Project of Strategic Interest NEXTDATA

D2.3.2: Report on the ice core archives

WP Coordinator: Mattia De Amicis
DISAT, Università Milano Bicocca

Authors:
M. De Amicis, I. Frigerio, D. Strigaro, M. Mattavelli, R. Garzonio, L. Castellano
Univ. Milano Bicocca

Ice core database, IDB

The research group at UNIMIB, Environmental Department (University of Milano Bicocca, Italy) has implemented in the framework of WP 2.3 an Ice Core Database, called IDB, in collaboration with the Remote Sensing and GIS group of the University of Cagliari.

The IDB database uses the principal structure of an existing database called WDB (Water and Weather Database System) (Institute T.N.M., 2012), created by The Norwegian Meteorological Institute to stock hydro-meteorological data. WDB is released according to the GNU General Public License and it is completely configurable, customizable and sharable.

WDB was designed to archive weather data, but its general structure could also be appropriate to stock data derived from ice cores. This type of structure can be used to store ice core parameters as these two entities have two common principle aspects from a conceptual point of view:

- both ice cores and weather stations are represented geographically with a couple of coordinates that in a GIS environment can be treated as a geometrical vector point;
- they both record climate data but, more specifically, the ice cores give information about the past climate trend whereas the weather stations give information about the current climatic system. In fact, they store the same type of data, characterized by a numerical value with a parameter related to temporal information.

In spite of this, paleoclimate data are peculiarly different from weather data: one of the most important difference is the temporal factor. The first weather observations date back to 1654; WDB allows storing data that are not older than 319 years while Ice Core data can go back more than 500 yrs. There are several ice cores that provide data for the last 20 kyrs, in particular in the Tibetan Plateau (Thompson et al., 1989, 1990, 1995, 1997, 2000; Thompson, 1992; Yao et al., 1990, 1995 a, b, 1996, 1997). The Guliya ice core, drilled on the western side of the Plateau, has a length of 309 m and the data extend back over 120 kyrs (Yang M et al., 2006).

The WDB server architecture is composed by a WDB core (PostgreSQL), a Command Interface (WCI) and a series of loading programs (wdb-fastload, wdb-gribload, ecc) to load data from the Data Storage System. WDB is designed to be:

- Robust enough to handle high volume of data.
- Flexible to handle for example new type of data.
- Able to support quality and consistency of data.
- Simple to use, easy to maintain and operate.

The core of WDB is a list of 36 SQL functions to set up the entire schema (schemaDefinition.sql) and functionality of the database system (administration, geometry, parameters, etc.).

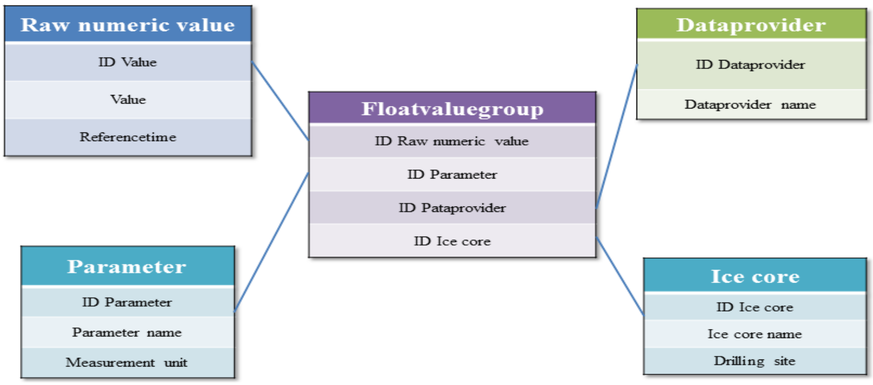


Fig. 1. IDB schema.

Starting from the whole WDB database, for our IDB database, we used only 5 tables (figure 1):

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

The parameter in IDB identifies the characteristic or measurable factor of the value being parameterized. Parameters provide a definitive description of what the data represent, including chemical and physical properties. When ice cores are drilled, they are cut and prepared to be catalogued and stored for analysis. Ice cores contain many proxy-parameters to help scientists to reconstruct past climates. For example, regarding chemical analysis, the concentration of atmospheric trace gases such as nitrous oxide (N_2O), methane (CH_4) and carbon dioxide (CO_2) provide information about natural variation and man-made change of atmospheric composition.

Otherwise, the physical analysis supplies different information. Conductivity allows investigating volcanic activity or particle size and concentration gives information of wind speed. The ice measurements aim to determine the chronological extension of possible atmospheric records. In particular, non-destructive measurements, such as FTIR (infrared) and DEP (dielectric properties), aim to define horizons of historical reference (137Cs, 3H, volcanic tephra, insoluble powder levels), to determine seasonality and compositional trends (oxygen and hydrogen stable isotopes, ice chemistry, mineral powders contained, and others).

After an accurate investigation about the main physical and chemical factors, 80 parameters with a proper measurement unit were selected (figure 2). To standardize the data, each parameter was defined by a IUPAC name for chemical value and SI (International System of Units) for units of measurements. Afterward, data were stored in the IDB “parametername” table.

Parameter name	***Measurement unit***
d18O	Ratio
Calcium	Ppb
Chloride	Ppb
Ammonium	Ueq/L
Cerium	Ppb
Conductivity	µS per cm
Fluoride	ppb
...	...
72 parameters	

Fig. 2. List of some parameters and their measurement units in the IDB database.

Raw numeric value is the number obtained from a specific chemical or physical analysis of ice core samples. This step was critical as each raw numeric value of chemical and physical measure is linked to the three parts mentioned above (ice core, data provider and parameters).

First, before loading data into IDB, the original txt and xls files were modified in CSV format with a precise formatting. After a careful analysis of these requirements, 281,728 values were collected to be inserted into the database. To populate the IDB tables a Bash shell script was developed to automate data upload, even in large quantities.

A bash shell script was written in order to simplify the loading procedure. It reads CSV files where ice cores data were been previously prepared with a precise column order. After it recalls a SQL function that can distribute each attribute inside the right tables fields. This software aims to help future users in loading new data.

The chemical and physical characterization about ice cores is available for 36 ice cores of the 178 stored in the database. As shown in figure 3, the oxygen 18 is one of the most common ice core proxies in the analysis of stable isotopic ratios. In fact, the 4% of the entire values stored in the database refer to the $\delta^{18}O$ (d18O) ratio. These data are used to reconstruct time-series of past temperature. The 30% of the loaded data is relating to chemical analyses that are finalized to evaluate the amount of different elements in the ice cores samples. The values are expressed in different units like mq/l, ppb or ueq/l for the Ammonium, Calcium, Sulfate and the other chemical elements. For physical investigations, the value stored in IDB refers to different analysis, such as conductivity, accumulation rate, layer thickness and represents the 37% of the entire value (Figure 3).

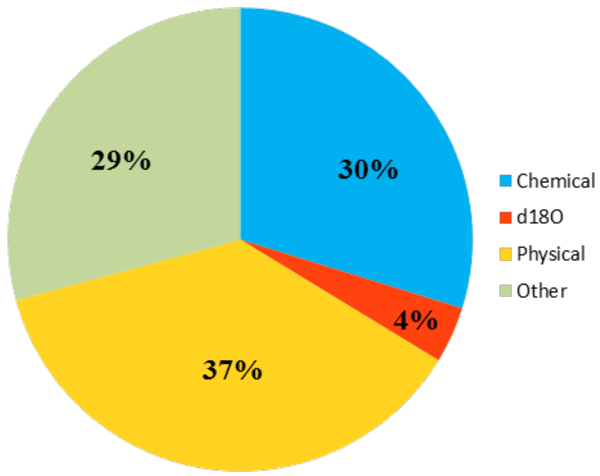


Fig. 3. Percentage and type of data stored in IDB.

The information about time series was fundamental because a lot of problems with the data/time field PostgreSQL were found. First, the 'timestamp with time zone' field with a storage size of 8 bytes was used. This field type can archive temporal data from 4713 BC to 294276 AD. Problems can therefore occur when starting to insert data referred to a period before 4713 BC. In order to avoid such problems, a WDB software was released which helps users to insert raw data in the database. In this case another software (like a bash script) was written, which uses the Boost library for time data. However the boost library presents an inferior limit of about 1400 BC. To solve the problem with PostgreSQL time field, a part of WDB source code was modified by inserting new functions which allow to write data into IDB without time limits. This has increased the value of temporal data aspects that is essential for paleoclimatic analysis. A 'real' data type field was used. Positive numbers are years Anno Domini (AD) and negative numbers are referred to years Before Christ (BC). The 'real' field types can archive 4 bytes information and can be positive, negative and with a precision of six decimals.

