CRYOSPHERE

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CRYOSPHERE

Introduction

Similarly to the hydrosphere, that includes all the planet's water in the liquid state, in any area and in any form that it may be present, or to the biosphere that consists of all the living organisms whatever kingdom they belong to, and whatever area they may live in, the cryosphere includes all the Earth's ice. When we think of ice, the image that comes to our mind is that of the clean twinkling stretches of the glaciers, however the Earth's ice may be found in many other forms, which at times are also well "hidden" and, surprisingly, also in unexpected geographic areas such as the centre of Africa!

Almost all the Earth's ice consists of ice from glaciers or sea ice. Large quantities of frozen ice can also be found in the permafrost areas, trapped in the ground and in the rock crevices, but, as they cannot be seen directly, it is very difficult to quantify their volume and extension. Also caves can contain ice deposits, at times with the characteristics of glacier ice, more often with ice that formed by freezing: generally these are rather small quantities, but they represent a very precious data bank of the climate of the past.

The Earth's ice

Where can they be found?

Glaciers may exist only on two conditions: the first, which is quite obvious, is that the annual temperatures must be below zero for a certain period of the year, so that ice can be preserved, the second, which is less intuitive, but equally indispensable, is that a sufficient amount of snow required to form a certain mass of ice must fall. In fact, just as excessive heat does not allow the preservation of a glacier, likewise, scarce precipitations prevent the formation of a glacier even where temperatures are below zero: for this reason, in the Polar desert areas glaciers do not form. Glaciers therefore are excellent indicators of two of the most important climatic parameters: temperature and precipitation.

Depending on their geographic location, the temperatures within and at the base of the glacier, where the glacier comes into contact with the bedrock, vary. This is why there is a distinction between cold or Polar glaciers, with temperatures that are constantly and entirely below zero, and temperate glaciers that may have higher temperatures on their surface and/or at the base, accompanied by melting phenomena: the presence or not, of water in the liquid state influences the behaviour of the glaciers, and the response to climatic variations is very different in the two cases. The former are to be found in the high latitudes, the latter in the lower latitudes, but at high levels, where the air becomes cool because of the altitude, and the heat of the low latitude is compensated by this effect: temperate glaciers are the glaciers we find in the Alps, but also particular glaciers as those which can be found in tropical or equatorial areas, such as the glaciers of Mount Kilimanjaro or Mount Kenya in Africa, or the glaciers in the Peruvian and Bolivian Andes.

The Earth's ice

Clear distinction must be made between the ice covering lands above sea level and sea ice floating in the Polar seas. In order to be considered a glacier, the ice must move under the thrust of its own weight: therefore sea ice or icebergs, even though they move at times, cannot be considered glaciers, as their movement is passive, generated by sea currents, wave motion or winds.

Even though they are formed by the same material, the Earth's glaciers are very different one from the other, in extension, ice-thickness, geographical position and climate regime, topographical situation and shape. All these factors determine, besides quite a different appearance, also a very different behaviour and a different response to climatic variations. Researchers who study glaciers use many different classifications, some are rather complex, also depending on the type of study that one intends carrying out. A first, important distinction can be made between frozen ice, that includes sea ice and permafrost, and glacier ice, that includes the ice-sheets, ice shelves and mountain glaciers.

How much ice is there on the Earth?

Most of the Earth's ice that we see is to be found in large masses of "nearly" pure ice (due consideration must be given to the aspects described above): ice-sheets and glaciers of various types, ice shelves and sea ice packs. It is quite easy to calculate the surface of the areas covered with ice: it has been calculated that this amounts to approximately 15 million km^2, equal to one tenth of the surface of the Earth's emersed land. It is more difficult, on the contrary, to calculate the volume of ice because the thickness of the entire covered area must be known: using special techniques it is possible to measure the ice thickness in various points of a glacier and therefore to estimate the volume. For example the average thickness of the Antarctic sheet is 2.100 m, with peaks of 4.800 m in Land of Wilkes, in the Eastern sector: with a surface of little less than 13,600,000 km2, the total volume of the Antarctic ice is 30 million km^3. Someone had fun calculating that this is equivalent to 9×10^{16} ice cubes!

