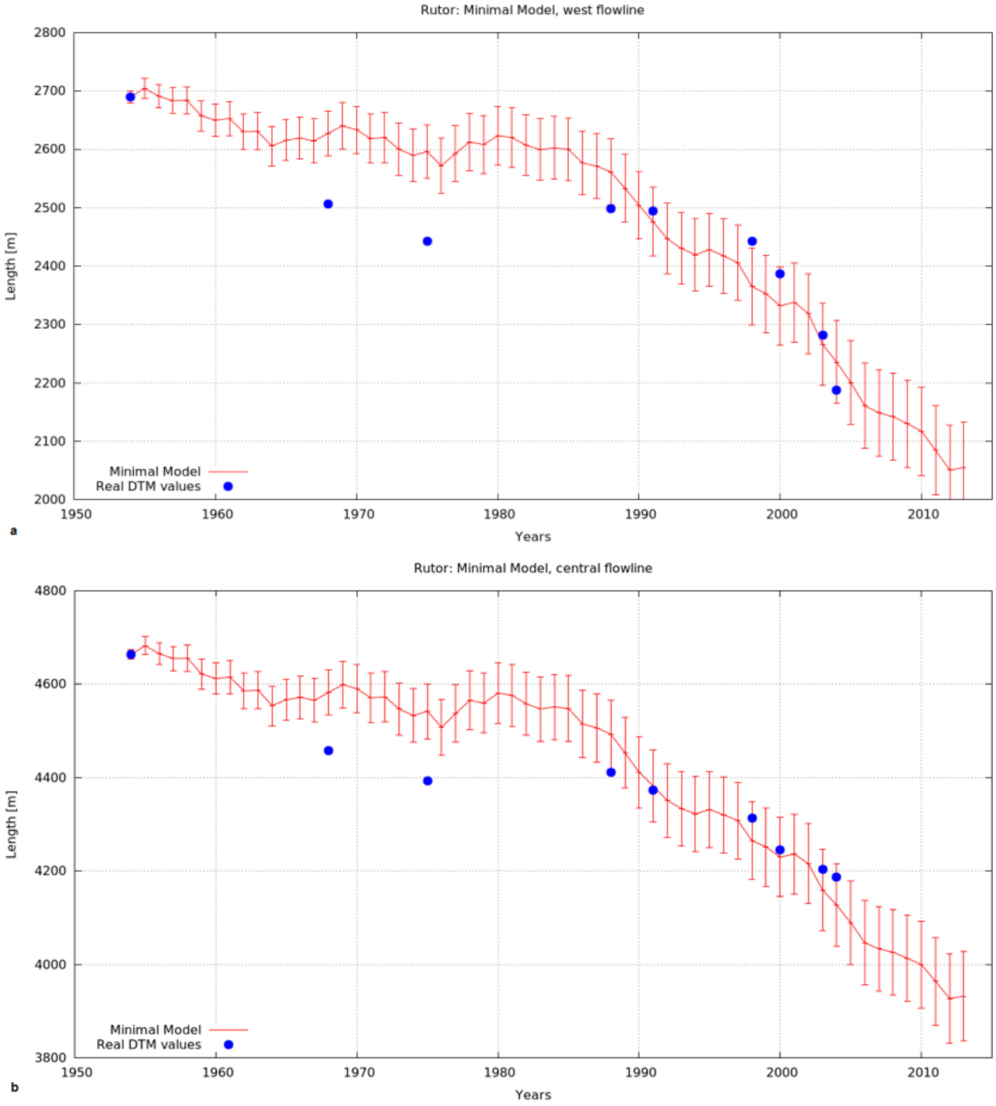


Figure 45 Model results for Rutor glacier. The red line is the flow line length value calculated by the MGM. The real values (blue dot) are the validation points come from GIS analysis by intersection between polygons and flow lines.

To evaluate the goodness of the prediction of the flow line length calculate by MGM calibrate with data coming from GDM, a retro-analysis was carried out. The MGM was calibrated to the 1954 for the east flow line with two different data-set. The first one derived by the GDM results for 1954, other data for different year obtained with the GDM analysis were used to force the model. The second calibration was carried out with the values retrieve from bibliographic research, parameters in bibliography were found related to the entire glacier body and not only in a neighbourhood zone around the flow line and not for all years evaluated with the GIS analysis. The difference between the accuracy of the results of the MGM calibrate with data recovered by bibliography and data retrieve using GDM are shown in the graph below (fig. 46).

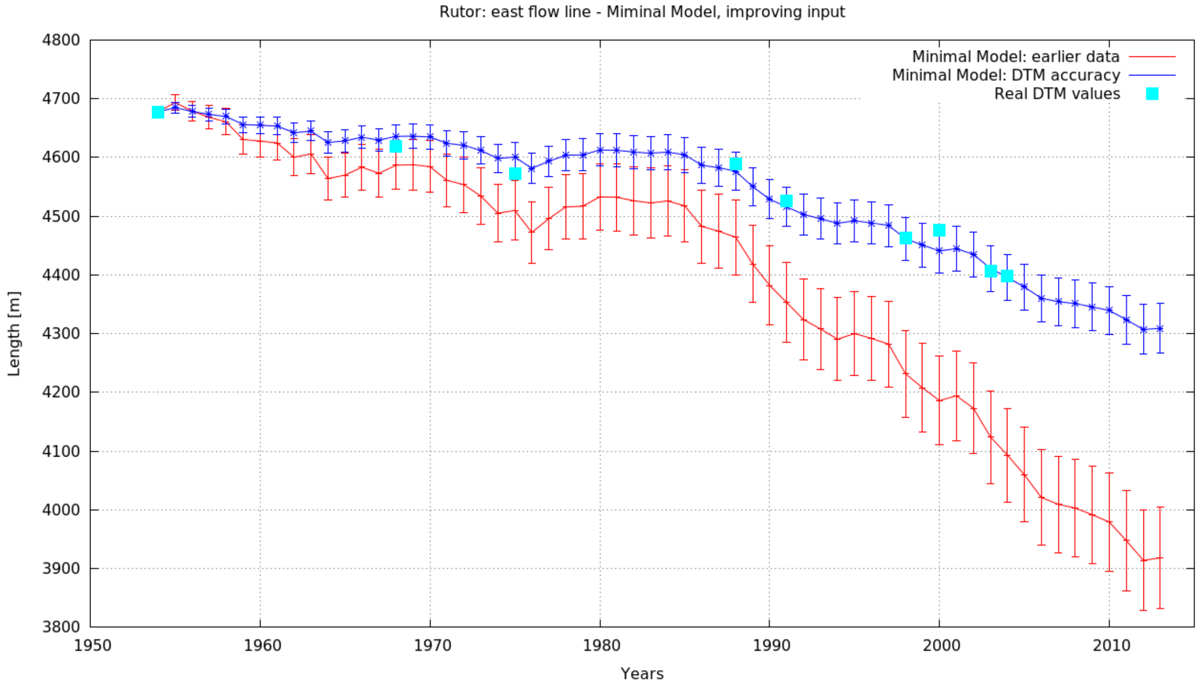


Figure 46 Comparison of model results in back analysis. Blue dot represents the east flow line length measured on DTM, the blue line is the results of the model calibrate using the MGD algorithm and the red line is the results of the model calibrate with data derived from literature research.

Overall, the use of a minimal glacier model combined with GIS information is a simple but effective way of simulating glacier response to climate change and climate variability, for this reason it is possible use it with a large scale-data set, in this study I applied the GDM at a sub-set of glaciers of the Greater Alpine Region.

4.4 *GlacierDataModule* application on Greater Alpine Region

4.4.1. Greater Alpine Region

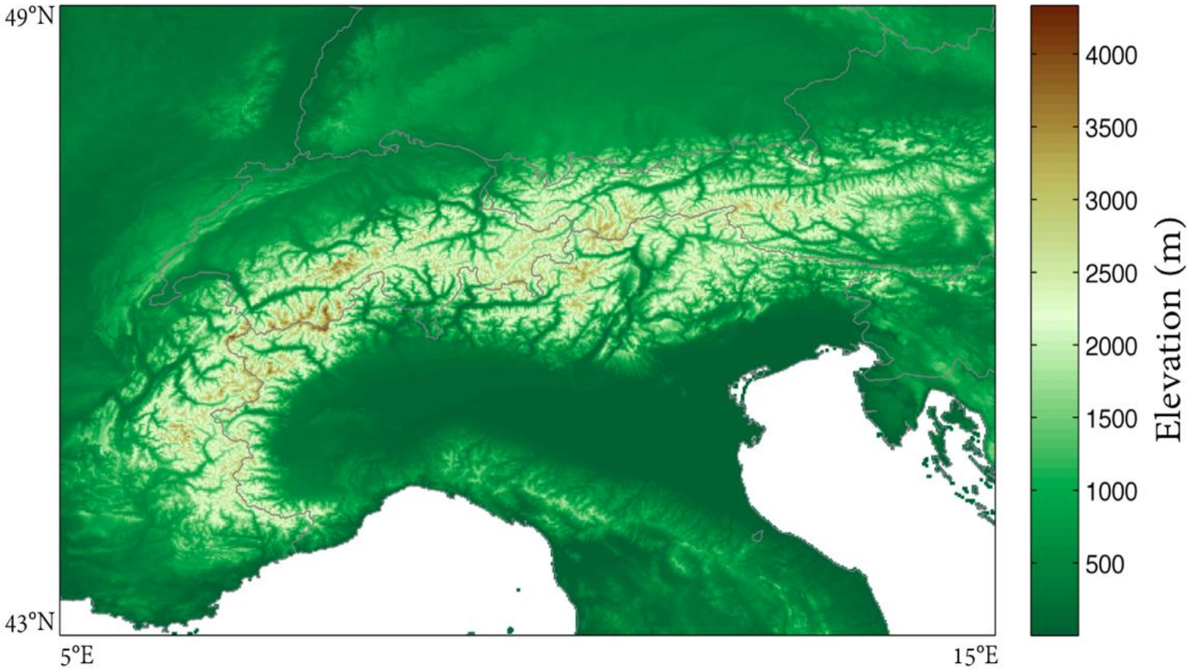


Figure 47 Greater Alpine Region (GAR) located between 5–15°E and 43–49°N.

Greater Alpine Region (GAR) is an area between 5°-15° East Longitude and 43°-49° North Latitude and range from the Mediterranean Sea level to a maximum altitude of 4,810 m a.s.l. at Mont Blanc summit in the western part of the Alps (fig. 47). This area includes the entire territory of Switzerland, Liechtenstein, Austria, Slovenia and Croatia and the mountainous part of France, Italy, Germany, Czech Republic, Slovakia, Hungary and Bosnia and Herzegovina, covering a total area of 724,000 km^2. (*Brunetti. et Al., 2009*). The Alpine arc is geologically young, with its orogenesis mainly in the Oligocene and Miocene of the Tertiary (Coward & Dietrich, 1989). Consequently, the area is characterised by extreme physiogeographic conditions with many peaks above 4000 m and steep topographic and climatic gradients. This is accompanied by a particularly high vulnerability to climate and environmental changes (*IPCC 2013*).

4.4.2. Alpine Climate

In general, the climate of the Alpine region is characterised by a high degree of complexity, due to the interactions between mountain ridges and the general circulation of the atmosphere, which result in features such as gravity wave breaking, blocking highs, and Foehn winds. A further cause of complexity inherent to the Alps results from the competing influences of a number of different climatological regimes in the region, namely Mediterranean, Continental, Atlantic, and Polar *(Beniston M., et al., 2005; Zampieri M., et al., 2013*). Furthermore, accumulation of vast masses of snow, constantly converted into permanent glaciers, maintains also a variation of very different climates. Simplify the heterogeneous situation described above, the alpine climate depends on four principal factors: the continentally position (I), latitude (II), altitude (III), and local topography (IV).