The predefined reference system (CRS) in WDB is the 4030 EPSG. This RS is based on the WGS84 ellipsoid but it has an unknown datum. In a geospatial database the information about geographical position is fundamental. Our department carries on a project to define suitability for ice core drilling based on morphologic glacier parameters. To offer and to work with spatial correct information it was decided to work with the EPSG 4326 that is used by GPS satellite navigation system and NATO military geodetic surveying.

In most cases, the reference papers from which the spatial information was obtained, reported identical coordinates for different ice cores drilled in the same glacier. This problem is due to the fact that the GPS coordinates were taken with poor precision and they refer to the drilling site and not to the single ice core. To respect the topological rules, in order to insert the geographic data in the IDB, a GIS operation (shift points) was applied. This function moves overlapped points with same coordinates in a circle around the original position. At the end of this operation, 178 points with ice core name and drilling site attributes were stored.

During this first year a total of 178 different ice cores were found from 4 different sources, NOAA-NIDC database, NICL table, DISAT ice cores and scientific literature. Of these, 56 ice cores comes from NOOA and NICL, 2 from DISAT and 120 are new geo referenced and first time stored ice cores.

	Project	*Perforations*	*Icecores*
America	17	24	56 (30)
Europe	9	30	44 (44)
Africa	2	2	8 (0)
Asia	24	40	70 (48)
TOT	***52***	***96***	***178***

Fig. 4. Summary of the Projects, Perforations and Ice cores found. Numbers in parentheses shown new ice cores which were never censed before.

WebGIS and raw data downloading

To share data, a web platform was developed on the Geomatic Laboratory server of the Department of Environmental and Earth Sciences (University of Milano-Bicocca). The working environment is based on open source structure: S.O Ubuntu GNU/Linux 12.04 LTS server with implementation of FTP, SSH, Apache Tomcat services and PostgreSQL with PostGIS extension for geospatial database. The web GIS, based on Geoserver and Mapstore software, visualized the ice cores geographic data registered in the IDB database. In order to make the results available, the Geoserver software was used also to provide WMS (Web Map Service), WFS (Web Feature Service), and WCS (Web Coverage Service). In addition, the connection to PostGIS layers from GIS client (Quantum GIS), allows expert users to execute spatial queries, as well as geoprocessing operations.

Furthermore, a visual interface for downloading the data was developed. Both the webgis and the downloading platform are available at geomaticlab website:

http://geomatic.disat.unimib.it/idb

Geonetwork, metadata sharing

The NextData Project also chose to follow the Infrastructure for Spatial InfoRmation in Europe (INSPIRE, 2007). This European infrastructure for spatial information will help to make spatial or geographical information more accessible and interoperable for a wide range of purposes supporting sustainable development. To answer at INSPIRE framework, NextData has chosen to use the SHARE GeoNetwork approach.

To create a better structure, it was decided to archive metadata according to a hierarchical structure Parent/Child (Figure 5). The project domain (parent) contains information about the perforation project such as: Scope work of the project, geographic region and point of contact of principal investigator. After the parent there is the first child: Drilling campaign. The first child contains the name of the campaign, the reference time, the methods used for drill, number of Ice core taken from each extraction. The last is the Ice Core, which contains: ID of the Core, device, abstract of the principal paper written on that ice core, information about the point of contact and finally the spatial information and the coordinates of the ice core. In GeoNetwork it is actually possible to check metadata only for Europe; this is due to the high time consuming uploading procedure.

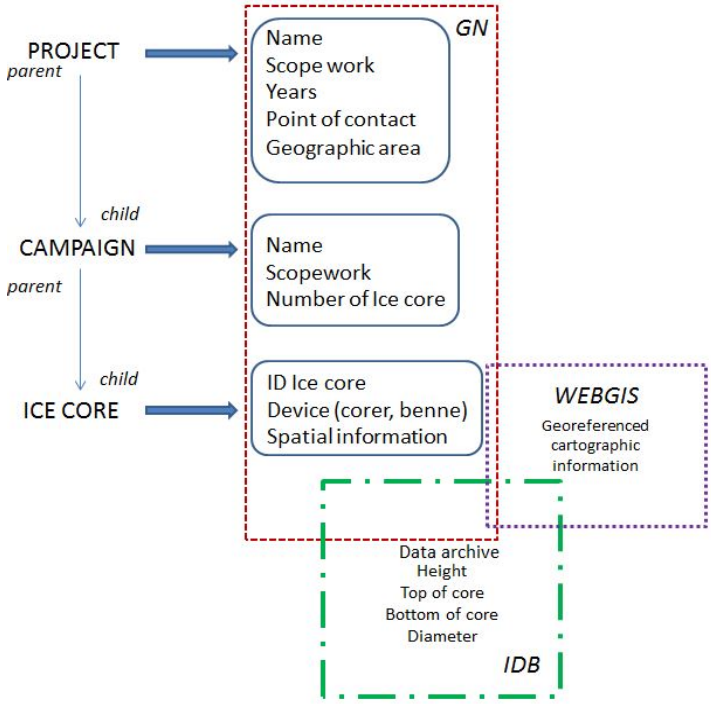


Fig 5. Hierarchical structure for data/metadata archive

Suitability for ice core drilling

Definition

The suitability of glacier for ice core drilling is here defined as the possibility to drill an ice core within a glacier to retrieve useful stratigraphic information.

Beside, this definition is important also to provide the meaning of the following terms:

- **Drilling campaign**: campaign suitable for the collection of one or more ice cores in the same site in a short period of time.
- **Drilling site:** area within glacier where the drilling is done.
- **Ice core:** core sampled, extracted from a drilling site.

In the contest of the research, the drilling site is the basic element to describe the suitability for ice core drilling. For these areas, the appropriate characteristics will be defined.

Guidelines for the site selection for ice core drilling

The criteria to choose a drilling site were identified through the study of literature concerning ice cores and the comparison with experts. According to some authors (Oerter et al., 1982; Preunkert et al., 2000; Schwikowski et al., 2006; Gabrielli et al., 2010; Konrad et al., 2013), the basics variables considered in the choice of a drilling site are: firn temperature profile (it allows to estimate whether a high elevation mid-latitude glacier site is located in the recrystallization and cold infiltration zone); mass balance reconstructions and snow accumulation rate; glacier thickness and Ground Penetrating Radar (GPR) profile; ice flow and alteration of snow layers; glacio-chemical investigation of various chemical species deposits.

The following main topics were investigated to define the guidelines for the selection of appropriate sites for ice cores drilling holding the best stratigraphy for climatic studies:

1. Suitability for glaciological reconstruction;
2. Technical suitability and logistics;
3. Climatic interest.

Suitability for glaciological reconstruction

The suitability for glaciological reconstruction concerns physical and morphological parameters that determine the temporal resolution and the quality of the stratigraphy. The ice core should show the high temporal resolution of the stratigraphic layers and a well preserved stratigraphy. For example Puruogangri ice core (extracted from Puruogangri Ice Cap, Tibetan Plateau, Thompson et al., 2006) is 118 metres long and describes 400 years of climate history whereas Dunde ice core (Dunde Ice Cap, Tibetan Plateau, Thompson et al., 1989) is 117 meters long and describes 4550 years of climate history.

Temporal resolution

The temporal resolution refers to the length of the series (numbers of years) described by the stratigraphy and its seasonal details. The temporal resolution depends on two main parameters: glacier thickness and snow annual accumulation besides seasonal snowfall.

The general approach is to select a site which allows the best temporal resolution and is characterized by larger thickness. Consequently, areas with small accumulation are not apt to ice core drilling; moreover, thick layers of seasonal snow accumulation may hinder the reach of the underlying ice layers.

Glacier thickness

The length of ice core that can be extracted and the number of years that it describes depend directly on the thickness of the glacier. Several authors proposed methods for deriving glacier thickness from Digital Elevation Model (DEM) and glacier outlines with hydrological and climatically purpose. Paul et Linsbauer presented a simplified method implemented in a Geographic Information System (GIS) to approximate sub-glacial topography at a regional scale from spatial interpolation of local ice thickness values. The thickness was derived from local surface slope, total vertical extent and basal shear stress (Linsbauer et al., 2009; Paul et Linsbauer, 2012;Linsbauer et al., 2012). Bahr and others proposed a volume-area scaling analysis showing that glacier volume can be related by a power low to glacier surface areas; hence thickness can be related to glacial length (Bahr, 1997; Bahr et al., 1997).