Sea ice: cold polar seas

Sea ice has a completely different origin from glacier ice. Sea ice in fact forms due to direct freezing of sea water, when the temperature of the air remains below -1.8°C for a few days.

Its formation, which is seasonal, is spectacular: at first ice needles and thin plates form. These, floating, give the sea surface a particular "oily" appearance, the so-called greasy ice. The crystals aggregate, originating slabs that get increasingly thick, and due to the continuous collisions provoked by wave motion, they take on a circular form with raised borders, which look like large white pancakes, from which the name pancake ice. As the low temperatures persist, the slabs join together thus forming a continuous sheet, the pack. The thickness varies between 1 to 5-7 metres and increases continuously due to sea water that freezes at the base and supply of snow on the surface. Currents, winds, tempests keep the pack in constant movement, causing breakage of the big slabs, overlapping or piling up and collisions, creating a tormented landscape, made up of ridges jutting from the ice and large fractures, making exploration very difficult. It is a very dangerous area for navigation: even very large tonnage ships have been trapped between drifting slabs and have been literally crushed by ice. The history of polar exploration is studded with adventures and tragedies connected with the dangers of the pack.

Unlike in the Antarctic, that is a continent, in the Arctic, the few lands above sea level are made of archipelagos of islands. Therefore there are no large glaciers or big ice-sheets, but only an enormous extension of sea ice floating on the Arctic sea. However a vast area of sea ice also surrounds the Antarctic, and reaches its maximum extension in September, reaching a width of 2,000 km. Unlike glaciers and the ice-sheets, whose size remains practically unaltered during the course of the year, sea ice undergoes spectacular variations in its expanse, which can be appreciated particularly when observed from a satellite on areas that cover 15-20 million km2 of the Polar seas. The variations are particularly evident around the Antarctic, where sea currents tend to push away the fragments of the pack, dispersing them, when these are not so big, in the Arctic Sea, where currents tend, on the contrary, to concentrate the large drifting ice floes around the North Pole. Their moving away is also hindered by the presence of the surrounding land above sea level. Unlike glacier ice, which may date back various thousands of years, the age of sea ice is rarely more than a year. Large ice floes that are many years old can be found only in the Arctic Sea.

Permafrost: frozen ground

When the mean annual temperatures of the air remain below zero for long periods of time, the water in the ground is always in the solid state, and the land is permanently frozen. This state is named permafrost (i.e. permanent ice). The land, hardened and without any liquid water, is made up of mineral particles (particles of soil, grains and rock debris of various sizes) cemented together by ice. The depth of the ice depends on how cold the climate is, and can reach many dozens of metres (in some areas in Siberia and Alaska, with mean annual air temperature ranging between -7 and – 16°C, permafrost was found at a depth of 300-600 m, with a maximum depth of 1,500 m in an area of Northern Siberia).

In summer, a thin layer on the surface, the so-called active layer, is heated by the sun and the ice can melt. Since the permafrost below is impermeable, the melted water cannot be moved away and the thawed land becomes soft and drenched with water, often marshes and swamps form, and there may be serious problems with the stability of buildings that are built on this kind of terrain.

In order to build in these areas, particular construction techniques are required, where the buildings rest on poles dug into the ground till they reach the permanent frozen layer: similar to “pile dwellings” on the soft, loose active layer. Permafrost may be found in small areas in the high mountains (also in the Alps), but mainly in very vast areas in the high latitudes: approximately one fifth of the emersed land is affected by this phenomenon (half of the territory of the former Soviet Union, half of the Canadian territory, three quarters of Alaska, almost the whole of Greenland and the Antarctic).