I -With continentally it means the proximity of the region to an ocean. The proximity to the sea reduces the annual and diurnal temperature range (*Lolis C.J., et al., 2002*), water has in fact a higher heat capacity than the soil and the rock, and then it takes more time to respond at the quantity of solar radiation that hit its surface, so it takes more time to change its temperature. Ocean is also a great source of moisture, the proximity of the alps to the ocean increase the quantity of rainfall.

II -The latitude affects the amplitude of thermal annual cycle and, to a lesser extent, the amount of precipitation.

III- The altitude is the most characteristic and important among the factors that can affect the mountain climate (fig. 48). The air density and temperature tend to decrease with altitude. Instead the thermal excursion increases because of the increasing heat capacity of the air, due to the fact that air is more and more rarefied.

IV-The topography plays a key role in determining the local climates, especially with the steepness of the slopes and exposure to climatic factors.

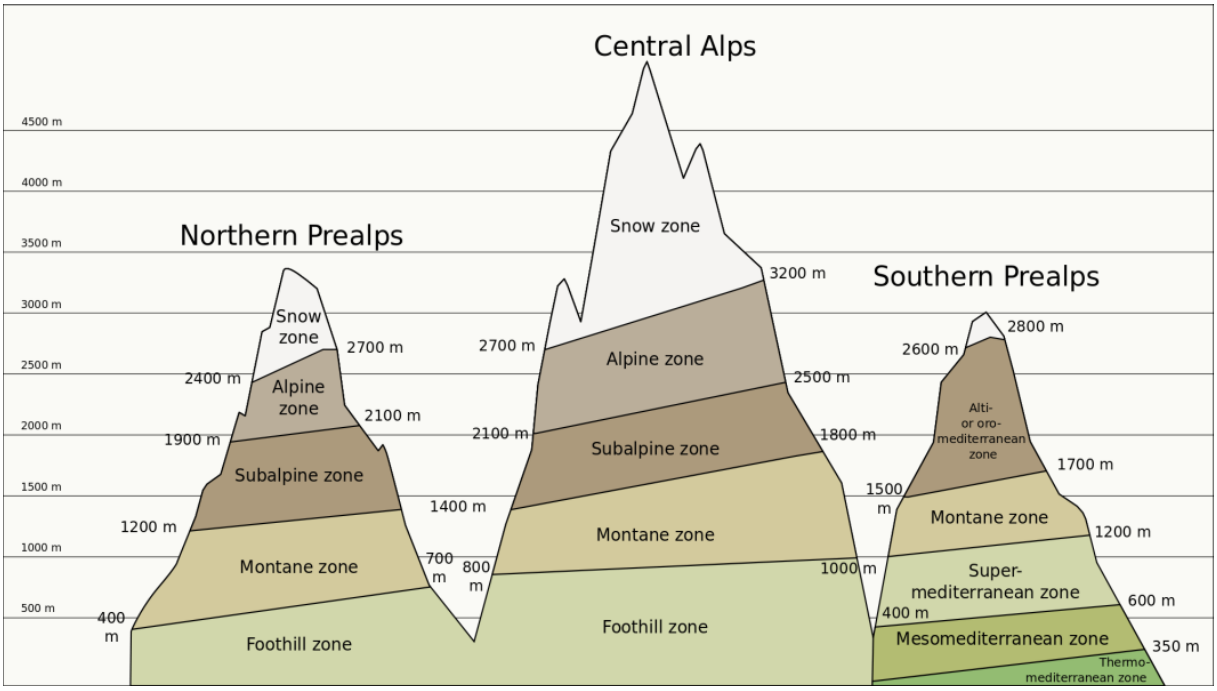


Figure 48 The Altitude and Latitude influence on Alpine climate. This two factor are two of four most important factors that affect the alps climate (https://en.m.wikipedia.org/wiki/Nival_zone).

These factors governing the distribution of the absorption of solar energy and precipitations and although dominated by winds from the west, the alps are unusual in comparison with other mid-latitude regions, where strong linear gradients are found as precipitation diminishes away from west coasts for example in the Western Cordilleras of America (*Østrem G., et al., 1981*). This happens because alps receive precipitation and winds from various direction (*Frei C., et al., 1998*) and the differences is due to east–west elongation of the Alps, their curvature, and the generation or revival of cyclonic systems on the Po Plain on their southern flank (*Cantu V., 1977*). Glaciers on Alps are strictly dependent on this factor. The geographical position is the most important factor of alpine glacier's health (*Evans. S., et al., 2006*).

4.4.3. Data source

Goal of this work is offer a friendly instrument to retrieve all data needed to model a great number of non-polar glaciers on GAR to assess their behaviour in a climate change scenario using a simply model as MGM as describe before. Input data for run the GDM on GAR was obtained from:

- Flow line were calculated with the methodology describe in the previous section
- Digital elevation model from ASTER GDEM2,
- Glacier boundary from *Randolph Glacier Inventory* (RGI).

Flow line

For each glacier evaluated the flow lines were calculated with r.flow and then digitalized following the procedure described in the previous paragraph. It was decided to maintain one flow line for small glaciers without a defined tongue and very small accumulation area, in opposite, for large glaciers with one or different tongue and large accumulation area it was decided to calculate more than one flow line to offer the possibility to run the GDM or calibrate the MGM in different area of the glacier.

Aster gdem2

In this study it was decide to used ASTER GDEM2 as global DEM source (fig. 50). The GDEM2 (Global Digital Elevation Model Version 2) is a map of Earth's surface, a raster representation consisting in a grid of regularly spaced elevation points, where each point is represented as a squared cell. The GDEM2 is derived from ASTER (Advanced Space borne Thermal Emission and Reflection Radiometer) mounted on the Terra Satellite. ASTER is an optical stereo instrument that include 3 bands in VNIR (visible and near infrared) with 15 m resolution, 6 bands in the SWIR with 30 m, 5 bands in the TIR with 90 m, that observes the landscape. (*Kaab. A.,et al., 2002*). The first version of the ASTER GDEM coverage spans from 83 degrees' North latitude to 83 degrees South, encompassing 99 percent of Earth's landmass. The improved GDEM2 adds 260,000 additional stereo-pairs, improving coverage and reducing the occurrence of artefacts. GDEM2 maintains the GeoTIFF format and the same gridding and tile structure as V1, with 30-meter postings and 1 x 1 degree tiles.

The studies conducted on GDEM2 have shown that it has 30 meters' horizontal resolution, with an RMSE of 8.68 meters and the absolute vertical accuracy, expressed as a linear error at the 95% confidence level (LE95), is 17.01 meters. (*Tachikawa T.et Al., 2011*).

Was choose ASTER GDEM2 for different reason:

- is suitable for the compilation of topographic parameters in a glacier inventory because the average differences from the parameter values from different global DEM (STRM, GLSdem, GLOBE) are not larger than ±7 m for the elevation parameters, which is in the same order of magnitude than the vertical accuracy of these DEMs. (*Frey P., et al., 2012*).

- North of 60° N and south of 56° S, where many unmapped and huge glaciers and icecaps are located, the GDEM is often the only available dataset.(*Cogley, 2009*).

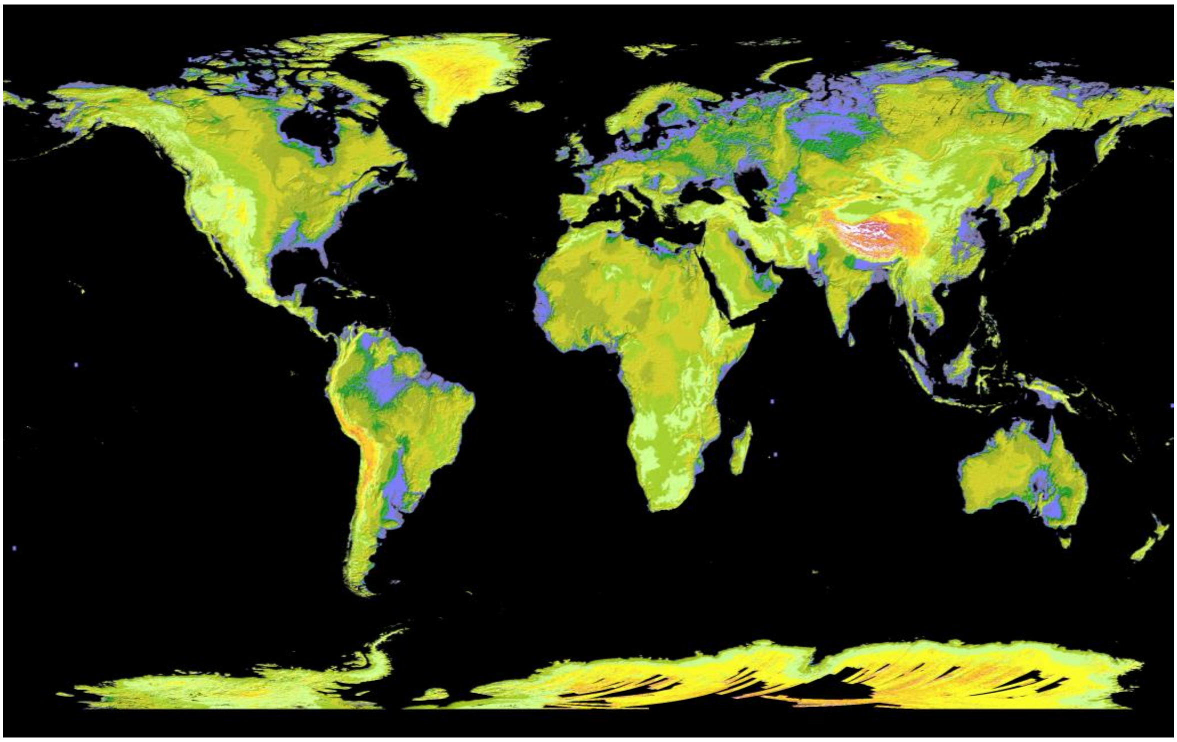


Figure 49 ASTER-GDEM V2 Colorized Map (Tachikawa.T.et Al., 2011).

Glacier boundary from Randolph Glacier Inventory

The Randolph Glacier Inventory (RGI) is a globally complete inventory of glacier outlines. It is supplemental to the Global Land Ice Measurements from Space initiative (GLIMS). The RGI was not designed for the accurate measurement of one single glacier rates of area change, for which the greatest possible accuracy in dating, delineation and georeferencing is essential, even if many RGI outlines pass this test, in general completeness of coverage has had higher priority. Rather, the strength of the RGI lies in the capacity it offers for handling many glaciers at once, for example for estimating glacier volumes and rates of elevation change at regional and global scales and for simulating cryospheric responses to climatic forcing. In harmony with the goal of this study. RGI IDs for selected glaciers were identify by query at IDB2, so, also in this case, the built SDI has become a data provider.

4.4.4. Subset of the study area

The area on which this study is focused is a subset of the GAR where all territories without glaciers and data relating to them are excluded. The Saint-Sorlin and Sarennes glaciers are the South-East boundary of our study area, in the North-East we stopped at Vernagt and Wurten glaciers, two glaciers of Golberg group (fig. 50).