Snow annual accumulation

The snow annual accumulation leads the formation of the glacial layers and their relative temporal resolution, while the annual distribution of snowfall determines the detail of the seasonal stratigraphy. The glacier differentiation of snowfall precipitation can be done by using meteorological reanalysis model as ERA-Interim (ERA-Interim project report series) or by using average monthly precipitation maps from different source as the Worldclim global climate data (interpolation of average monthly climate data from weather stations, 1960-90, 30 arc-second resolution grid, 1 km^2 resolution)(Hijmans et al., 2005).

Stratigraphic conservation

The stratigraphic conservation refers to the quality of the data layers present in the glacier (extracted with ice core drilling). High air temperatures, wind erosion, snow avalanche, glacial flow, and other processes affect the quality of the ice layers. The best stratigraphy is important in order to reconstruct the history of the climate. For this reason the areas suitable for ice core drilling should not be affected by alteration processes. The main variables concerning the stratigraphic conservation are described below.

Snow melting

Glaciers can be classified according to geophysical parameters such as their heat state and thermal regime below the active layers. The englacial temperature distribution produces different areas of a glacier characterized by different processes, such as recrystallization/ infiltration zones (Kotlyakov, 2009). Positive temperatures produce infiltration, percolation and refreezing phenomena. The meltwater percolation through the glacier and refreezing of parts of the meltwater in firn layers may blur the original stratigraphy and distribution of isotopic and chemical characteristics (Oerter et al., 1982; Preunkert et al., 2000).

For these reasons, the suitable areas for ice cores drilling are preferably characterized by negative temperature (in °C). These are placed at high altitude within areas less exposed to solar radiation.

A large variety of melt model of different complexity have been developed during recent decades for hydrological purposes, as the assessment and the management of water resources, glacier hydrology, dynamics and mass balance, to assess changes in the cryosphere associated with climate change. Surface melt rates can be calculated by means of two different approaches: physical energy-balance models attempting to quantify melt as residual in the heat balance equation, and empirical temperature-index models assuming an empirical relationship between air temperatures and melt rates.

Temperature index models are the most common approach for melt modelling due to three reasons: wide availability of air temperature data; relatively easy interpolation and forecasting possibilities of air temperature; generally good model performance despite their simplicity. Different models were proposed from several authors in which melt rate is calculated from an empirical formula where air temperature is the sole measured input variable, although additional input variables such as incoming shortwave radiation may be incorporated (Cazorzi and Dalla Fontana, 1996; Hock, 1999; Hock, 2003; Ohmura, 2000; Pellicciotti et al., 2005; Heynen et al., 2013).

In order to differentiate glaciers surfaces, the temperature of the warmest month, taken from meteorological models or average monthly temperature maps like the Wordclim global climate data (Hijans et al., 2005), could be used. Furthermore, some simple maps about insolation time and incoming solar radiation, useful in parameterisation of snow melting, can be generating using GIS functions.

Persistence of snow cover

The Equilibrium Line Altitude (ELA) is the average elevation at which accumulation of snow exactly balances ablation, taken over period of one year. There is therefore a close relationship between ELA, snowfall and air temperatures (Benn and Lehmkuhl, 2000). The persistence of snow allows the formation of snow layering and negative temperatures prevent layer alteration; for these reasons the suitable areas for ice core drilling are necessarily placed above the Equilibrium Line Altitude within the accumulation zone.

There is a variety of methods to estimate ELAs, principally based on Digital Elevation Models (DEM) and glacier outlines or remote sensing techniques.

ELAs of glaciers are commonly reconstructed by using the Accumulation-Area Ratio method (AAR), based on the assumption that the accumulation area of the glacier occupies some fixed proportion of the total glacier area. The most rigorous way to do this is the balance ratio (BR) method, which is based on the hypsometry function (Benn and Gemmell, 1997; Benn and Lehmkuhl, 2000). Furthermore, where the accumulation and ablation gradients are approximately linear, ELAs can be calculated by a similar method, described by Osmaston, considering the relative sizes of the accumulation and ablation areas in order to satisfy the requirement of zero mass balance (Osmaston, 2005).

Leonard and Fountain propose the validity of two methods for estimating glacier ELAs from topographic maps. They showed that the ELA determined by the transition or inflection from concave to convex contour lines on a topographic map of a glacier (kinematic ELA) is close to the location of the average ELA determined from mass-balance data (observed ELA) (Leonard and Fountain, 2003).

In addition, several authors use information provided by a variety of remote sensing techniques to find the position of a glacier's ELA. Assuming that the snowline at the end of the Summer is a good approximation of the ELA, aerial and ground-based methods are attractive to monitor inferred changes in ELA (Kulkarni, 1992; Brown et al., 1999; Khalsa et al., 2004; Rabatel et al., 2005; Racoviteanu et al., 2008; Shea et al., 2013).

Wind and avalanche transport and mixing

Much of the spatial heterogeneity of snow in alpine regions is the result of redistribution by wind and avalanches (Hartman et al., 1999). Wind and avalanche transport leads to the mixing of the snow deposited by snowfall with consequential alteration of the layer stratigraphy.

In particular, the wind produces differences in the snow accumulation through the erosion of the snow in wind exposure areas (e.g. ridge and saddle) and the transport and deposition of snow in the sheltered areas. The best suitable zones for ice core drilling are characterized by low wind exposure and low wind deposition. The latter has a smaller influence on the suitability. Snow erosion occurs when the surface shear velocity of the wind exceeds the threshold velocity necessary to detach snow particles and snow deposition occurs when the surface shear velocity of the winds drops below the threshold necessary to maintain transport (Lapen and Martz, 1993). Topographic exposure is a topographic characteristic representing the degree of protection by a surrounding topography of a given site (Mikita and Klimanek, 2010). The degree of a topographic exposure of a site is dependent on the relative height and on the distance of the two points. In addition with other climatic data on wind direction and speed, this factor is used to define the degree of terrain ventilation. Various authors propose different methods to derive the Topographic Exposure Index on the basis of the digital elevation model (DEM) (Lapen and Martz, 1993; Winstral and Marks, 2002; Mikita and Klimanek, 2010). In particular, the maximum upwind slope parameter (Sx) was defined by Winstral to quantify the extent of shelter or exposure provided by the terrain upwind of each pixel. To determine the value of the Sx parameter, all cells were examinated along a vector emanating from the cell of interest, identifying the cell that had the greatest upward slope relative to the cell of interest, and estimating the slope between this cell and the cell of interest (Winstral et al., 2002).

Avalanches cause mixing of snow and destruction of layers stratigraphy, and can be an hazard to drilling operations. For these reasons, the areas suitable for ice core drilling should be free of avalanches. Different authors developed methods for the estimation of avalanche release zones and the determination of run-out paths based on computer simulation running in a GIS environment (Gruber and Bartelt, 2007; Biskupič and Barka, 2010; Suk and Klimánek, 2011). Avalanche trigger zones were described as areas with certain topographical features. The factors taken in account are: slope, aspect, altitude, landform and roughness. With the purpose of modelling avalanche run out, the model developed by Lied and Bakkehoi (Lied and Bakkehoi, 1980) was implemented in GIS.

Ice flow and topographic features

The dynamics of the glacier and the ice flow can wrap the layers producing alterations of data, making the reading of the stratigraphic information rather complex. The ice flow is related to the slope gradient and relief energy: stronger ice flows are associated with larger slopes and important relief energy. Based on these assumptions, these parameters can be estimated in order to evaluate the flow of the glacier; therefore, the suitable zones for ice core drilling are placed principally within flat summit areas. To select flat summit areas, a classification of landscape forms can be done as described by Tagil and Jenness (2008). The ice flow can be evaluated by studying the flow and speed velocity (Hastenrath, 1983; Kaab, 2005). Other parameters to be considered are: the local relief defined as the difference between the highest and lowest elevations occurring within that area (Mark, 1975); the elevation-relief ratio (ERR) which provides hypsometric information about a watershed expressing the relative proportion of upland to lowland within a sample region (Pike and Wilson, 1971; Sivakumar et al., 2011); the Topographic Position Index (TPI) i.e. the difference between the elevation at a cell and the average elevation in a neighborhood surrounding that cell (Tagil and Jenness, 2008).

Technical suitability and logistics

The technical suitability and logistics concern the anthropic and technical factors related to the drilling survey. In particular, the area of glacier has to be accessible and characterized by topographical features which permit the drilling operations.

Site accessibility

The site accessibility means the possibility to reach the drilling site. The aim is the selection of a drilling site which is easily accessible through the available transport means (helicopter, walking transport, etc.). The area suitable for ice core drilling can be placed in remote areas, therefore is important considering this topic. The two main variables that described the site accessibility are the support points and the access facility.

Support point

The presence and proximity of support points (villages, refuges, bases and resorts) promote the choice of the site and facilitate the transport of materials and ice samples. To evaluate this variable, the number and the distance of the drilling site from the support points are proposed as index.