Ice-sheets: continental glaciers

Ice-sheets, also known with the Norwegian term, *inlandsis*, continental ice, are expanse of ice with a surface area of over 50,000 km^2, where ice buries and masks the underlying relief that does not influence its trend.

The surface is generally mildly convex, like a kind of very flat dome, from which higher peaks of the underlying relief may emerge; these are named nunatak, an Inuit term that means “isolated mountain”. The central, more raised sector, of an ice-sheet is known as the dome.

Ice caps are similar to ice-sheets but their size is smaller.

From the ice-sheets, ice flows branching off radially in various directions, forming the so called outlet glaciers. These are veritable rivers of ice, at times their size is immense: the world’s largest glacier is Lambert Glacier that flows from the Antarctic sheet. It is 400 km long and over 50 km wide.

Most outlet glaciers reach the sea where they form snout of ice floating on the sea surface and extend even for many kilometres – through a process called calving most icebergs are formed here. The Lambert Glacier for example, flows into the Amery Ice shelf forming a floating tongue that extends up to 300 km with a front that is 200 km wide.

Approximately 85.7% of the ice on world’s surface is found in the large ice-sheets of Antarctica, about 10.9% are in the Greenland ice-sheet: these two areas together account for almost the entire amount of the world’s ice (96.6%). Much smaller ice-sheets and ice caps are found in Alaska, on the islands of the Canadian archipelago (Baffin, Ellesmere, Heiberg, Victoria) and in Iceland, on the Jan Mayen, Svalbard and Franz Josef Land archipelagos and on the Scandinavian peninsula (where the most extensive glacier is Jostedalsbre, where bre means glacier, the largest in Europe, excluding Iceland). In the Southern hemisphere, vast extensions of ice, similar to ice-sheets can be found in the Patagonian Andes, forming the Hielo Continental (hielo means chill or ice in Spanish) with a surface area of 17,000 km^2 and 50 outlet glaciers spreading from it: some of these terminate in large ice contact lakes, like Lake Vidma and Lake Argentino.

Ice shelves

When a glacier reaches the sea, it stretches into a floating snout. The confluence of various floating snouts gives origin to the formation of an ice shelf: a kind of flat shelf that floats on the sea and is anchored to the ground by the tongues that feed it. The most extensive ice shelf is the Ross Ice Shelf in Antarctica, with an average thickness of 300 m and a surface area of 472,960 km^2, equal to the area of France – it is bounded on the sea-front by ice walls up to 200 m high. The various tongues of ice that feed the ice shelves move at different speeds, and this, together with sea currents and wave motion, causes a great instability of the margins. In fact enormous fractures called chasms form, as for example the one seen on the Filchner Ice Barrier in Antarctica, that is 100 km long and 400 m to 5 km wide. These impressive fractures are the prelude to the detachment of enormous portions of the ice shelf that form gigantic tabular icebergs, which drift away. Scientific research base camps built on ice shelves were involved in the formation of these enormous icebergs that drifted away, as in the case of two American base camps and a Soviet one.

Icebergs

Icebergs (from ice and berg, mountain, mountains of ice) form in two conditions:

- when a glacier descends to the sea or to a lake, the terminal part of the snout starts floating when it comes into contact with water. Because of a phenomenon known as calving, large fractures form in the mass of ice, with the consequent detachment of portions of different sizes. The shape of this kind of iceberg is generally irregular, and the surface is jagged, tormented;
- the movements of currents and tides of the underlying water, together with the constant thrust of the glaciers that feed the ice shelves, cause fractures and fragmentation of the ice shelves. Every year, in Antarctica, for example, 1,450 to 2,000 km3 of ice are lost in this way (a volume that is equivalent to about half the annual amount of drinking water consumption worldwide).

These kinds of icebergs generally have the shape of flat tablelands whose surface is relatively smooth and regular. These are typical in the Antarctic zone, while icebergs of the first type form more easily in the Arctic seas, where lands are not surrounded by ice shelves of floating ice and the numerous glaciers from the land can therefore flow directly into the sea. Small sized icebergs may also form from blocks of ice collapsing from the fronts, which do not necessarily have to be floating on the sea or on a lake.