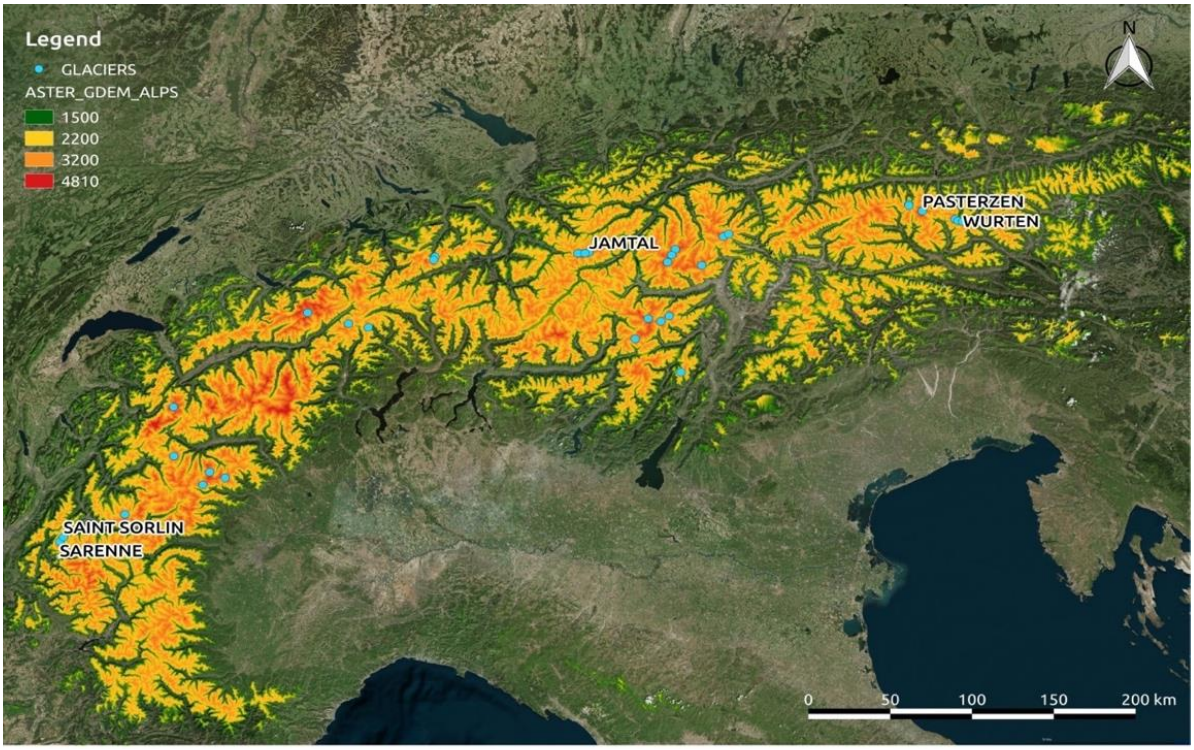


Figure 50 Subset area of GAR used in this study

It was choosing this part of GAR for two main reason:

1. The Alps constitute the most relevant topographic ridge of Europe. They influence atmospheric circulation over a wide range of scales, and exhibit a variety of different climates, ranging from maritime influences (from the Mediterranean, the Atlantic and Arctic ocean) to continental features (such as the plains of Eastern Europe and the inner Alpine valleys).

2. There are a lot of high-quality secular proxy records (such as the ice core data) of the last two centuries (*Brunetti M., et al., 2006; Brunetti M., et al., 2009; Beniston M,, 2005*). This amount of data

could be used to reconstruct the climatic variations of the area and also could be used to conduct a retro analysis.

This study focalizes in particular on the 34 glaciers that have the longest historical series of data related to the mass balance, a primary input for calibrate the Minimal Glacier Model (tab. 10).

Table 10 Table containing the 34 glaciers studied with certain parameters: Latitude & Longitude in degrees, Area in km^2, Altitude in meters.

NAME	RGI ID CODE	LONG	LAT	AREA(km^2)	Z_AVG(m)
AGOLA	RGI50-11.01580	10.86	46.15	0.16	2713
ARGENTIERE	RGI50-11.02835	6.99	45.94	11.73	2851
BASODINO	RGI50-11.01987	8.48	46.41	2.10	2871
CARESER	RGI50-11.01140	10.71	46.45	2.83	3072
CIARDONEY	RGI50-11.03254	7.38	45.52	0.34	3076
FILLECK	RGI50-11.02489	12.59	47.14	0.03	2862
FONTANA BIANCA	RGI50-11.01704	10.77	46.48	0.56	3182
GEBROULAZ	RGI50-11.03432	6.63	45.29	0.86	2824
GRAND ETRET	RGI50-11.03298	7.22	45.47	0.49	2946
GRIESGLETSCHER	RGI50-11.01876	8.33	46.44	5.29	2935
GROSSER ALETSCH	RGI50-11.01450	8.01	46.50	82.20	3162
HINTEREISFERNER	RGI50-11.00897	10.75	46.80	8.04	3050
JAMTAL	RGI50-11.00781	10.16	46.85	3.82	2813
KESSELWANDFERNER	RGI50-11.00787	10.79	46.84	3.96	3185
KLEINFLEISS	RGI50-11.00251	12.94	47.05	0.79	2846
LANGTALER	RGI50-11.00929	11.01	46.78	2.38	2901
LIMMERN	RGI50-11.00918	8.97	46.81	2.01	2781
LUNGA	RGI50-11.01776	10.61	46.47	2.16	3140
LUNGA VEDRETTA	RGI50-11.00804	10.07	46.85	2.88	2780
MALAVALLE	RGI50-11.00597	11.18	46.95	6.33	2999
OCHSENKAR	RGI50-11.00289	12.97	47.04	0.63	2647
OCHSENTALERG	RGI50-11.00797	10.10	46.85	2.35	2910
PASTERZE	RGI50-11.00106	12.69	47.09	17.77	2984
PENDENTE	RGI50-11.00603	11.22	46.96	0.84	2784
PLATTALVA	RGI50-11.00892	8.98	46.83	0.42	2748
RUTOR	RGI50-11.03140	7.00	45.65	8.11	2986
SAINT SORLIN	RGI50-11.03503	6.16	45.16	2.87	2912
SARENNE	RGI50-11.03515	6.13	45.13	0.43	3267
SFORZELLINA	RGI50-11.02214	10.51	46.35	0.21	2894
STUBACHER S	RGI50-11.00080	12.59	47.13	1.19	2791
TIMORION	RGI50-11.03198	7.27	45.55	0.20	3132
VERMUNTGL	RGI50-11.00807	10.13	46.85	1.67	2801
VERNAGTFERNER	RGI50-11.00719	10.81	46.88	8.56	3142
WURTEN	RGI50-11.00300	13.00	47.03	0.21	2617

4.5 Results

For each of this 34 glaciers flow lines were extracted and GDM was running. The results are show below (tab. 11). The most important extracted parameters from the 34 glaciers, as flow lines length, aspect, maximum and minimum elevation and slope was used to set boundary conditions of the MGM. The results were upload in IDB2 in the dedicated entities *Glacier Data* (paragraph 3.1).

Table 11 The 34 glaciers studied with six parameters extracted through GDM from the most relevant flow line of each glacier.

NAME	RGI ID CODE	SLOPE (%)	Z MIN(m)	Z MAX(m)	ASPEC(°)	FLOW LENGHT(m)
ALETSCH	RGI50-11.01580	17.37	1580	4086	231.59	22125
ARGENTIERE	RGI50-11.02835	27.94	1636	3760	132.01	9220
BASODINO	RGI50-11.01987	36.51	2659	3149	77.83	1486
CARASER	RGI50-11.01140	16.22	2867	3290	273.12	1200
CIARDONEY	RGI50-11.03254	24.32	3002	3138	129.04	767
FILLECK	RGI50-11.02489	15.23	2820	2894	90.02	240
FONTANA	RGI50-11.01704	43.60	3004	3283	101.42	829
GEBROULAZ	RGI50-11.03432	23.85	2628	3006	111.59	2267
GRAND_ETRET	RGI50-11.03298	40.70	2676	3122	95.96	1228
GRIESGLETSCHER	RGI50-11.01876	24.99	2427	3364	129.21	5392
HINTEREIS	RGI50-11.01450	23.86	2434	3692	147.34	7230
JAMTAL	RGI50-11.00897	30.26	2427	3020	100.60	2427
KESSELWAND	RGI50-11.00781	23.13	2772	3489	245.76	4038
KL.FLEISS	RGI50-11.00787	32.25	2704	3038	186.74	1208
LAGOL	RGI50-11.00251	46.95	2605	2893	122.46	632
LANGTALER	RGI50-11.00929	24.27	2501	3345	102.62	4285
LIMMERENFIRN	RGI50-11.00918	40.61	2305	3422	69.39	3448
LUNGA	RGI50-11.01776	30.45	2671	3389	110.76	2919
MALAVALLE	RGI50-11.00804	22.87	2563	3228	198.81	4054
OCHSENTALER	RGI50-11.00597	30.00	2440	3073	91.02	2350
PASTERZEN	RGI50-11.00289	21.84	2069	3424	208.02	7927
PENDENTE	RGI50-11.00797	29.00	2668	2949	223.00	1160
PLATTALVA	RGI50-11.00106	34.22	2726	2958	215.70	792
RUTOR	RGI50-11.00603	22.83	2552	3418	123.09	4458
SAINT_SORLIN	RGI50-11.00892	32.72	2670	3437	89.98	2752
SARENNES	RGI50-11.03140	45.74	3104	3375	277.00	615
SFORZELLINA	RGI50-11.03503	46.00	2834	3043	117.00	499
SILVRETTA	RGI50-11.03515	23.80	2521	3106	164.00	2912
SONNBLICK	RGI50-11.02214	38.38	2492	2985	86.41	1667
TIMORION	RGI50-11.00080	43.17	2986	3330	114.74	854
VERMUT	RGI50-11.03198	30.00	2511	2910	110.00	1637
VERNAGT	RGI50-11.00807	21.17	2866	3309	238.45	2689
OCHSENKAR	RGI50-11.00719	31.06	2376	2775	108.52	1621
WURTEN	RGI50-11.00300	25.10	2526	2698	219.19	804

Geomorphological results analysis

Different statistical methods to evaluate the obtained data were done. By the construction of frequency histograms, it was possible evaluate the frequencies distribution for each parameter. Using scatter plot was possible searching some possible clusters or any degree of correlation between geographic location of our glaciers sample and calculated geomorphological parameters. Different scatter plots were drawn for each glacier; the six geomorphological parameters (z min, z max, z average, slope, aspect, flow length) were plotted each one with latitude and with longitude, to underline contingent correlations or identify some trends. In this paragraph I show significant results obtained from this statistical analysis on geomorphological data obtained from GDM.

Glaciers Altitudes

The scatter plot below (fig. 51), shows average altitude related to longitude. There is a significant linear gradient underlined by trend line in red where the glaciers average altitude diminishes away from west.

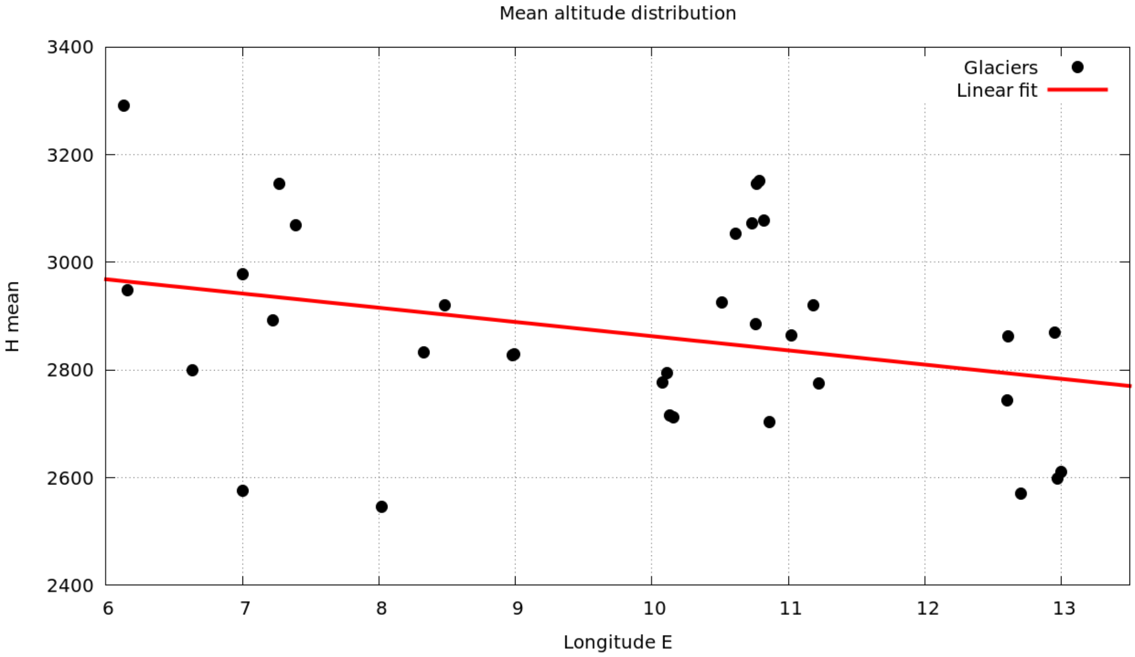


Figure 51 Altitude-Longitude Scatter plot diagram with trend line

This underling linear trend is not a strong trend, as expected, because the altitude of a mid-latitude glacier is influenced not only from the geographical position but also by the gradient, the glacier size and the detailed topographic position (*Evans. I.S., 2006*). However, it is possible assume that the reason of this gradient is due to the location of the centre of High Pressure from May to September over the Alpine arc. During summer period, both Azores and North African anticyclone, the first from the Ocean, and the second from the Sahara Desert, usually place their centre with maximum geopotential height closer to the Western Alps. Since the air temperature, into a dynamic high pressure, diminishes away from the centre, the air masses are ordinarily hottest over the Western alps than Eastern (fig. 52) (*Lolis C.J., et. al., 2002, Brunetti M., et al., 2009*). Other two diagrams were carried out for minimum altitude and maximum altitude and the results shows the same behaviour for all the three parameters.