Access facility

Access facility refers to the possibility to reach the drilling site with different transport types according to the path route available. The technical difficulty and the length of the path, the time required to reach the site and the available types of transport are useful to evaluate this variable.

Topographic features

The drilling sites need to have topographic features allowing the drilling operations. The two basic issues that should be considered are the slope and the presence of areas with flat to gently sloping surfaces.

Drilling requires flat areas, whereas steep slopes or severe ridges are generally not suitable for ice core drilling. The slope and the topographic curvature are the basic parameters taken into account to evaluate this variable. These are easily extracted in GIS representations.

The candidate suitable areas should however have a size that permits the arrangement of a drilling camp, therefore also this variable has to be considered in the guideline definition.

Environmental criticality

Some environmental criticalities have to be contemplated in order to prevent the possibility of environmental risks coming from avalanches and landslides or from the presence of crevasses. For these reasons, areas potentially exposed to gravitational risks that compromise the safety of the drilling survey (proximity of slopes suitable for the triggering of avalanches and rock faces) have to be avoided. The indices that can be used for this purpose are: the relief energy, the flows lines and the avalanche release and run-out zones already described before.

Furthermore, other geopolitical issues (i.e. authorization and visas) and other difficulties should be considered in addition to the aspects described above, in order to assess the possibility to do the drilling survey.

Climatic interest

The choice of a drilling site is also based on climatic criteria. The principal question is related to the geographical position of the site and its climatic relevance. This could be evaluated by taking into account possible drills that were already done, the representative area of the data stratigraphy, the importance of the site concerning the study, the geographic representative scale of glacier and the trend of glacier melting.

Proposed methodology

The guidelines and the relative variables identified are the basis for deriving the suitability for ice core drilling. Figure 6 shows the guidelines for the selection of an ice core drilling site as identified and described above. Such characteristics are classified in three main categories:

suitability for glaciological reconstruction, technical suitability and logistics, climatic interest. For each topic, the variables and the relative proxy useful to evaluate it are shown.

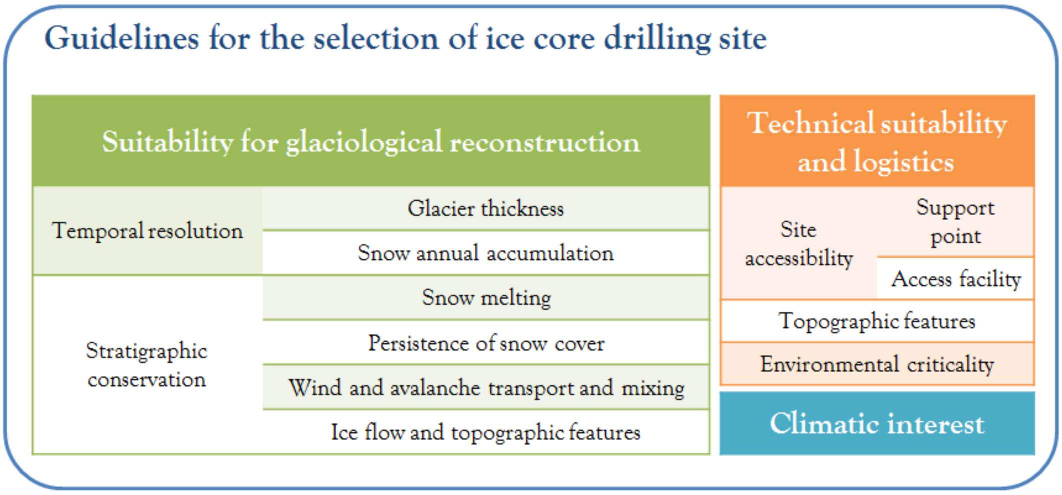


Fig. 6. Guidelines for the selection of an ice core drilling site: main characteristics, parameters and proxies.

The parameters are the basic indices that must be taken into consideration to define the methodology to evaluate the suitability of a glacier for ice core drilling. In this study not all the variables and the relative proxies have been used; in fact, some of them are not directly available and it is necessary to devise a methodology (that can be implemented in GIS environmental) to evaluate them. The parameters selected and the proxies used in this research are illustrated in the section 4.3.1.

The proposed methodology to determine the suitability of glacier areas is based on the extraction of these parameters and it consequently makes a classification of environmental variables according to a factorial scoring system. This method, successfully applied in environmental analyses at a variety of scales (Vogt et al., 2003), was used by Vogt et al. to derive the landscape drainage density index and, furthermore, to provide powerful techniques for identifying homogeneous areas.

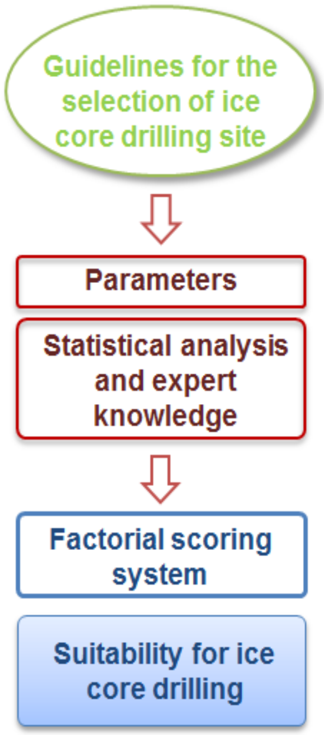


Fig. 7. Proposed methodology

As described by these authors, this methodology consists in dividing the area into sectors and to score the various environmental variables for each sector separately. According to this method, the environmental factors will be classified on the basis of statistical analysis; besides, expert knowledge and a weighting score is defined for each class based on the relationship between the environmental parameters and the suitability for ice core drilling. Finally, all environmental scores are added up in order to determine the suitability for ice core drilling. Figure 7 shows the methodology proposed.

Deriving suitability for ice core drilling

The evaluation of suitability for ice core drilling was made on the basis of the ice cores already drilled and stored in IDB. The accuracy of ice core geographical coordinates is essential for the evaluation of suitability. All the ice core perforation data, stored in IDB, were plotted by using also others geographic data such as glacier outlines and by using GLIMS polygon. This intersection showed that ice core perforation coordinates taken from the literature had a low accuracy and they often represent a location near the ice core hole but not the real position where the core was taken. To study the suitability for ice core drilling, knowing the exact position of the drill sites is a necessary step; the maps in the original papers and the elevation of the drilling sites were therefore used, in order to position all the ice cores in the correct location. In order to describe the accuracy of the replacement on the base of the data available, a number and a note were associated to every point. Figure 8 shows the ice core drilling sites in the database. There are 23 drilling sites in the Alpine area and 39 drilling sites in the Himalayan region. These are used to evaluate the variables described in section 4.3.1 and to understand if they may provide information on the suitability for ice core drilling. Figure 9 shows the area of study with the drilling sites present in the database.

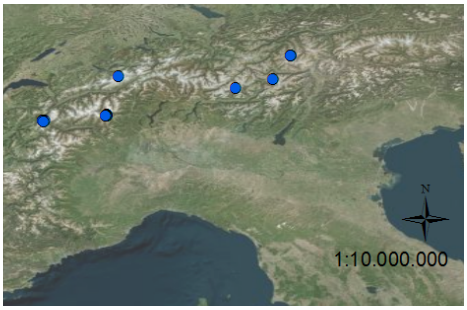
Alps

Place name of perforation point	N Drilling Site	N Ice core	Replacement accuracy
Alto dell'Ortles	1	5	3
Col de Brenva	1	1	2
Col du Dome	5	10	3
Colle del Lys	2	6	4
Colle Gnifetti	9	12	4 / 3
Fiescherhorn Glacier	1	2	3
Mont Blanc Summit	1	1	3
Piz Zupo	1	2	3
Vernagtferner	3	3	3
9	24	42	

Himalaya

Place name of perforation point	N Drilling Site	N Ice core	Replacement accuracy
Belukha	2	5	4 / 3
Bomi	1	1	2
Chongce	3	3	3
Dasuopu	3	3	2
Dunde	4	4	2
East Rongbuk	1	5	2
Fedchenko	2	2	4
Grigoriev	1	1	4
Guliya	4	9	3
Guoqu	3	3	3
Inilchek	3	3	1 / 4
Lanong	1	1	4
Malan	1	1	3
Muztagata	1	4	2
NaimonaNyi	1	5	1
Palong-Zanbu	1	1	3
Puruogangri	2	4	1
Rikha Samba	2	2	3
Sofiyskiy	1	1	4
Tsambagarav Uul	1	1	4
Urumqi	2	3	3 / 2
Yala	1	6	2
Yulong	1	1	1
23	42	69	

Fig. 8. Ice cores drilling site and number of ice core present in the database for the different mountain areas. (Alps and Himalaya regions).