Since the density of ice is less than the density of water, icebergs float on the surface of the sea; the submerged part is therefore 7-10 times (depending on the difference in density of water and ice) taller than the part above sea level. If we consider that some icebergs can be many dozens of metres high, above the surface of the sea, then we can well understand how the name “mountains of ice” is particularly indicated: for example, an iceberg that shows a 30 metre wall continues below sea level up to a depth of over 200 metres! The largest iceberg to be seen was an iceberg in the Antarctic, observed in 1956, whose size was 335 x 97 km, with a surface area of 31,000 km^2, equal to the area of Belgium.

Once they detach from the glacier or the ice-shelf, icebergs begin to drift pushed by winds, currents and tides. The erosion of wind and waves and the progressive melting process they undergo as they move towards warmer latitudes, decrease their size, besides the fragmentation caused by violent tempests or collisions with other icebergs or with the land. The destiny of icebergs, therefore, is to decrease in size till they disappear, however their life-span can be of many years.

Mountain glaciers

These, as their definition describes, are bodies of ice that are found in the mountains. These can be classified in many ways, bearing in mind their geographical position, shape, temperature. Size is not a criterion used to distinguish these glaciers, some of them are very small, as the Calderone glacier on the Gran Sasso d’Italia mountain in the Apennines, which is little more than a thin strip of old snow (at present it is considered practically “extinct”), or the gigantic ice “rivers”, that are dozens or even hundreds of kilometres long, with ice thicknesses over 1000 m, as the large Alaskan glaciers, among which the most extended is the Bering Glacier, followed by the Malaspina Glacier whose outlet on the planes expands into a piedmont lobe that is the largest in the world.

Where is ice found?

The Antarctic

The "Antarctic ice-sheet" actually consists of two distinct ice-sheets. A Western one, which is smaller and is anchored to a group of islands, and an Eastern one, which is very vast and which, alone, accounts for 78% of the world's glaciers; the latter covers the Antarctic continent and rises with a number of domes, to heights over 4,000 m. The two ice-sheets are separated by the Transantarctic mountain chain, which has peaks over 4,000 m high.
The Western ice-sheet has a maximum thickness of 3.5 km, and its base is prevalently below sea level, while the Eastern ice-sheet reaches thicknesses up to 4.5 km and it is prevalently above sea level. Antarctic ice forms slowly due to the scarce precipitations, however it melts equally slowly due to the very low temperatures: it is here that we can find the most ancient ice on Earth. It is still not possible to make any forecasts about the state of health of the Antarctic ice-sheet: its balance still seems positive, even though the Western part has incurred large losses due to calving as its base is below sea level.
The Ross Ice Shelf, which is the most extensive in the planet, is named after James Ross, who was navigating on account the British government to reach the South Pole, and discovered it in 1841: the enormous walls bordering this ice shelf brought an end to the Captain's explorations, Ross did not reach the South Pole, but wrote a detailed report on the margins of the ice shelf, leaving extremely precious historical information for the study of the evolution of Antarctic ice.

The Greenland Ice Sheet

Greenland, the green land, named this way by Eric the Red in the 10th century, to encourage the Vikings to colonize the land. At the time, in fact, it was truly green, however the subsequent advance of ice forced the colons to abandon the island: only the Inuits survived the Little Ice Age. The Greenland Ice Sheet occupies seven eights of the island, with a surface area of 1.73 million km2 and a volume of 2.6 million km^3, leaving only a small mountainous coastal strip that limits and "contains" the ice-sheet. The ice thickness is 1,790 m on average, but in some parts it is over 3,000 m, culminating in two domes that are 3,300 m high. Many tongues flow out of the ice-sheet, but due to the mountainous characteristics of the coast, only few are able to reach the sea, therefore Greenland practically has no ice shelves. One of the most important outlet glaciers is the Jakobshavn Glacier, a real factory of an enormous number of icebergs. It is the fastest glacier in the world, and near its front it moves at an impressive speed of 1 m per hour, producing continuous collapses and an enormous quantity of icebergs, over 20 million tons per year.