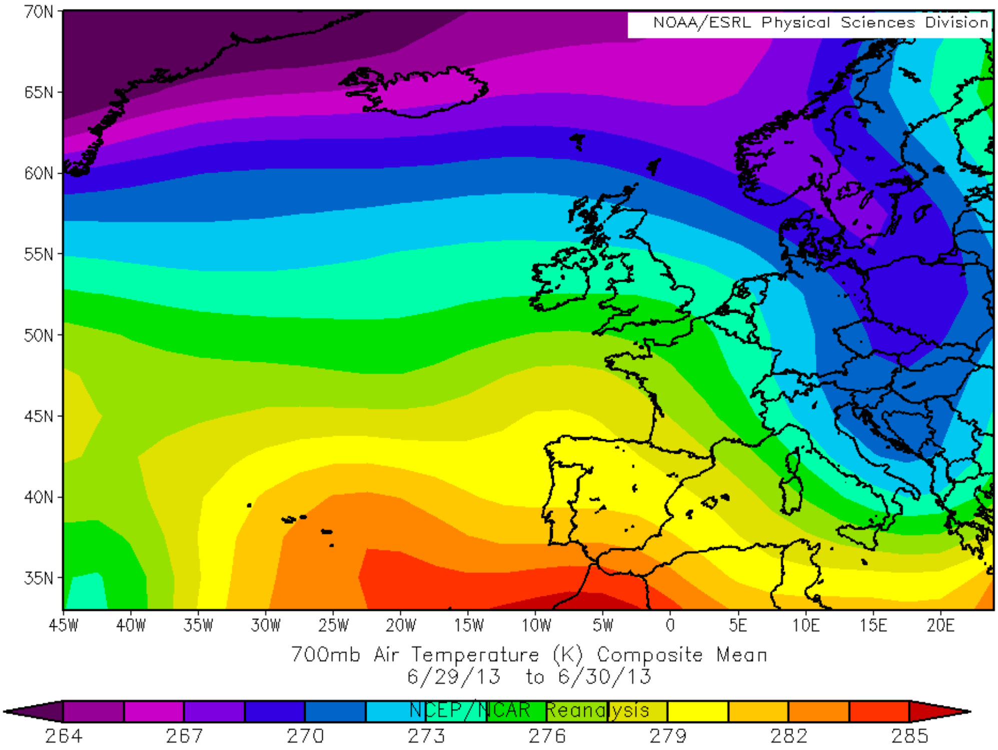


Figure 52 typical European climatic summer situation

Glaciers Aspect Distribution

A statistical analysis was performed over the entire sample by the construction of frequency histograms for *aspect* parameter (fig. 53/a). Aspect is the parameter that describe the orientation of glacier body. In our dataset the aspect frequency is not homogeneous along all directions. An important peak for orientation N-NW and other three minor peaks for orientation N, NW, SW are notable. A small group of glaciers favours other directions but, is it important notice that, in our dataset there are no glacier that present orientation from S-SE to N-NE creating a lack of about 135 degrees (fig. 53/b).

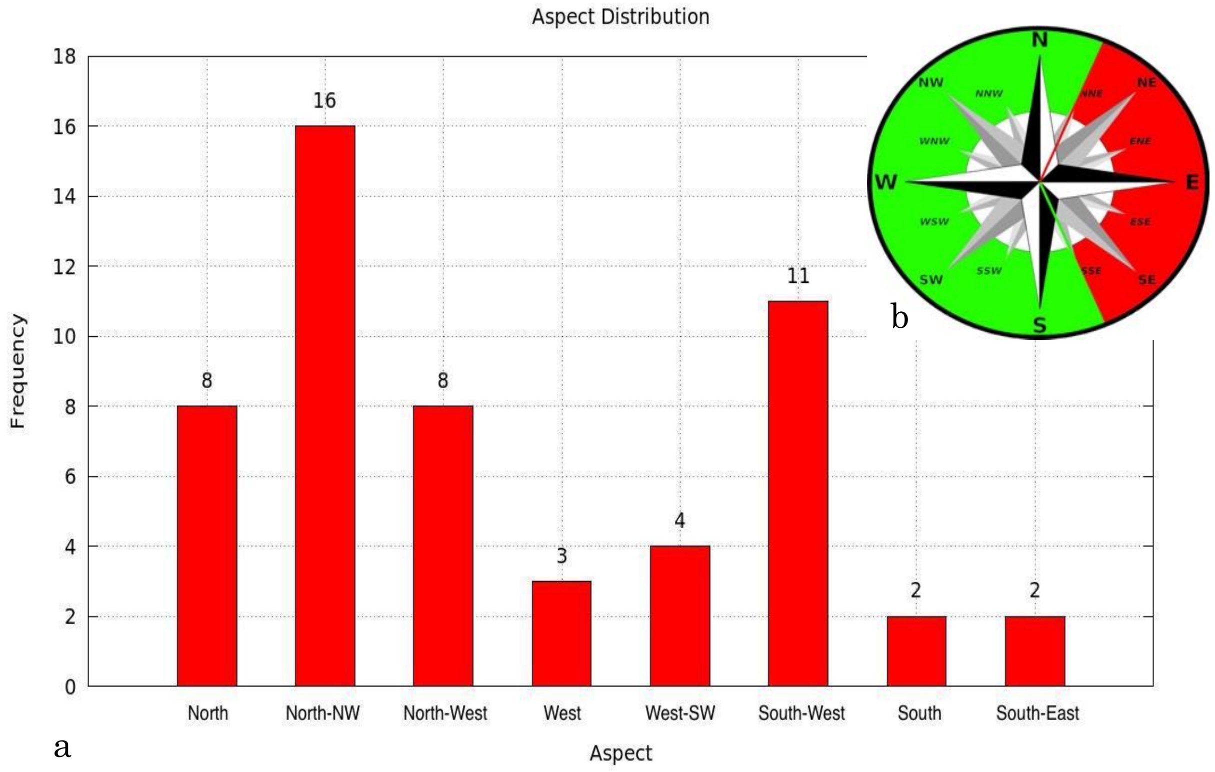


Figure 53/aAspect distribution frequency histogram, b Compass rose with sixteen points. In red, directions without aspect.

The histogram shows that a preferred orientation between S-SW and N is pervasive through the data. The north orientation is simple to explain because North is where the solar insolation is lower and then glacier has less melting. Regarding other orientations, it’s hypothesized that tendencies west of north are due to differential cloudiness between morning and afternoon. The major parts of the Alps less affected by maritime air have a stronger convective regime in summer, triggering afternoon cloud. This reduces melting on slopes with a westward aspect: glaciers facing eastward suffer stronger insolation from the morning sun (*Evans. I., 2006*). Aspect with latitude for all 34 glaciers were also plotted. As it can see in figure (fig. 54) from 45°N until 46.5°N the glaciers are oriented N-W and N. Otherwise above 46.5°N the glaciers have orientations between S-E and N.

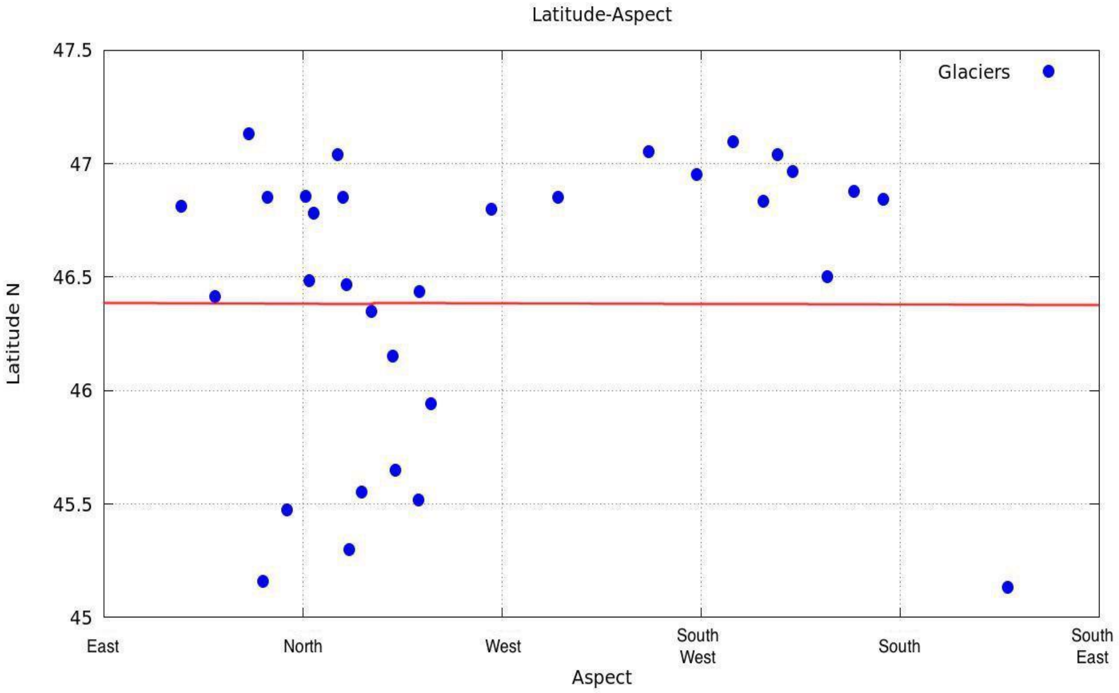


Figure 54 Latitude-Aspect Scatter plot with red transect to divide the two groups of data with different behaviour

The reason that explains this different aspect's distribution may be found in their geographical position. The southernmost glaciers are more influenced by hot air masses, that are brought by subtropical anticyclones. Thus they better survive to melting if are N, N-NW oriented as showed in the previous figure (fig. 54/a). The point at right bottom is the Sarenne glacier, the westernmost glacier of our sample. This glacier presents the highest minimum altitude, over 3000 m a.s.l, and receive a great amount of winter precipitations both from Atlantic Ocean and Mediterranean

Cyclones. This must be the reason why the Sarennes in his southern orientation, survives.

The statistical analyses performed on the parameters resulting from the GDM for our dataset of glaciers of the GAR are definitely not exhaustive, more work needs to be done and many other glaciers are to be taken into account in order to get a reliable result. But the comforting fact is that, for now, our results are comparable to those obtained by Evans in his study (I. Evans, 2006) in which about 3,000 alpine glaciers were analyzed.

4.6 Conclusion

In this part of the work a GIS tool to obtain data for evaluate the glaciers response to climatic fluctuation called *GlacierDataModule* was developed. The GDM that was proposed it is originate from the necessity to have specific data to calibrate Glaciological Minimal Model that are not available in literature. It's a user-friendly instrument for a GIS user and it require a readily available data as input. It can be applied at larger dataset but also to a single glacier with high resolution data to conduct multitemporal analysis as shown for the Rutor glacier.