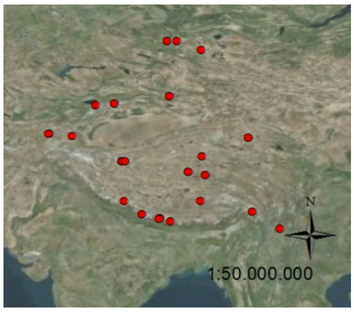


Fig. 9. Areas of study and ice core drilling sites.

Pre-processing digital elevation model

Several Digital Elevation Models (DEM) from the Alps and the Himalaya were compared. The two main DEMs with a global coverage evaluated are the ASTER Global Elevation Model (G-DEM) and the Shuttle Radar Topography Mission (SRTM)(Frey and Paul, 2012).

The SRTM DEM was acquired by radar interferometry (InSAR) during 10 days in February 2000 through the Space Shuttle Mission. It has a 3 arc-seconds resolution (~90 meters) and the comparison with ground control points revealed vertical and horizontal errors of approximately 10 m (Farr et al., 2007). The ASTER sensor on board of the Terra spacecraft (launched in 1999) has an along-track stereoscopic capability in the Near Infrared (NIR) spectral band. The ASTER GDEM has a horizontal resolution of 1 arc-second (~30 m). ASTER scenes were acquired between 2000 and 2007 and a photogrammetric DEM was generated with vertical accuracies of ±15–30 m (Toutin, 2008; Hayakawa et al., 2008)

The Digital Elevation Model DEM chosen was the ASTER Global Elevation Model (G-DEM) in order to have a better resolution and a global coverage. The tiles downloaded from NASA reverb site were merged using ArcGis software. This DEM was the basis to extract the geomorphological parameters (Bolch et al., 2005;Bolch and Kamp, 2006).

Defining suitability for ice core drilling

As defined before, the suitability for ice core drilling is the possibility to drill ice cores from an area within glacier in order to retrieve the best stratigraphic information. To establish the method to evaluate the suitability for ice core drilling we opted for to considering the guidelines concerning the suitability for glaciological reconstruction and the technical suitability and logistics. These contain all the principal aspects which are necessary to select the best areas suitable for ice cores drilling. The criteria of climatic interest are an additional topic that can be considered from expert in a second step. The suitability for drilling is based on physical and morphological parameters rather than on logistics aspects; they determine the quality of ice core data to be extracted and possibility to do an ice core drill operation respectively.

Suitability for Ice Core Drilling = f (suitability for glaciological reconstruction, technical suitability and logistics)

Selection of the parameters

On the basis of the selection criteria (guidelines) previously identified, basic geo-morphometric maps and other preliminary maps were created from the DEM using Grass GIS. These parameters represent the proxy that can be considered for selecting a suitable area in term of suitability for glaciological reconstruction and technical suitability and logistics. They were computed to understand whether they can estimate the suitability for ice core drilling.

The maps have a spatial resolution of 1 arc-second (~30 meters) and are in WGS84 long/lat projection system:

- **Elevation**: digital elevation model, elevation of the surface.
- **Slope**: the slope values represent the stated in degrees of inclination from the horizontal.
- **Aspect**: direction that slopes are facing, the aspect categories represent the number degrees of east and they increase counterclock wise.
- **Profile and Tangential Curvature**: curvatures in the direction of steepest slope and in the direction of the contour tangent respectively. The curvatures are expressed as 1/metres (curvature of 0.05 corresponds to a radius of curvature of 20 m). Convex form values are positive and concave form values are negative.
- **Insolation time**: time of insolation in hours.
- **Direct and global solar irradiation**: maps of direct and global radiation for given day, latitude, surface and atmospheric conditions.
- **Flow accumulation:** amount of rain that would flow through each cell.
- **TCI: Topographic convergence index** (Hartman et al., 1999).

$TCI = \ln\left(\frac{A}{\tan\beta}\right)$ $A =$ *upslope area drained, β = local slope.*

Further maps were also created for other morphological indices that could identify the suitable area of a glacier for ice core drilling. These maps were generated by developing appropriate Grass modules using the Python programming language. These modules will be published as Grass add-ons and made available to the Grass-users community.

- **Topex wind exposure index** (Winstral et al., 2002).

$$Topex = \max\left[\tan\left(\frac{elev\,(x_v y_v) - elev(x_i y_i)}{[(x_v - y_v)^2 + (x_v - y_v)^2]^{0,5}}\right)\right]$$

- **Elevation-relief ratio** (Pike and Wilson, 1971).

$$ERR = \frac{Z_{avg} - Z_{min}}{Z_{max} - Z_{min}}$$

- **Topographic position index** (Tagil and Jenness, 2008).

$$TPI = Z_{pixel} - Z_{avg}$$

- **Avalanche release zone** (Biskupic and Barka, 2010).

$$Av = (Al + Ex + Fx + Fy) * S * Rg$$

Av= potential avalanche trigger zones, Al =elevation factor, Ex=aspect factor, Fx=profile curvature, Fy=plan curvature, S=slope, Rg=roughness factor

- **Landform classification** (Tagil and Jenness, 2008).

Preliminary results

The parameters for studying the suitability for ice core drilling are listed in table 2. These can be considered a preliminary result of this study.

The ice core drilling sites presented in the database were used to extract the values in the cells of the different raster maps.

Parameters
Elevation (meter)
Slope (degree)
Aspect (degree)
Profile curvature (degree)
Tangential curvature (1/metres)
Insolation time (hours)
Direct solar irradiation (W/m^2)
Global solar irradiation (W/m^2)
Flow accumulation
Topographic Convergence Index (Hartman et al. 1999)
Topex Wind Exposure Index (Winstral et al. 2002)
Elevation-Relief Ratio (Pike and Wilson, 1971)
Topographic Position Index (Tagil and Jenness, 2008)
Avalanche release zone (Biskupic and Barka, 2010).
Landform classification (Tagil and Jenness, 2008)

Tab. 2. GIS maps created from DEM. Parameters for deriving the suitability for ice core drilling.

Characteristics of the drilling sites

Basic statistics were computed for the parameters listed in table 2. The parameter values are extracted from the ice core drilling sites present in the database, using a 3x3 windows pixel around the point. This takes into account an area around the drilling point which is suitable for ice core drilling.

Elevation

Figure 10 shows the variability of ice core elevation within Alps and Himalayan environment. For the Alps the values of altitude are generally higher than 4000 meters. For the Himalayan region at lower latitudes the average elevation of drilling is, as expected, higher.

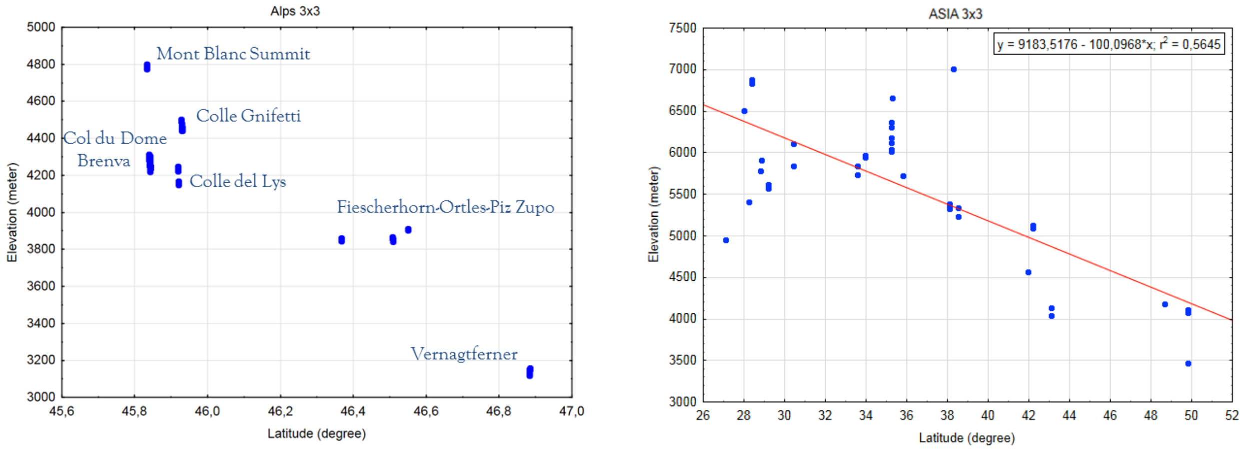


Fig. 10. Elevation of ice core drilling sites for the Alpine and Himalayan regions, relation with latitude.