Icebergs falling into the sea from the fronts can provoke tsunamis up to 10 m high. The iceberg that sank the Titanic originated in Greenland.
Since December 2002 the thickness of the Greenland Ice Sheet is monitored by the NASA satellite ICE Sat, which also monitors the Antarctic ice with laser equipment that can measure up to 1 cm variations in thickness.

Glaciers in the Alps

Glaciers in the Alps account, on the whole, for less than 0.02% of the world glaciers, but are very important because it is here that the first glaciology studies were started, and we have a lot of information about these glaciers over a long period of time. The 1989 International Glacier Registry recorded 5,154 glaciers in the Alps with a surface of a little less than 3,000 km^2, of which the largest are in the Northern slopes, where large valley glaciers form frequently. The largest glaciers are in Switzerland in the Bernese Alps, where there is also the largest Alpine glacier, the Aletschglätscher (24 km long, with a surface area of 170 km$_2$, and a thickness of a little less than 900 m), in the Vallese Alps, where the largest glacier is the Gornerglätscher, in the Monte Rosa mountain group, and in the Rhetic Alps, where the most extended is the Morteratsch Glätscher, in the Bernina Group (Glätscher means glacier in German). Important glaciers are also to be found in the Mont Blanc group, among which the famous Mer de Glace (sea of ice) one of the first glaciers ever to be studied, in Austria, in Ötztal and in Alti Tauri.

Glacier inventories

In Italy, the Italian Glaciology Committee, in collaboration with the Consiglio Nazionale delle Ricerche, (the Italian National Research Council) published the Italian Glacier Inventory in the years between 1959 and 1962, and up dated it in 1989. It is a fundamental document that clearly shows the situation of Italian glaciers and is complete with historical data and images of great importance. In many other countries where research about glaciology has ancient traditions dating as far back as the 19th century, similar detailed compilations regarding national glaciers exist (for example in Switzerland, Norway, Austria, the ex-USSR and Canada). From 1970 all these data flow into an international inventory, promoted by UNESCO and by the International Association of Scientific Hydrology, that has founded the World Glacier Monitoring Service, based in Zurich. The World Glacier Inventory is the most up-dated document regarding the world glacier situation.

Italian glaciers. The Italian Glaciers Registry identified 838 glaciers with a total surface of 540 km^2 of which almost 100 km^2 in the Ortles-Cevedale Massif, followed by the Adamello-Presanella group and the Mont Blanc Group. On the Apennines there is only one glacier which is becoming extinct, the Calderone Glacier, a small strip on the Gran Sasso d'Italia.
The glaciers with the largest extension in the Italian Alps are the Forni Glacier in the Ortles-Cevedale Massif, with a surface area of 13 km^2 in 1989, which competes for the first position in Italy with the Adamello Glacier with a surface area of 18 km^2, which is however divided into various distinct flows. The Forni Glacier consists of three accumulation basins whose flows

converge in a vast tongue that descends into the valley while the Adamello Glacier is on a plateau, a kind of small ice-sheet called Pian di Neve, from which numerous minor tongues and ice streams descend.