It is also important notice that the results of the *GlacierDataModule* can be upload in the build SDI called IDB2. In this way the SDI became a dynamic structure that provides data to run the GDM tool and can receive the results of the analysis in a dedicated entity. This tool was also integrated as a calibration tool in the *r.glacio.model*, A GRASS-GIS module that offer a GIS instruments to evaluate the glacier dynamics along the flow line following the same equations that drives the MGM *(Strigaro et al., 2015).*

5 FINAL CONCLUSION

Summary of the research

Glaciological data collected in non-polar and mid latitude mountain chains are crucial for monitoring and understanding global climate change and related phenomena. In fact, even if the non-polar glaciers constitute a minor amount of the whole glaciated land surfaces of the planet (~4%), they play the role of rapid response proxies and indicators of global changes.

Despite their importance, glaciological datasets are to few as compared to their environmental relevance; this is mostly due to the remoteness of areas to be inspected, and the lack of both financial resources and common strategies for glacier monitoring. Only in the last decade some international consortiums are starting to produce world glaciological datasets such as WGI, RGI, GLIMS, WGMS, PANGEA.

In this work, a system for retrieval and manage multisource and heterogeneous information coming from glaciological area has been proposed. This system aims to organize and aggregate both the ice cores proxy data (useful to evaluate climatic fluctuations on the past) and glaciers geomorphic parameters (useful to assess the glaciers response to climatic fluctuations in the past or in the future).

The method adopted involves the exploitation of the well-established principles for Spatial Data Infrastructures: modularity, interoperability of components and services. The use of standards for the implementation of the architecture was also a key concept: the main international and European standards, and their Italian actualizations were used to profile data and metadata and for publishing them via geo-spatial web services (§2.4).

The aim of this research in particular was to create a methodology for recovery, storage, to access and disseminate glaciological data starting from the development of an open source geodatabase and use it to study the evolution of the glaciers in relation with climate fluctuations.

The first step of the work has been to develop a non polar ice-core spatial database for paleoclimatic analysis. The database was called "*Ice Core Database*" -IDB1 and was based on existing database called "WDB" ("Water and Weather Database System") to answer at the deliverables of the NextData project (§2.2). This database was designed to store the ice cores' chemical and physical characterizations (§2.3).

IDB1 showed some weaknesses due to the constraints of using an existing structure designed for storing meteorological data, the WDB (§3.1).

In particular, the database structure:

- Is not suitable to store information such as validation of measurements and spatial and temporal distribution as indicate by Bradley (*1999*) to evaluate the spatial validity of a proxy,
- Is not suitable to store different level of territorial data,
- Is not possible relate the Ice core to any glacier nor as a simple association, nor by territorial point of view,
- Low accuracy of spatial positioning due to the low precision of found or supplied data.

To overtake the critical issues previously mentioned a new structure (IDB2) was set-up with these improvements (§3.1.1):

- Different entities with information about project of perforation, drilling-site, references of data and additional information about ice core were added to the IDB1 structure.
- Better accuracy of ice cores' coordinates by the repositioning methodology developed.

- Linked ice cores with glaciological databases of glaciers containing spatial information, geomorphometric data and several information about glaciers where ice cores were taken.
- New entities were added to store data coming from geomorphological analyses conducted on glaciers and in particular on glacier flow lines.

About the general structure of IDB2 (§3.1.1): five logical entities, regarding ice cores were created; *project*, *drilling*, *ice core data*, *references*. These entities are linked to each other and all of them have a primary link with the Ice core tab. Two entities regarding glaciers were also added and linked with ice cores.

Due to the precision of the coordinates found in literature an accuracy problem has emerged. Only few ice cores reported coordinates with the accuracy from 1 to 10 meters, in most cases the available coordinates showed an accuracy of 100m or higher. In literature only the coordinates of the mountain summits where drilled glaciers are, or just a dot in a topographic 1:50.000 or at most 1:100.000 maps, were found.

This problem has been evaluated and a repositioning methodology has been created (§3.1.2).

To increase the strength of IDB2 and to offer a complete and useful instrument to evaluate the past climatic fluctuation, to obtain data to calibrate numerical models for model the glaciers behaviour in a climate change scenario two entities with data about glacier body was added in IDB2 (§3.1.3):

- *Glacier Code* stores the union between the different glaciers databases available at the scientific community.
- *Glacier Data* contains the geomorphological parameters such as flow line length, min and max elevation, average slope and aspect calculated using the GlaciersDataModule.

The ID of glaciers contained in 4 different glaciological databases were joined with a spatial analysis (§3.1.4). The results were added at the IDB2 in a dedicated entity (*Glacier code)* that contains 132890 glaciers. From this tab it was possible find the ID of the glaciers that were drilled or that are potentially drillable, or the ID used to identify the glaciers that could be modelled using Minimal Glacier Model.

The third part of the research was aimed to create a GIS tool able to satisfy the request of scientist to obtain geospatial data for conducting analysis on glaciers flow lines. So a useful and simple tool for users to obtain flow lines and geospatial data on flow line was developed.

A GIS module called *GlacierDataModule* (GDM) (§ 4) was developed during the third year (§4.2). The tool was developed to extrapolate from DTMs, all the geomorphic parameter needed to evaluate the glacier response to climatic fluctuation and in particular the necessary data to calibrate Minimal Glacier Model (MGM). To set the MGM parameters and initial conditions through DTMs, the *GlacierDataModule* requires, as inputs, DTMs, POLYGONs and FLOW LINEs of the glacier body (§4.2.1). The output of the GDM are geomorphic parameters calculated in 100 meters of buffer along the digitalized flow lines. In particular, GDM calculates: flow line length, altitude range along the flow lines and average slope and aspect. The GIS tool was validated on Rutor glacier (§4.3).

The GDM was used to extrapolate data for 34 glaciers of the Greater Alpine Region (GAR) (§4.4). Input data for running the GDM were recovered from IDB2 and ASTER GDEMv.2 was used as DTM input source. Flow lines were calculated and digitalized.

Statistical analysis was also done on the geomorphic parameters calculated with the GIS algorithm. The orientation, the maximum, minimum and average altitude, slope and exposition were evaluated (§4.5).

The results were compare with the results presented by Evans in his study where 6561 glaciers on the GAR were evaluated (Evans, I.S., 2006).

General results

A total of 185 different ice cores were found (fig. 29) from 5 different sources, NOAA-NIDC database, NICL table, PANGEA database, DISAT repository and scientific literature. Of these 185, 52 ice cores come from NOAA and NICL, 3 from PANGEA, 2 from DISAT repository and 128 are new georeferenced and stored for the first time in a spatial database. To better identify these ice cores, a total of 56 project of perforation and 98 drilling site entity were compiled with the needed information. A list of 116 papers were added as references.

The chemical and physical characterizations of ice cores are available for 34 ice cores out of the 185 stored in the database (§3.2).

132890 unique glaciers ID coming from the union of 4 different glaciers repository were also upload in the IDB2.

Data coming from the application of GDM on GAR were used to populate the *glacierdata* entity in IDB2 and then used to calibrate the MGM to assess glaciers' response to climatic fluctuations.

Data dissemination

A geoportal with a webgis available at geomatic laboratory website: geomatic.disat.unimib.it/home/geomatic/idb2/ was developed to share data. Webgis display the ice cores and the data about glaciers. A pop-up with info about name, ice core temporal coverage and other parameters appear when an ice core is selected. For every characterized ice core, a webpage with info and graphs about the selected parameter is shown.

Contributions to body of knowledge and practices

The work carried out brings an original, tangible contribution to the management of the glaciological information related to climatic fluctuation. Moreover, it introduces some theoretical representations and practical solutions, which could be of interest not only for glaciologists, but also for other researchers in the field of climatic reconstruction and paleoproxy data management. Scientists, professionals and stakeholders share the need for an integrated system to retrieve, access and analyse this kind of information, since currently there is not a unique gateway to obtain up-to-date glaciological proxy and also there is not a quickly and user-friendly tool to retrieval geomorphic data about glaciers flow lines on large scale dataset.

Conclusive remarks

In conclusion, during this Ph.D. work, a glaciological Spatial Data Infrastructure called *Ice Core Data Base v2* was developed and made available to stakeholders. By the creation of an advanced-object-relational database I was able to adsorb the complexity due to join together different data typology (chemical-physical for the ice core and geomorphic for glaciers) and different temporal scale (100 kyears for ice core in the past, 100-200 years in past and in the future for glaciers) in a single Spatial Data Infrastructure that embraces 4 dimension: the 3 spatial dimension (latitude, longitude, elevation) of ice cores and glaciers body and the temporal dimension of the ice core characterization and the value of geomorphic parameters of the glacier in the past and in the future. Starting from the information retrieval by the IDB2 it is also possible through web-crawling search other sources of proxy data comparable and temporally overlap with the ice cores record to built the best probable scenario of climatic evolution of the Earth.

IDB2 allows at the scientific community to compare different ice cores and obtain the parameters to modelling the suitability for ice core drilling of mountains glaciers. It also provides parameters to run the developed *GlacierDataModule* GIS tool already used to obtain geomorphic parameters to calibrate glaciological mathematical model to study and to evaluate the glaciers response at climatic fluctuations.

This tool represent also one of the three part of r.glacio, a GRASS-GIS plugin that spatialize the MGM (Strigaro D., 2015).

The SDI implemented is compliant to the recommendation of the European directive INSPIRE and to the main international standards for geo-spatial information (OGC). In this way the web services deployed can be invoked by users starting from several clients' applications, and the data can be accessed from different interfaces (GIS software, web mapping applications, geoportal, virtual globes).

The system developed is deliberately composed by open-source and free modules, compliant to widespread standards. In this way it results scalable, customizable and replicable without licensing costs.

Future development

In the future all data coming from analysis carried out on ice core recovered in *Colle del Lys* in 2012 will be uploaded in IDB2. All the available ice cores characterization will be uploaded and the entire SDI will be continuously updates. The IDB2 will be also used to identify paleo-climatic proxies that could be useful, within the interaction of other paleo-climatic proxies (lake sediments; marine sediments; pollen and corals), to reconstruct the last 2K years of climate variability in Italy (*Moinuddin A., et al., 2013*) and its structure will be insert in a greater SDI that will contain climatic proxy data coming from different sources (*Stringaro, 2015*). About the *GlacierDataModule*, the flow line calculation will be made automatic

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APPENDIX

Appendix A

List of 80 parameters with their corresponding units of measurement selected to be stored in IDB1. Selection was made after an accurate bibliography review and only parameters that may results useful to paleoclimatic analysis were selected.