Slope and flow accumulation

Figure 11 shows the variability of slope and flow accumulation for the alpine ice core drilling sites.

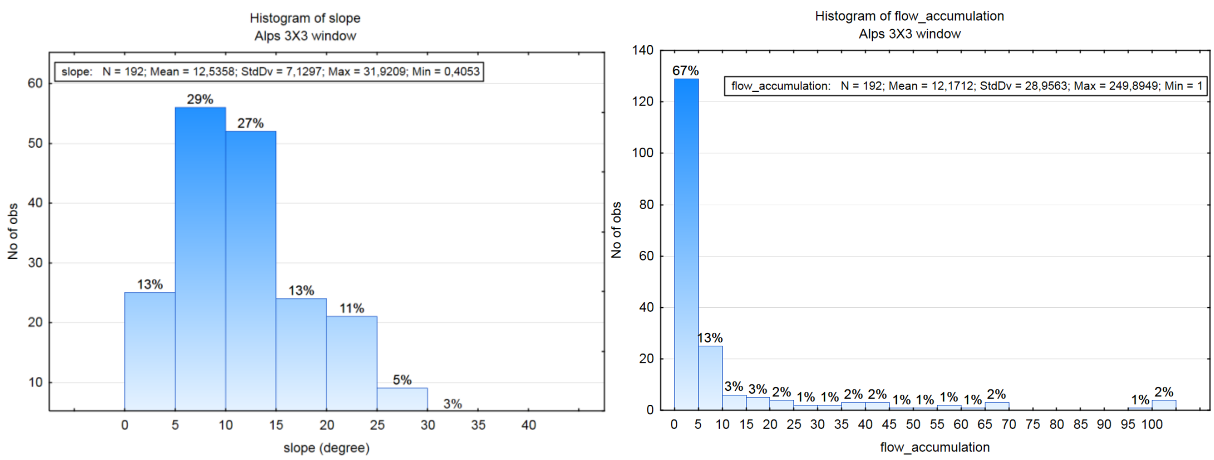


Fig. 11. Slope and flow accumulation of ice core drilling sites for Alpine region.

The slope values represent the angle with respect to the horizontal. This value is important for estimating the ice flow. The distribution shows that a value of slope between 5 and 15 degree is apt to drill an ice core. Of course, also lower values (0-5 degree) of the slope are suitable to perform a drill.

The flow accumulation map is useful to extract the upper area. The area suitable for ice core drilling is characterized by small values of flow accumulation.

Aspect and profile curvature

Figure 12 shows the value of aspect and profile curvature for the drilling sites in the Alps. The aspect does not affect the possibility to drill, the drilling sites are distributed in all aspect classes.

The profile curvature in the drilling sites always attains small values, but they are not different from the values in other areas. For these regions the curvature is not an important parameter to define the suitable drilling areas.

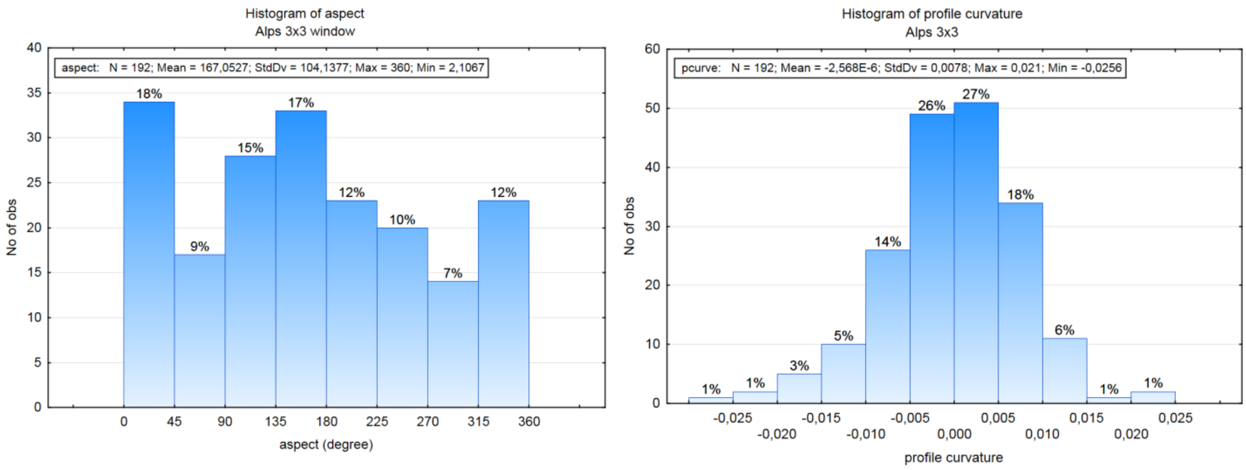


Figure 12. Aspect and profile curvature of ice core drilling sites for Alpine region.

References

BAHR B., MAIER, F. PECKHAM S.D., 1997: The physical basis of glacier volume-area scaling. *Journal of Geophysical Research*, Vol. 102, No. B9, 20,335-20, 362.

BAHR D., 1997: Width and length scaling of glaciers. *Journal of Glaciology*, Vol. 43, No. 145.

BENISTON, M &STOFFEL M., 2006: On the incidence of debris flows from the early Little Ice Age to a future greenhouse climate: a case study from the Swiss Alps. *Geophysical Research Letters*, 33(16), L16404.

BENN D.I., GEMMELL A.M.D., 1997: Calculating equilibrium-line altitudes of former glaciers: a new computer spreadsheet. *Glacial Geology and Geomorphology*.

BENN D.I., LEHMKUHL F., 2000: Mass balance and equilibrium-line altitudes of glaciers in high-mountain environments. *Quaternary International* 65/66, 15-29.

BISKUPIC M., BARKA I., 2010: Spatial modelling of snow avalanche run-outs using GIS. *GIS Ostrava* 2010 24. - 27. 1.

BOLCH T., KAMP U., 2006: Glacier Mapping in High Mountains using DEMs, Landsat and ASTERData. Grazer chriftenfür Geographie und Raumforschung, Proceedings of the *8th International Symposium on High Mountain Remote Sensing Cartography*, La Paz, Bolivia, 20-27 March, 2005 -, 37-48.

BOLCH T., KAMP. U., OLSENHOLLER J., 2005: Using ASTER and SRTM DEMs for studying geomorphology and glaciation in high mountain areas. *New Strategies for European Remote Sensing*, Olui, Millpress, Rotterdam.

BROWN I.A., KIRKBRIDE M.P., VAUGHAN R.A., 1999: Find the firn line! The suitability of ERS-1 and ERS-2 SAR data for the analysis of glacier facies on Icelandic icecaps. *International Journal of Remote Sensing,* 20:15-16, 3217-3230.

BURTON G. R., ROSMAN K. J. R., VAN DE VELDE, K. P., &BOUTRON C. F. (2006): A two century record of strontium isotopes from an ice core drilled at Mt Blanc, France. *Earth and Planetary Science Letters*, 248(1), 217-226.

CAZORZI F., DALLA FONTANA G., 1996: Snowmelt modelling by combining air temperature and a distributed radiation index. *Journal of Hydrology* 181, 169-187.

CHEN J. L., WILSON C. R., &TAPLEY B. D. (2013): Contribution of ice sheet and mountain glacier melt to recent sea level rise. *Nature Geoscience*.

DELMAS R. J. (1992): Environmental information from ice cores. *Reviews of Geophysics*, 30(1), 1-21.

DUAN K., THOMPSON L. G., YAO T., DAVIS M. E., & MOSLEY-THOMPSON E. (2007): A 1000 year history of atmospheric sulfate concentrations in southern Asia as recorded by a Himalayan ice core. *Geophysical Research Letters*, *34*(1), L01810.

EPICA Community Members, 2004.

FARR T.G. 2007.:The Shuttle Radar Topography Mission. *Rev. Geophys*, 45, RG2004.

FREY H., PAUL F., 2012: On the suitability of the SRTM DEM and ASTER GDEM for the compilation of topographic parameters in glacier inventories. *International Journal of Applied Earth Observation and Geoinformation*, 18, 480-490.

GABRIELI J., CARTURAN L., GABRIELLI P., KEHRWALD N., TURETTA C., COZZI G., & BARBANTE C. (2011): Impact of Po Valley emissions on the highest glacier of the Eastern European Alps. *Atmospheric Chemistry and Physics*, 11(15), 8087-8102.

GABRIELLI P., CARTURAN L., GABRIELI J., DINALE R., KRAINER K., HAUSMANN H., DAVIS M., ZAGORODNOV V., SEPPI R., BARBANTE C., DALLA FONTANA G., THOMPSON L.G., 2010: Atmospheric warming threatens the untapped glacial archive of Ortles mountain, South Tyrol. *Journal of Glaciology*, Vol. 56, No. 199.