Glaciers caves

And inside? Glacier caves

Melting water on a glacier surface collects in small seasonal water streams that erode their bed in the ice, and are called bédières (a French term): in fact, ice is impermeable and does not allow the water to seep in deep. However, glaciers are characterized by a number of fractures that run across the surface. Through these fractures surface water can filter in and flow within the glacier. Liquid water is obviously warmer than the ice it comes into contact with, and determines its melting, creating a system of empty spaces, underground passages, shafts and galleries that are similar to the systems of caves in the rock. The difference is that caves in the rock are created by chemical processes, (dissolving limestone) while ice caves are formed due to a physical process (ice melting). The ice cavities form in all the glaciers that are "warm" enough for water in the liquid state to be present. The formation of ice caves is very rapid, and can be observed, one may say, in "real time": the cavities form and change during the course of a few weeks or a few days and this offers the opportunity to understand analogous forms that developed, in much longer times, in the rocks. For ice caves to form, ice, which is impermeable, must be broken by fractures that enable water to penetrate deeply and, as it melts the surrounding ice, to widen these fractures giving rise to the formation of shafts and galleries, which may even be several metres in diameter.

On the surface shafts and sinkholes are noted, known as glacier sinkholes or moulins (glacier mills), because the water spins like in a water mill, through which water seeps into the depths of the glacier. Due to the effect of gravity, water tends to follow a way as vertical as possible, creating large shafts and deep gorges in the ice that is fractured due to the enormous tensions that develop within its mass, and flows slowly under the thrust of its own weight. Beyond a certain depth (approximately 150-200 m, and it is equal for all glaciers, independent of their thickness), ice becomes plastic and behaves like an impermeable barrier that prevents water from seeping more deeply in its course: thus horizontal galleries are formed, these are completely flooded and convey water from the sinkholes right to the front where, due to the presence of deep crevasses, it can reach the base of the glacier, and then flow outside through the "mouths" of the glacier, with galleries that can be several metres wide, out of which the turbulent greyish waters of the glacier drainage channels flow. The "mouths" of a glacier often really look like large "mouths", similar to the opening of an oven, from which the toponyms of some of the Alpine glaciers derive (oven is forno in Italian) (The Forni Glacier in the Ortles-Cevedale group, the Forno Glacier in the Bregaglia valley, Switzerland).

The best places to observe glacial sinkholes are the plain areas, far from the areas with crevasses, or along the medial moraines, or on the sides of the glacier. These may be found in all the Alpine glaciers, but only in some cases these reach a size that can be penetrated by man. Large sinkholes may be found, for example, on the Gorner Glacier, on the Mer de Glace and on the Forni Glacier.

Evolution of a cave

A moulin forms in a precise point of the glacier where fractures are favourable, and like whatever is on top of or inside the glacier, it is then slowly dragged downstream by the movement of the ice: next spring a new moulin will form in the same point, and the old moulin, deprived with water, which has been captured by its younger upstream companion, will slowly close, due to the plastic swelling of the ice, till it finally disappears after a few years, while new moulins continue to form further upstream. For this reason moulins are almost always in groups, aligned in a precise direction and always in the same point of the glacier: from upstream, moving downstream, it is possible to observe all the stages of the life of a moulin, from moulin "embryos" that are fractures slightly widened by water, to baby moulins, cylindrical holes with a diameter of only a few centimetres, which are often many metres deep, up to large shafts dozens of metres deep, and a few metres wide, with complex forms, and finally old inactive shafts, fossil and silent, that year after year become inexorably narrower, till they disappear without leaving a trace.

We are used to thinking of geological phenomena as processes that are mostly slow, even though inexorable, and it is surprising to see the speed at which glacier caves form, modify, and disappear: when returning, even only few days later, to observe the same moulins, it is possible to note deep changes in shape, size, quantity of water supply, so much so that at times one may even doubt one is observing the same structure. In order to study these kinds of cavities therefore it is necessary to mark them with stakes so as to be able to recognize them year after year, and to draw their topographical features, in order to monitor the variations in their shape and depth. In this way, for example, it has been possible to study the moulins of the Forni glacier and to establish that moulins have an average life of at least 6 years, of which the first three are necessary to reach the maximum size and the following years show the progressive decline. In larger glaciers, as in the Svalbard islands, old moulins over 25 years old were observed. In any case, independently from the ice thickness, the maximum depth of ice caves does not exceed 200 m (203 m, to be precise, in Greenland): no cave in fact can exist below this depth, considering the limit of fragile ice.