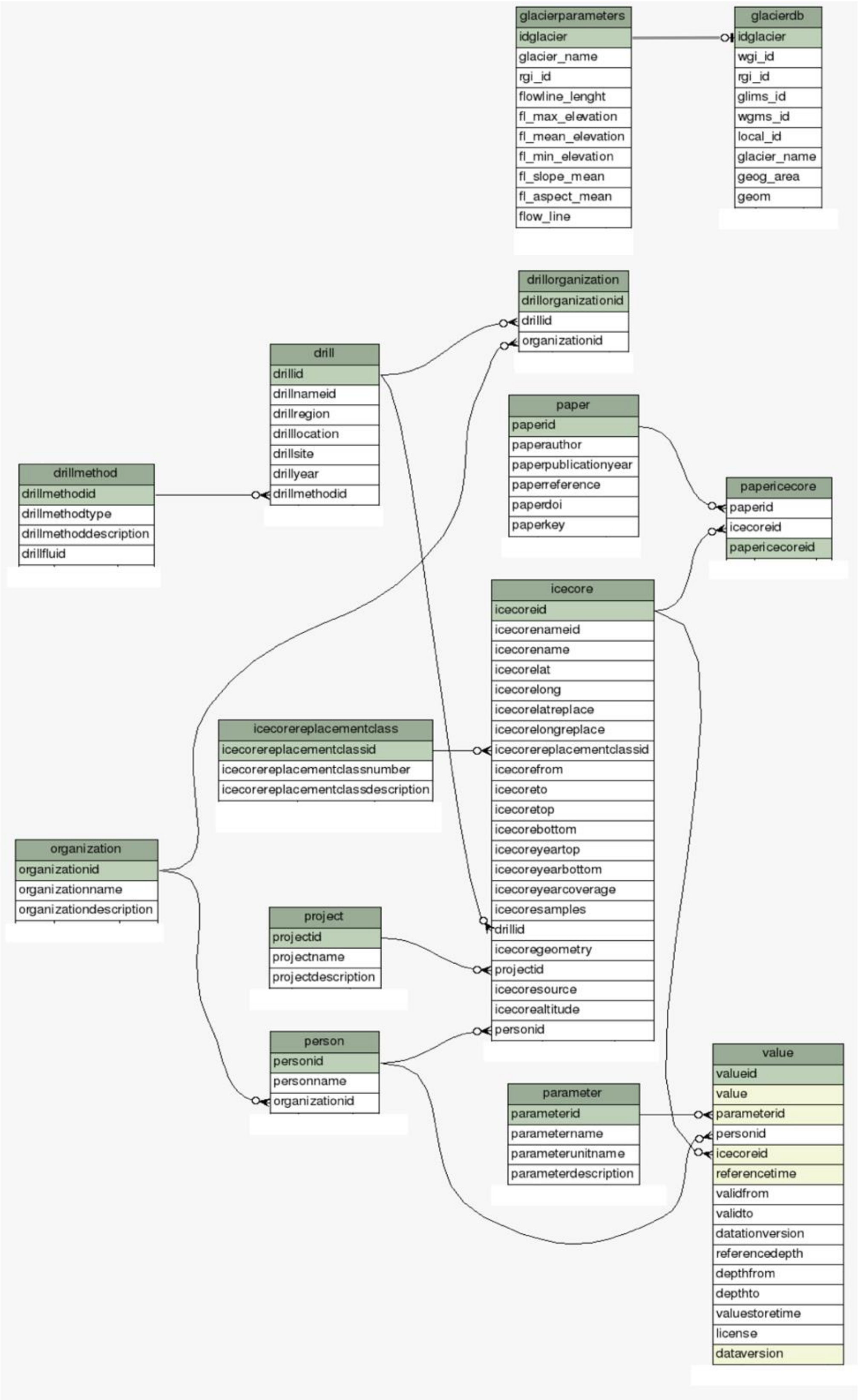
NAME	UNIT
1sigma [error (deg C) (including SE of d18O and calibration)]	°C
Acc (std dev) Avg of p= 1.5 & 2.0	m.w.eq.
Accumulation (m)	m
Aluminium (ppb)	ppb
Ammonium (ppb)	ppb
Antimony (ppt)	ppt
Atm d18o (respect to present)	‰
Barium (ppt)	ppt
Black Carbon (ugc/L)	mgc/L
Bismuth (ppt)	ppt
Cadmium (ppt)	ppt
Calcium (mq/L)	meq/L
Cerium (ppt)	ppt
Cesium (ppt)	ppt
Chloride (mg/L)	mg/L
Chlorine 36/g (x10^4)	
Chromium (ppt)	ppt
Cobalt (ppt)	ppt
Conductivity (µs/cm) (thermal year)	µS/cm
D(32/38) with respect to present	‰
D(Ar/N2) with respect to present	‰
D(CO2/N2) with respect to present	‰
D15n	ratio
Dd (per mil) 5 years average	per mil
Depth (cm)	cm

Dysprosium (ppq)	ppq
Erbium (ppq)	ppq
Europium (ppq)	ppq
Fluoride (ppb)	ppb
Formate (mq/L)	meq/L
Gadolinium (ppq)	ppq
Gas age (yrs BP)	yrs BP
H2O depth (m)	m
Holmium (ppq)	ppq
IED layer thickness	
Iron (ppb)	ppb
Lanthanum (ppt)	ppt
Layer thickness (Thermal year)	
Lead (ppt)	ppt
Lead flux	
Lutetium (ppq)	ppq
Magnesium (mq/L)	meq/L
Manganese (ppb)	meq/L
Max estimate from multiple cores (Tg SO42-)	Tg SO42-
Maximum enrichment factors (EF) 1 year data	
Mercury (ng/l)	ng/L
Methane (ppbv)	ppbv
Min estimate from multiple cores (Tg SO42-)	Tg SO42-
Minimum enrichment factors (EF) 1 year data	
Neodymium (ppt)	ppt
Nitrate (mg/l)	mg/L
Number of particles with diameters 0.63 micrometers or larger	
Number of particles with diameters 2.0 micrometers or larger	
Number of particles with diameters 0.5 micrometers or larger	
Number of particles with diameters 0.80 micrometers or larger	
Number of particles with diameters 1.0 micrometers or larger	
Number of particles with diameters 1.6 micrometers or larger	
Number of particles with diameters 10.0 micrometers or larger	
Number of particles with diameters 12.7 micrometers or larger	
Number of particles with diameters 2.52 micrometers or larger	

Number of particles with diameters 3.17 micrometers or larger	
Number of particles with diameters 5.0 micrometers or larger	
Number of particles with diameters 8.0 micrometers or larger	
Potassium (mq/L)	meq/L
Praseodymium (ppt)	ppt
Samarium (ppq)	ppq
Sample lenght (cm)	cm
Sodium (mq/L)	meq/L
Sulfate (mg/L)	mg/L
Sulfur (ppb)	ppb
T anom [**temperature (deg C anomaly vs. 1250-1980 s)]**	°C
Terbium (ppq)	ppq
Thallium (ppt)	ppt
Thulium (ppq)	ppq
Titanium (ppt)	ppt
Tritium (TU)	TU
Trop Volc SO42- aerosol loading (Tg SO42-)	Tg SO42-
Uranium (ppq)	ppq
Ytterbium (ppq)	ppq

Appendix B

IDB2 scheme and relationship between entities.



Appendix C

Principal entity and data available in the IDB2. *All the tables reported in the next pages are referred at the European ice cores and they are an example to show the typology of data contained in IDB2.*

Drill tab:

ID	Region	Location	Place name	Year		Method
CD84	France	Alps, Mont Blanc	Col de Brenva	1984	LGGE	NULL
CD94	France	Alps, Mont Blanc	Col du Dome	1994	LGGE	NULL
CD97	France	Alps, Mont Blanc	Col du Dome	1997	LGGE	NULL
CD73	France	Alps, Mont Blanc	Col du Dome	1973	LGGE	NULL
CD76	France	Alps, Mont Blanc	Col du Dome	1976	LGGE	NULL
CD74	France	Alps, Mont Blanc	Col du Dome	1974	LGGE	NULL
CD80	France	Alps, Mont Blanc	Col du Dome	1980	DRA-	NULL
CD86	France	Alps, Mont Blanc	Col du Dome	1986	LGGE	2
CD91	France	Alps, Mont Blanc	Col du Dome	1991	LGGE	NULL
CK04	France	Alps, Mont Blanc	Col du Dome	2004	LGGE	NULL
DG99	France	Alps, Mont Blanc	Dome du Guter	1999	LGGE	NULL
MB73	France	Alps, Mont Blanc	Mont Blanc	1973	LGGE	NULL
CD99	France	Alps, Mont Blanc	Mont Blanc	1999	LGGE	2
CL96	Italy	Alps Monte Rosa	Colle del Lys	1996	DISAT	2
CL00	France	Alps Monte Rosa	Colle del Lys	2000	LGGE	2
CL03	Italy	Alps Monte Rosa	Colle del Lys	2003	DISAT	2
CL12	Italy	Alps Monte Rosa	Colle del Lys	2012	DISAT	2
CG76	Swiss	Alps Monte Rosa	Colle Gnifetti	1976	DCB	2
CG77	Swiss	Alps Monte Rosa	Colle Gnifetti	1977	DCB	NULL
CG82	Swiss	Alps Monte Rosa	Colle Gnifetti	1982	ETH	NULL
CG95	Swiss	Alps Monte Rosa	Colle Gnifetti	1995	UNIBE	7
CG03	Swiss	Alps Monte Rosa	Colle Gnifetti	2003	NULL	NULL
CG05	Swiss	Alps Monte Rosa	Colle Gnifetti	2005	LGGE	NULL
OR09	Italy	Alps Ortles	Alto dell'Ortles	2009	OSU	8
OR11	Italy	Alps Ortles	Alto dell'Ortles	2011	OSU	2
PZ02	Swiss	Alps Morteratsch	Piz Zupo	2002	ETH	NULL
FH89	Swiss	Grossfiescherhorn	Fiescherhorn	1989	PSI	2
FH02	Swiss	Grossfiescherhorn	Fiescherhorn	2002	WAV-ETH	2
VF79	Austria	Oetztal Alps, Austria	Vernagtferner	1979	GFS	NULL

Ice core tab:

IceCore ID	Name	Ref Lat	Ref Long	Lat rep	Long rep	Rep class	Altitude	Top	Bottom	Diameter	Samples N
CB8400652E04550NCB6	CDB 6	45°50′27″N	6°52′22″E	45,842225318	6,873583761	2	4350	0,00	10,00	NULL	NULL
CD7300652E04550NIC2	CDD 2	45°50′28″N	6°50′52″E	45,838828018	6,850423739	3	4280	0,00	24,50	NULL	NULL
CD7400652E04550NIC3	CDD 3	45°50′28″N	6°50′52″E	45,838828018	6,850423739	3	4270	0,00	21,00	NULL	NULL
CD7600652E04550NC2b	CDD 2b	45°50′28″N	6°50′52″E	45,838828018	6,850423739	3	4250	0,00	30,60	NULL	NULL
CD8000652E04550NIC5	CDD 5	45°50′28″N	6°50′52″E	45,840723259	6,847467853	3	4250	0,00	20,00	NULL	NULL
CD8600652E04550NIC7	CDD 7	45°50′28″N	6°50′52″E	45,842253252	6,847473207	3	4250	0,00	70,00	NULL	NULL
CD9100652E04550NIC8	CDD 8	45°50′28″N	6°50′52″E	45,842253252	6,847473207	3	4250	0,00	13,00	NULL	NULL
CD9400652E04550NC10	CDD 10	45°50′28″N	6°50′52″E	45,842798149	6,846952105	3	4250	0,00	126,00	NULL	1500
CD9400652E04550NC11	CDD 11	45°50′28″N	6°50′52″E	45,842798149	6,846952105	3	4250	0,00	139,00	NULL	NULL
CD9700652E04550NC12	CDD 12	45°50′28″N	6°50′52″E	45,842534029	6,845541085	3	4250	0,00	20,50	NULL	NULL
CK0400652E04550NCDK	CDK	45°50′28″N	6°50′52″E	45,842798149	6,846952105	2	4250	0,00	124,00	NULL	NULL
CL0000751E04555NC01	CdL 00/1	45°55′11,64″N	7°51′13,41″E	45,919900000	7,853725000	4	4248	0,00	23,75	NULL	NULL
CL0300751E04555NC31	CdL 03/1	45°55′7,78″N	7°51′32,73″E	45,918800000	7,859091670	4	4248	0,00	102,38	9,8	NULL
CL0300751E04555NC32	CdL 03/2	45°55′7,78″N	7°51′32,73″E	45,918800000	7,859091670	4	4248	0,00	102,38	9,8	NULL
CL0300751E04555NC33	CdL 03/3	45°55′7,78″N	7°51′32,73″E	45,918800000	7,859091670	4	4248	0,00	102,38	9,8	NULL
CL1200751E04555NC12	CdL 12/1	45°55′7,78″N	7°51′32,73″E	45,918800000	7,859091670	4	4248	0,00	120,00	9,8	NULL
CL9600751E04555NC96	CdL 96	45°55′11,64″N	7°51′13,41″E	45,919900000	7,853725000	4	4248	0,00	80,00	9,8	NULL

Paper Tab:

ID paper	of pubblic	Principal Autor	Citation	DOI
CDD1	1999	S. Preunkert	S.PREUNKERT, D.WAGENBACH, M.LEGRAND, C. VINCENT Col du Doˆme (Mt Blanc Massif, French Alps) suitability for ice-core studies in relation with past atmospheric chemistry over Europe. T ellus (2000), 52B, 993–1012	NULL
CDD2	2013	S. Preunkert	S. Preunkert and M. Legrand Towards a quasi-complete reconstruction of past atmospheric aerosol load and composition (organic and inorganic) over Europe since 1920 inferred from Alpine ice cores Clim. Past Discuss., 9, 1099–1134, 2013	10.5194/cpd-9-1099-2013
CDD3	2003	S. Preunkert	Preunkert, S., D. Wagenbach, and M. Legrand, A seasonally resolved alpine ice core record of nitrate: Comparison with anthropogenic inventories and estimation of preindustrial emissions of NO in Europe, J. Geophys. Res., 108(D21), 4681.	10.1029/2003JD003475, 2003.
CDD4	2001	S. Preunkert	Preunkert, S., Legrand, M., Wagenbach, D., Sulfate trends in a Col du Dbme (French Alps) ice core: A record of anthropogenic sulfate levels in the European midtroposphere over the twentieth century, JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 106, NO. D23, PAGES 31,991-32,004, DECEMBER 16, 2001	NULL
CDD5	1976	L. LLIBOUTRY	LLIBOUTRY, L., BRIAT, M., CRESEVEUR, M., POURCHET M., 15 m DEEP TEMPERATURES IN THE GLACIERS OF MONT BLANC (FRENCH ALPS), Journal of Glaciology, Vel. 16, No. 74, 1976	NULL
CDD6	1990	M. De Angelis	DeAngelis, M., Gaudichet, A., Saharan dust deposition over Mont Blanc (French Alps) during the last 30 years. Tellus (1991), 43B, 61-75.	NULL
DDG1	2006	G.R. Burton	Burton,G.R., Rosman,K.J.R., Van de Velde, K,P, Boutron, C.F., A two century record of strontium isotopes from an ice core drilled at Mt Blanc, France Earth and Planetary Science Letters 248 (2006) 217–226	10.1016/j.epsl.2006.05.021
DDG2	1997	C. Vincent	VINCENT, C., VALLON, M., PINGLOT, F., FUNK, M., REYNAUD, L., Snow accuDlulation and ice flow at Dome du Gouter (4300 Dl), Mont Blanc, French Alps, Journal rifGlaciology, T70l. 43, No. 145, 1997	NULL
CG1	2006	D. Bolius	Paleo climate reconstruction based on ice cores from the Andes and the Alps pp 147	NULL
CG2	2000	M. Luthi	Luthi, M., Funk, M., Dating ice cores from a high alpine glacier with a flow model for cold firn, Annals of Glaciology 31, 2000	NULL

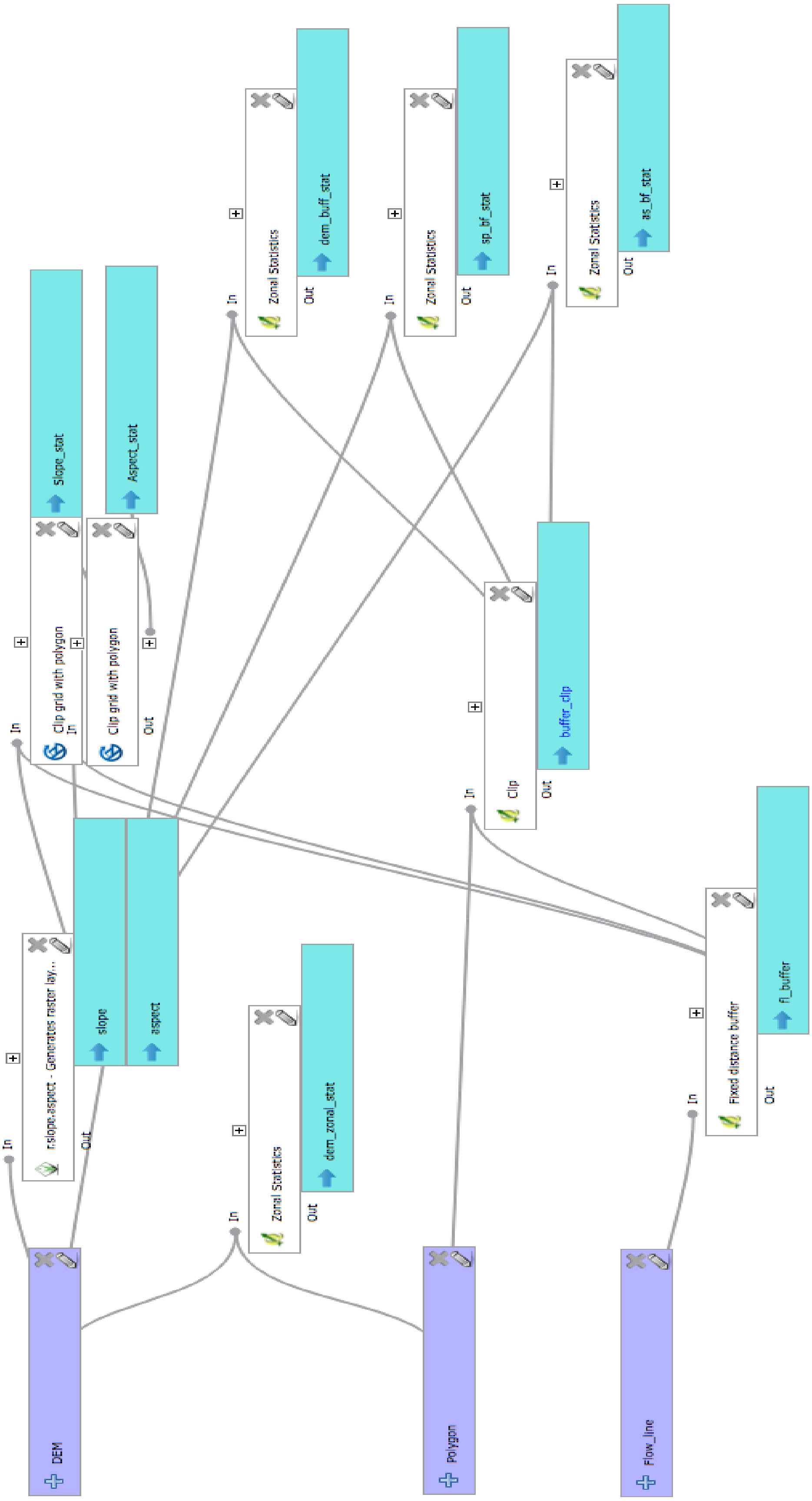
ID paper	of pubblic	Principal Autor	Citation	DOI
CDD1	1999	S. Preunkert	S.PREUNKERT, D.WAGENBACH, M.LEGRAND, C. VINCENT Col du Doˆme (Mt Blanc Massif, French Alps) suitability for ice-core studies in relation with past atmospheric chemistry over Europe. T ellus (2000), 52B, 993–1012	NULL
CDD2	2013	S. Preunkert	S. Preunkert and M. Legrand Towards a quasi-complete reconstruction of past atmospheric aerosol load and composition (organic and inorganic) over Europe since 1920 inferred from Alpine ice cores Clim. Past Discuss., 9, 1099–1134, 2013	10.5194/cpd-9-1099-2013
CDD3	2003	S. Preunkert	Preunkert, S., D. Wagenbach, and M. Legrand, A seasonally resolved alpine ice core record of nitrate: Comparison with anthropogenic inventories and estimation of preindustrial emissions of NO in Europe, J. Geophys. Res., 108(D21), 4681.	10.1029/2003JD003475, 2003.
CDD4	2001	S. Preunkert	Preunkert, S., Legrand, M., Wagenbach, D., Sulfate trends in a Col du Dbme (French Alps) ice core: A record of anthropogenic sulfate levels in the European midtroposphere over the twentieth century, JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 106, NO. D23, PAGES 31,991-32,004, DECEMBER 16, 2001	NULL
CDD5	1976	L. LLIBOUTRY	LLIBOUTRY, L., BRIAT, M., CRESEVEUR, M., POURCHET M., 15 m DEEP TEMPERATURES IN THE GLACIERS OF MONT BLANC (FRENCH ALPS), Journal of Glaciology, Vel. 16, No. 74, 1976	NULL
CDD6	1990	M. De Angelis	DeAngelis, M., Gaudichet, A., Saharan dust deposition over Mont Blanc (French Alps) during the last 30 years. Tellus (1991), 43B, 61-75.	NULL
DDG1	2006	G.R. Burton	Burton,G.R., Rosman,K.J.R., Van de Velde, K,P, Boutron, C.F., A two century record of strontium isotopes from an ice core drilled at Mt Blanc, France Earth and Planetary Science Letters 248 (2006) 217–226	10.1016/j.epsl.2006.05.021
DDG2	1997	C. Vincent	VINCENT, C., VALLON, M., PINGLOT, F., FUNK, M., REYNAUD, L., Snow accuDlulation and ice flow at Dome du Gouter (4300 Dl), Mont Blanc, French Alps, Journal rifGlaciology, T70l. 43, No. 145, 1997	NULL
CG1	2006	D. Bolius	Paleo climate reconstruction based on ice cores from the Andes and the Alps pp 147	NULL
CG2	2000	M. Luthi	Luthi, M., Funk, M., Dating ice cores from a high alpine glacier with a flow model for cold firn, Annals of Glaciology 31, 2000	NULL

Principal investigator tab:

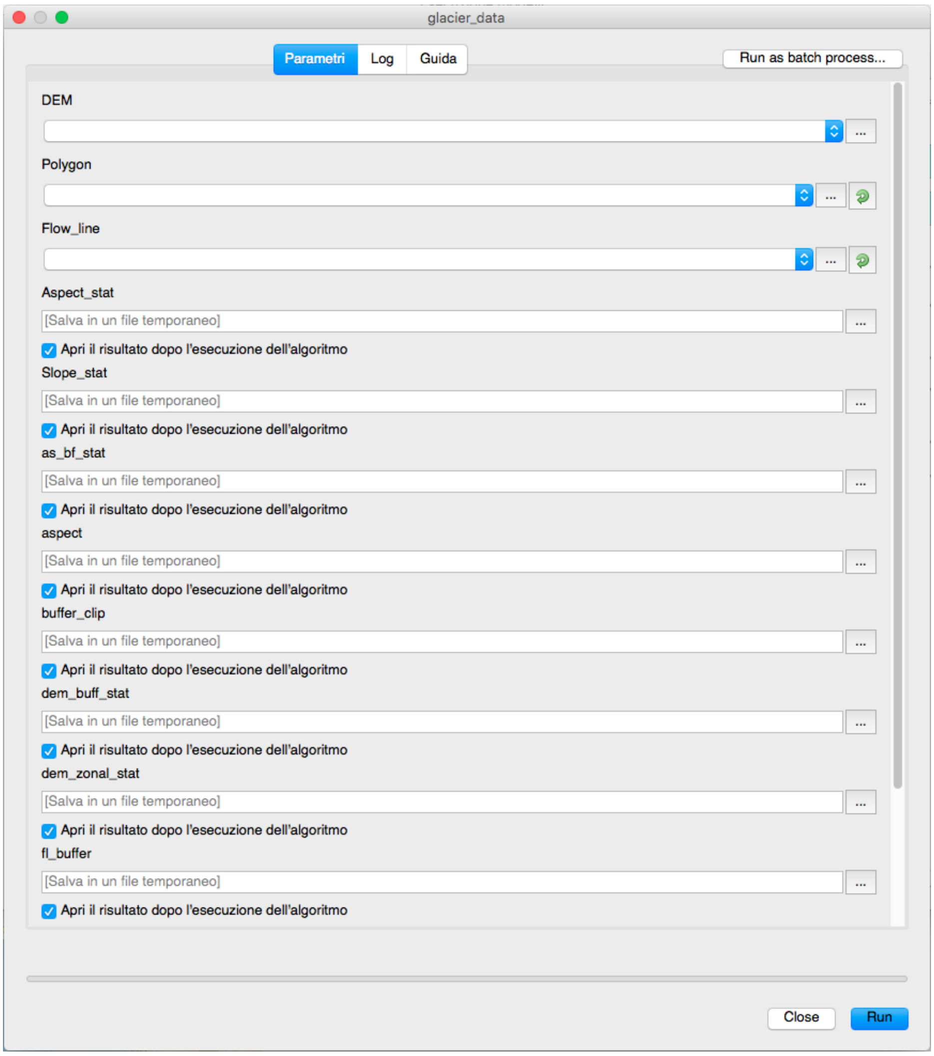
Name	Organization
L.G. Thompson	Byrd Polar Research Center, The Ohio State University
L.G. Thompson	U.S. National Science Foundation, Division of Atmospheric and Geospace Sciences
M. De Angelis	French Institut de Recherche pour le Developpement (IRD)
S. Preunkert	Laboratoire de Glaciologie et Géophysique de l'Environnement
M. De Angelis	Laboratoire de Glaciologie et Géophysique de l'Environnement
V. Maggi	Department of Earth and Environmental Sciences, UNIMIB, Milano
H.W. Gaggeler	Chemie und Biochemie, Universit/it Bern
A. Dallenbach	Climate and Environmental Physics, Physics Institute, University of Bern
M. Schwikowski	Paul Scherrer Institute, Switzerland
O. Eisen	Paul Scherrer Institute, Switzerland
P. Gabrielli	Mendenhall Laboratory, The Ohio State University
A. Schwerzmann	Laboratory of Hydraulics, Hydrology and Glaciology, ETH Zurich
B. Aizen	College of Science, University of Idaho
V. Aizen	Donald Bren School of Environmental Science and Management University of California at Santa Barbara