GRIP Members, 1993.

GRUBER U., BARTELT P., 2007: Snow avalanche hazard modelling of large areas using shallow water numerical methods and GIS. *Environmental Modelling& Software* 22, 1472e1481.

HARTMAN M.D., BARON J.S., LAMMERS R.B., CLINE D.W., BAND L.E., LISTON G.E., TAGUES C., 1999: Simulations of snow distribution and hydrology in a mountain basin. *Water Resources ReSearch*, Vol. 35, No. 5, Pages 1587-1603.

HASTENRATH S., 1983. Net balance, surface lowering, and ice-flow pattern in the interior of Lewis Glacier, Mount Kenya, Kenya. *Journal of Glaciology*, Vol. 29, No. 103.

HAYAKAWA Y.S., OGUCHI T., LIN Z., 2008: Comparison of new and existing global digital elevation models: ASTER G-DEM and SRTM-3. *Geophysical Research Letters*, Vol. 35, L17404.

HEYNEN M., PELLICCIOTTI F., CARENZO M., 2013: Parameter sensitivity of a distributed enhanced temperature-index melt model. *Annals of Glaciology* 54(63).

HIJMANS R.J., CAMERON S.E., PARRA J.L., JONES P.G., JARVIS A., 2005: Very high resolution interpolated climate surfaces for global land areas. *International Journal of Climatology* 25: 1965-1978.

HOCK R., 1999: A distributed temperature-index ice- and snowmelt model including potential direct solar radiation. *Journal of Glaciology*, Vol. 45, No. 149.

HOCK R., 2003. Temperature index melt modelling in mountain areas. *Journal of Hydrology* 282, 104–115.

HUSS M., & FARINOTTI D., (2012): Distributed ice thickness and volume of all glaciers around the globe. *Journal of Geophysical Research: Earth Surface* (2003–2012), 117(F4).

INSPIRE.: Directive 2007/2/EC of the European Parliament and of the Council of 14 March 2007 establishing an Infrastructure for Spatial Information in the European Community, 2007.

Institute, T.N.M., 2012: *WDB - Weather and Water Database*. http://wdb.met.no.

KAAB A., 2005: Combination of SRTM3 and repeat ASTER data for deriving alpine glacier flow velocities in the Bhutan Himalaya. *Remote Sensing of Environment* 94, 463–474.

KÅLLBERG P., SIMMONS A., UPPALA S., FUENTES M.: 17. The ERA-40 Archive. ECMWF ERA-40 Project Report Series.

KHALSA S.J.S., DYURGEROV M.B., KHROMOVA T., RAUP B.H., BARRY R.G., 2004: Space-Based Mapping of Glacier Changes Using ASTER and GIS Tools. *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 42, No. 10.

KONRAD H., BOHLEBER P., WAGENBACH D., VINCENT C., EISEN O., 2013: Determining the age distribution of Colle Gnifetti, Monte Rosa, Swiss Alps, by combining ice cores, ground-penetrating radar and a simple flow model. *Journal of Glaciology*, Vol. 59, No. 213.

KOTLYAKOV V.M., 2009: Classification of Glacier. Hydrological Cycle, Vol IV.

KULKARNI A.V., 1992: Mass balance of Himalayan glaciers using AAR and ELA methods. *Journal of Glaciology*, Vol. 38.

LAMBERT F. et AL.: Dust-climate couplings over the past 800,000 years from the EPICA Dome C ice core. *Nature* 452, 616–619, 2008.

LAPEN D.R., MARTZ L.W., 1993. The measurement of two simple topographic indices of wind sheltering-exposure from raster digital elevation models. *Computers & Geosciences*, Volume 19, Issue 6, Pages 769–779.

LEMKE P., REN J., ALLEY R. B., ALLISON I. ,CARRASCO J. ,FLATO G. , FUJII Y. , KASER G. , MOTE P. , THOMAS R. H. and ZHANG T. (2007): Observations: Changes in Snow, Ice and Frozen Ground, In: Climate change 2007: the physical science basis; summary for policymakers, technical summary and frequently asked questions. Part of the Working Group I contribution to the *Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, ISBN: 92-9169-121-6.

LEONARD K.C., FOUNTAIN A.G., 2003: Map-based methods for estimating glacier equilibrium-line altitudes. *Journal of Glaciology*, Vol. 49, No.166.

LIED K., BAKKEHOI S., 1980. Empirical calculation of snow-avalanche run-out distance based on topographic parameters. *Journal of Glaciology*,1980, vol. 25, issue 94.

LINSBAUER A., PAUL F., HAEBERLI W., 2012. Modeling glacier thickness distribution and bed topography over entire mountain ranges with GlabTop: Application of a fast and robust approach. *Journal of Geophysical Research*, Vol. 117.

LINSBAUER A., PAUL F., HOELZLE M., FREY H., HAEBERLI W., 2009. The Swiss Alps without glaciers – a GIS-based modelling approach for reconstruction of glacier beds. *Proceedings of Geomorphometry* 2009. Zurich, Switzerland, 31 Aug - 2 Sept.

LUZI L., HAILEMIKAEL, S., BINDI D., PACOR F., MELE F., &SABETTA F. (2008): ITACA (ITalianACcelerometric Archive): A web portal for the dissemination of Italian strong-motion data. *Seismological Research Letters*, 79(5), 716-722.

MARK M.D., 1975: Geomorphometric Parameters: A Review and Evaluation. *Geografiska Annaler. Series A, Physical Geography*, Vol. 57, No. ¾, pp. 165-177.

MARTIN E.:14. Validation of Alpine snow in ERA-40. *ECMWF ERA-40 Project Report Series*.

MELIS M. T., DESSÌ F., LOCCI F., BONASONI P., VUILLERMOZ E.: Share Geonetwork: a web-service platform for environmental data sharing. In *First International Conference on Remote Sensing and Geoinformation of Environment* (pp. 87951V-87951V). International Society for Optics and Photonics, 2013.

MIKITA T., KLIMÁNEK,M., 2010: Topographic Exposure and its Practical Applications. *Journal of Landscape Ecology*. Volume 3, Issue 1, pages 42–51.

MOSLEY-THOMPSON E., DAVIS M. E., BOLZAN J. F., DAI J., YAO T., GUNDESTRUP N., XIE Z.: Holocene-late Pleistocene climatic ice core records from Qinghai-Tibetan Plateau. American Association for the Advancement of Science, 1989.

NICL (National Ice Core Laboratory), 2009: *International ice core inventory*: http://nicl.usgs.gov/coresite.htm (Last modified 9 April, 2009).

NOAA (National Oceanic and Atmospheric Administration), 2013. *World Data Center for Paleoclimatology:* http://www.ncdc.noaa.gov/paleo/icecore/ (*Last Updated Thursday, 14-Mar-2013.*

OERTER H., REINWARTH O., RUFLI H., 1982: Core drilling through a temperate alpine glacier (Vernagtferner, Oetztal Alps) in 1979. *Zeitschriftfür Gletscherkunde und Glazialgeologie*, 18 (1), pp. 1-11.

OHMURA A., 2001: Physical Basis for the Temperature-Based Melt-Index Method. *J. Appl. Meteor.*, 40, 753–761.

OSMASTON H., 2005: Estimates of glacier equilibrium line altitudes by the Area_Altitude, the Area_Altitude Balance Ratio and the area_Altitude Balance Index methods and their validation. *Quaternary International* 138–139, 22–31.

PATERSON, 2000: The physics of glaciers. Butterworth-Heinemann.

PAUL F., LINSBAUER A., 2012: Modeling of glacier bed topography from glacier outlines, central branch lines, and a DEM. *International Journal of Geographical Information Science*, 26:7, 1173-1190.

PELLICCIOTTI F., BROCK B., STRASSER U., BURLANDO P., FUNK M., CORRIPIO J., 2005: An enhanced temperature-index glacier melt model including the shortwave radiation balance: development and testing for Haut Glacier d'Arolla, Switzerland. *Journal of Glaciology*, Vol. 51, No. 175.

PENCE H. E., & WILLIAMS A. (2010): Chem Spider: an online chemical information resource. *Journal of Chemical Education*, 87(11), 1123-1124.

PIKE R.J., WILSON S.E, 2013: Elevation-Relief Ratio, Hypsometric Integral, and Geomorphic Area-Altitude Analysis. *Geological Society of America Bulletin 1971*;82, no. 4;1079-1084.

PNR 2011-2013 NextData: Progetto di interesse strategico – un sistema nazionale per la raccolta, conservazione, accessibilità e diffusione dei dati ambientali e climatici in aree montane e marine. Piano esecutivo del progetto, 2012, PROVENZALE A. CNR-ISAC.

PREUNKERT S., LEGRAND M., MAY B., GUILHERMET J., HOFFMAN H., &WAGENBACH D., 2013: Major 20th century changes of the content and chemical speciation of organic carbon archived in Alpine ice cores: Implications for the long-term change of organic aerosol over Europe. *Journal of Geophysical Research: Atmospheres*.

PREUNKERT S., WAGENBACH D., LEGRAND M., VINCENT C., 2000: Col du Dôme (Mt Blanc Massif, French Alps) suitability for ice-core studies in relation with past atmospheric chemistry over Europe. *Tellus*, 52B, 993–1012.

QGIS, D. T., 2011: Quantum GIS geographic information system. *Open Source Geospatial Foundation Project.*

RABATEL A., DEDIEU J.P., VINCENT C., 2005: Using remote-sensing data to determine equilibrium-line altitude and mass-balance time series: validation on three French glaciers, 1994–2002. *Journal of Glaciology*, Vol. 51, No. 175.

RACOVITEANU A.E., WILLIAMS M.W., BARRY R.G., 2008: Optical Remote Sensing of Glacier Characteristics: A Review with Focus on the Himalaya. *Sensors*, 8, 3355-3383.

READINGER C., 2006: Ice Core Proxy Methods for Tracking Climate Change. *CSA, Discovery Guides.*

READINGER C.R., P MOSLEY-THOMPSON E,. CRAIGMILE L. G. THOMPSON, and C. A. CALDER, 2005: Regional sensitivity of Greenland precipitation to NAO variability. *Geophys. Res.* Lett. 32, L24707, doi:10.1029/2005GL024776.

RITTER M.E.: *The Physical Environment: an Introduction to Physical Geography*. http://www4.uwsp.edu/geo/faculty/ritter/geog101/textbook/title_page.html

SCHWIKOWSKI M., BRÜTSCH S., CASASSA G., RIVERA A., 2006: A potential high-elevation ice-core site at HieloPatagónico Sur. *Annals of Glaciology*, vol. 43, Issue 1, p.8-13.

SHEA J.M., MENOUNOS B., MOORE R.D., TENNANT C., 2013: An approach to derive regional snow lines and glacier mass change from MODIS imagery, western North America. *The Cryosphere*, 7, 667–680.

SIVAKUMAR V., BIJU C., BENIDHAR DESHMUKH, 2011: Hypsometric Analysis of Varattaru River Basin of Harur Taluk, Dharmapuri Districts, Tamilnadu, India using Geomatics Technology. *International Journal of Geomatics and Geosciences*.

SUK P., KLIMANEK M., 2011: Creation of the snow avalanche susceptibility map of the KrKonoše mountains using GIS. *Acta Universitatis Agriculturae et Silviculturae Mendelianae Brunensis*, Volume LIX, Number 5.

SUMATHI S., ESAKKIRAJAN S., 2007: *Fundamentals of relational database management system* (*Springer Science and Buisness Media*).

TAGIL S., JENNESS J., 2008: GIS-Based Automated Landform Classification and Topographic, Landcover and Geologic Attributes of Landforms Around the YazorenPolje, Turkey. *Journal of Applied Sciences,* 8: 910-921.

THOMPSON L.G., YAO T., DAVIS M.E., MOSLEY THOMPSON E., MASHIOTTA T.A., LIN PING N., MIKHALENKO V.N., ZAGORODNOV V.S., 2006: Holocene climate variability archived in the Puruogangri ice cap on the central Tibetan Plateau. *Annals of Glaciology* 43, Pages 61-69.

THOMPSON L. G., MOSLEY-THOMPSON E., DAVIS M. E., LIN,P. N., HENDERSON K. A., COLE-DAI J., LIU K. B: Late glacial stage and Holocene tropical ice core records from Huascaran, Peru. *Science*, 269 (5220), 46-50, 1995.

THOMPSON L. G., YAO T., DAVIS M. E., MOSLEY-THOMPSON E., MASHIOTTA T. A., LIN P. N., ZAGORODNOV V. S.: Holocene climate variability archived in the Puruogangri ice cap on the central Tibetan Plateau. *Annals of Glaciology*, 43(1), 61-69, 2006.

THOMPSON, L. G., YAO, T., MOSLEY-THOMPSON, E., DAVIS, M. E., HENDERSON, K. A., LIN, P. N.: A high-resolution millennial record of the South Asian monsoon from Himalayan ice cores. *Science*, *289*(5486), 1916-1919, 2000.

THOMPSON L.G., 2000: Ice core evidence for climate change in the Tropics: implications for our future. *Quaternary Science Reviews* 19, 19-35.

THOMPSON L.G., MOSLEY-THOMPSON E., DAVIS M.E., BOLZAN J.F., DAI J., YAO,T., GUNDESTRUP N., WU X., KLEIN L., XIE Z., 1989: Holocene-late Pleistocene climatic ice core records from qinghai-tibetan plateau. *Science*, 1989 Oct 27, 246(4929), 474-7.

THOMPSON L.G., THOMPSON E.M., DAVIS M., DAI J., YAO T.: Holocene–Late Pleistocene climatic ice core records from Qinghai–Tibetan Plateau. *Science*, 246, 474–477, 1989.

THOMPSON L.G., THOMPSON E.M., DAVIS M.E., BOLZAN J.F., DAI J., KLEIN L., GUNDESTRUP N., YAO T., WU X., XIE Z.: Glacial stage ice-core records from the subtropical Dunde ice cap, China. *Annals of Glaciology* 14, 289–297, 1990.

THOMPSON L.G., THOMPSON E.M., DAVIS M.E., LIN P.-N., HENDERSON K.A., COLE-DAI J., BOLZAN J.F., LIU K.-B.: A 1000 year climate ice core record from the Guliya ice cap, China: its relationship to global climate variability. *Annals of Glaciology* 21, 175–181, 1995.

THOMPSON L.G., YAO T., DAVIS M.E., HENDERSON K.A., MOSLEY-THOMPSON E., LIN P.-N., BEER J., SYNAL H.-A., COLE-DAI J., BOLZAN J.F.: Tropical climate instability: the Last Glacial Cycle from a Qinghai–Tibetan ice core. *Science,* 276, 1821–1825, 1997.

THOMPSON L.G., YAO T., MOSLEY-THOMPSON E., DAVIS M.E., HENDERSON K.A., LIN P. N.: A high-resolution millennial record of the South Asian monsoon from Himalayan ice cores. *Science*, 289, 1916–1919, 2000.

THOMPSON L.G.: Ice core evidence from Peru and China. In: BRADELY R.S., JONES P.D. (Eds.), *Climate Since A.D. 1500*. Routledge, London and New York, pp. 517–548, 1992.

THOMPSON L.G.: Ice core studies from Mt Kenya, Africa, and their relationship to other tropical ice core studies, Sea Level, Ice, and Climatic Change, *IAHS* Publ. no. 131. pp. 55-62, 1979.

TOUTIN T., 2008. ASTER DEMs for geomatic and geoscientific applications: a review. *International Journal of Remote Sensing* archive, Vol 29, Issue 7, Pages 1855-1875.

TROCCOLI A., KÅLLBERG P. 13: Precipitation Correction in the ERA-40 Reanalysis. *ECMWF ERA-40 Project Report Series.*

V. VOGT J.V., COLOMBO, R. BERTOLO F., 2003: Deriving drainage networks and catchment boundaries: a new methodology combining digital elevation data and environmental characteristics. *Geomorphology* 53, 281–298.

WINSTRAL A., ELDER K., DAVIS R.E., 2002: Spatial Snow Modeling of Wind-Redistributed Snow Using Terrain-Based Parameters. *Journal of Hydrometeorology*; Vol. 3 Issue 5, p524.

WINSTRAL A., MARKS D., 2002: Simulating wind fields and snow redistribution using terrain-based parameters to model snow accumulation and melt over a semi-arid mountain catchment. *Hydrological Processes*, Vol 16, Issue 18, pages 3585–3603.

YAO T., THOMPSON L. G., MOSLEY-THOMPSON E., ZHIHONG Y., XINGPING Z., & LIN P. N. 1996: Climatological significance of δ18O in north Tibetan ice cores. *Journal of Geophysical Research: Atmospheres* (1984–2012), 101(D23), 29531-29537.

YAO T., THOMPSON L. G., SHI Y., QIN D., JIAO,K., YANG Z., & THOMPSON E. M. 1997: Climate variation since the last interglaciation recorded in the Guliya ice core. *Science in China Series D: Earth Sciences,* 40(6), 662-668.