Appendix D

GLACIER DATA MODULE flowchart:



Glacier Data Module command panel and LOG window



DEM

Polygon

Flow_line

Aspect_stat
[Salva in un file temporaneo]
☑ Apri il risultato dopo l'esecuzione dell'algoritmo

Slope_stat
[Salva in un file temporaneo]
☑ Apri il risultato dopo l'esecuzione dell'algoritmo

as_bf_stat
[Salva in un file temporaneo]
☑ Apri il risultato dopo l'esecuzione dell'algoritmo

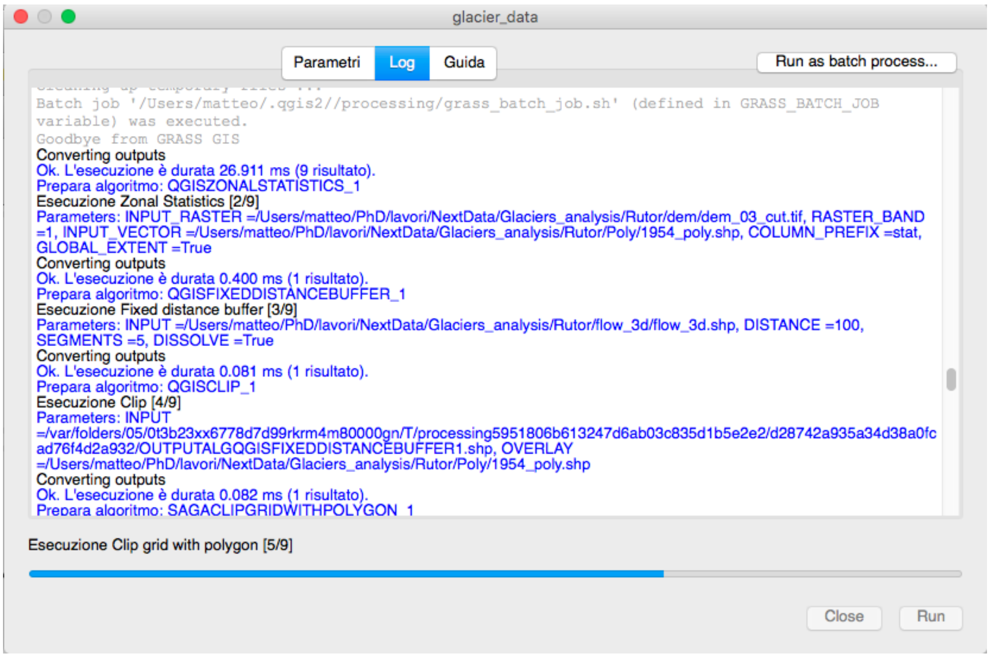
aspect
[Salva in un file temporaneo]
☑ Apri il risultato dopo l'esecuzione dell'algoritmo

buffer_clip
[Salva in un file temporaneo]
☑ Apri il risultato dopo l'esecuzione dell'algoritmo

dem_buff_stat
[Salva in un file temporaneo]
☑ Apri il risultato dopo l'esecuzione dell'algoritmo

dem_zonal_stat
[Salva in un file temporaneo]
☑ Apri il risultato dopo l'esecuzione dell'algoritmo

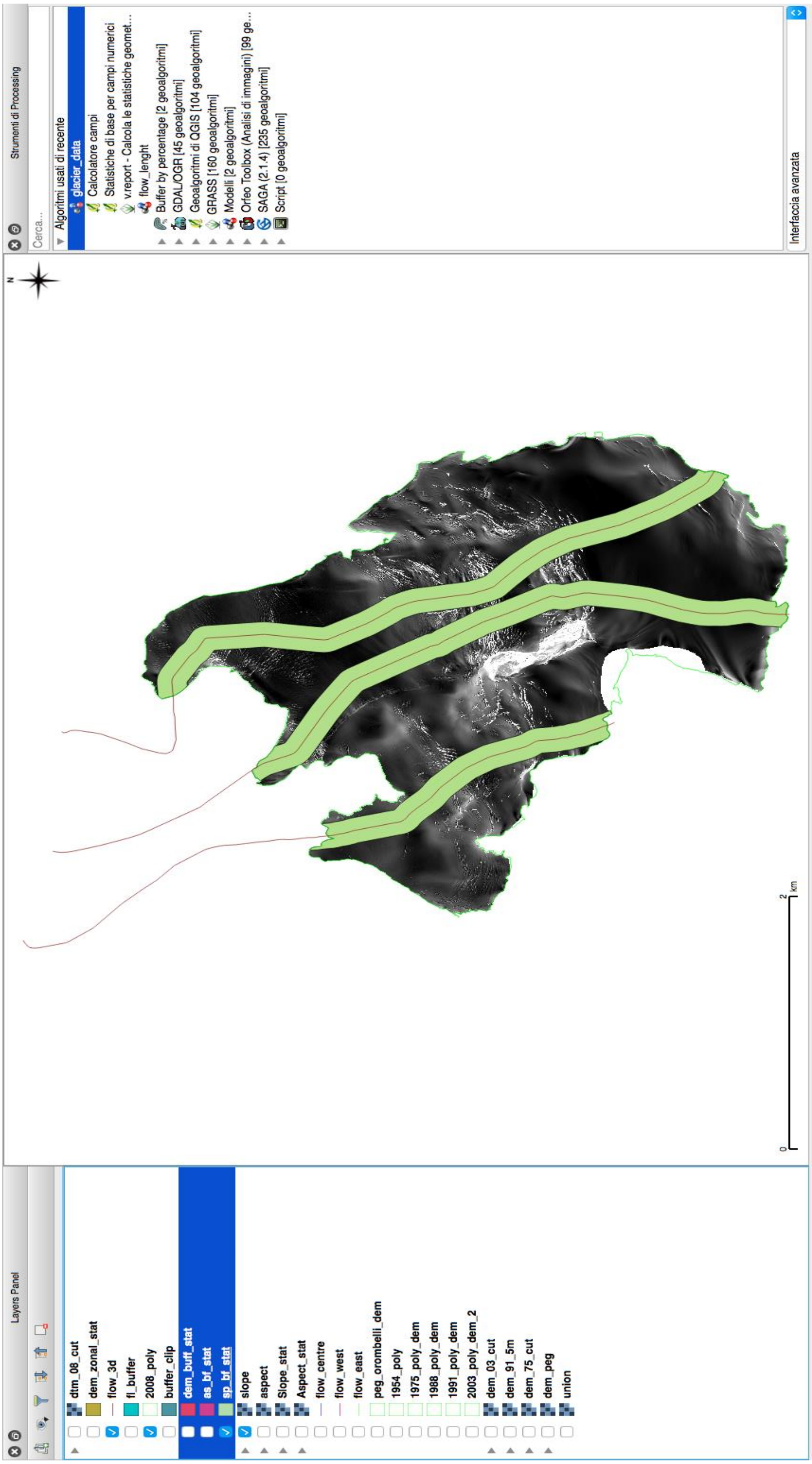
fl_buffer
[Salva in un file temporaneo]
☑ Apri il risultato dopo l'esecuzione dell'algoritmo



```
Batch job '/Users/matteo/.qgis2//processing/grass_batch_job.sh' (defined in GRASS_BATCH_JOB
variable) was executed.
Goodbye from GRASS GIS
Converting outputs
Ok. L'esecuzione è durata 26.911 ms (9 risultato).
Prepara algoritmo: QGISZONALSTATISTICS_1
Esecuzione Zonal Statistics [2/9]
Parameters: INPUT_RASTER =/Users/matteo/PhD/lavori/NextData/Glaciers_analysis/Rutor/dem/dem_03_cut.tif, RASTER_BAND
=1, INPUT_VECTOR =/Users/matteo/PhD/lavori/NextData/Glaciers_analysis/Rutor/Poly/1954_poly.shp, COLUMN_PREFIX =stat,
GLOBAL_EXTENT =True
Converting outputs
Ok. L'esecuzione è durata 0.400 ms (1 risultato).
Prepara algoritmo: QGISFIXEDDISTANCEBUFFER_1
Esecuzione Fixed distance buffer [3/9]
Parameters: INPUT =/Users/matteo/PhD/lavori/NextData/Glaciers_analysis/Rutor/flow_3d/flow_3d.shp, DISTANCE =100,
SEGMENTS =5, DISSOLVE =True
Converting outputs
Ok. L'esecuzione è durata 0.081 ms (1 risultato).
Prepara algoritmo: QGISCLIP_1
Esecuzione Clip [4/9]
Parameters: INPUT
=/var/folders/05/0t3b23xx6778d7d99rkrm4m80000gn/T/processing5951806b613247d6ab03c835d1b5e2e2/d28742a935a34d38a0fc
ad76f4d2a932/OUTPUTALGQGISFIXEDDISTANCEBUFFER1.shp, OVERLAY
=/Users/matteo/PhD/lavori/NextData/Glaciers_analysis/Rutor/Poly/1954_poly.shp
Converting outputs
Ok. L'esecuzione è durata 0.082 ms (1 risultato).
Prepara algoritmo: SAGACLIPGRIDWITHPOLYGON_1
```

Esecuzione Clip grid with polygon [5/9]

Glacier Data Module graphical results (Rutor Glacier, QGIS)



Appendix E

Research output

Extract of below mentioned publications have been integrated in this thesis:

- Strigaro D., **Mattavelli M**., Frigerio I. & De Amicis M.: PaleoProxy Data Base (PPDB): A comprehensive geodatabase to archive and manage paleoproxies data. Rend. Online Soc. Geol. It., Suppl. n. 1 al Vol. 31 118 (2014).
- Moretti M., **Mattavelli M.**, De Amicis M. & Maggi V.: GIS analysis to apply theoretical Minimal Model on glacier flow line and assess glacier response in climate change scenarios. Rend. Online Soc. Geol. It., Suppl. n. 1 al Vol. 31 110 (2014).
- Strigaro D., Moretti M., **Mattavelli M.**, De Amicis M., Maggi V., Provenzale A.: Development of GIS methods to assess glaciers response to climatic fluctuations: a Minimal Model approach. Geomorphometry for Geosciences, p. 205-208, (2015).
- Strigaro D., **Mattavelli M.**, Frigerio I., Locci F.,, Melis M.T., De Amicis M., The IDB: An ice core geodatabase for paleoclimatic and glaciological analyses (in discussion on GFDQ).