Two worlds not to be confused

Caves in the ice and ice in the caves

Many Karst caves, dug into the rock, contain ice inside, in amounts that can be also considered abundant. These must not be confused with ice caves that are formed entirely within the glacier. The mechanisms that lead to the formation of ice in a cave are numerous and very complex. Seasonal ice may form in winter because the water that percolates through the crevices freezes near the openings, where the temperatures of the cave are influenced by the cold external temperature. Larger quantities of ice may form due to the freezing of small surfaces of water, as it has been reported, for example, in some caves in the Northern Grigna mountains, in the Prealps of Lombardy: here the ice is quite ancient and can be dated back to the beginning of industrial activities. In some cases the nearness to a glacier may push glacier ice into the galleries as in the case of the famous Castelguard Cave in North America. In other cases, ice forms due to the accumulation and transformation of snow that falls into the entrance shaft. The study of the ice found in caves, performed in an analogous manner as the study of cores taken from the glaciers, can provide extremely precious information regarding more recent climatic variations.

Speleology in the cold

Since the first explorations on the Alpine glaciers, alpine climbers and experts have observed the spectacular display, which is both fascinating and frightening, of glacial sinkholes. Moulins were seen as bizarre natural anomalies, that drew attention and fear, due to the depth that at times could not be measured, and because of the violence with which the waters seemed to be sucked into the glacier's stomach: for over a century many wondered about the origin of these structures and the invisible course of water within the glaciers (the first recorded explorations date back to the end of 1800 on the Mer de Glace in France), however it is only since the Eighties that technical progress enabled direct exploration of glacial sinkholes, in safe conditions and relatively easily.
And so a new discipline has evolved, glacial speleology, which unites exploring and sports activities and scientific research. Thanks to the work of glaciospeleologists, we now are beginning to understand the mechanisms that give origin to glacial caves and the importance of studying them in order to understand glacier behaviour, and particularly how water circulates inside the glaciers. Many explorations have been performing on the immense and spectacular glaciers in Iceland, Svalbard, Patagonia and Greenland (it was here, in 1998, that a glacial lake was found at a depth of 203 m on the bottom of the spectacular moulin in the Malik ice-cave, the deepest ever to be explored), but since a few years even the most modest Alpine glaciers are drawing greater interest, specially due to the possibility of carrying out repeated studies over a number of years. Every year, during a short season, that stretches from late spring to the first autumn snowfall, the main moulins are descended, photographed, measured, marked with stakes, in order to capture, in the variations that are monitored, some elements that might enable a better comprehension of their future formation and evolution. Besides scientific research, which is still at the very beginning, what makes this discipline particularly stimulating for those who practice it, is that the descent in a moulin is one of the most thrilling experiences the mountain can offer, and surely is one of the last exploration frontiers. Because of the water, only the moulins and a small part of the cavity front are practicable, while the rest of the system remains inaccessible for direct explorations: only hypothesis may be made about the structure, using particular methods, as for example, sending coloured tracers inside. The horizontal caves that open on the glacier fronts, that apparently do not involve risks and do not seem to require particular precautions and equipment are explored: often, in fact, these are large environments where it is possible to walk on the rock substratum. Actually it is not advisable to venture into these

environments as they are structures that are subjected to the enormous thrust of the glacier mass, and can be extremely unstable.
The collapses of blocks of ice and stones, falling from the surface above, are frequent, specially during the warmer hours. Therefore if there are no precise indications or a guide of the place, it is advisable to admire these cavities from a distance. Instead, notwithstanding appearances, exploring glacial sinkholes is less dangerous, on the condition, of course, that you have suitable equipment and a sound technical know-how. In this case the usual techniques for climbing on vertical ice are not adopted (such as piolet traction), but a mix of mountain climbing and caving is used. In fact climbers go up and down hanging on ropes, like those used by cavers, with equipment that is typically used for exploring caves, while the tools derived from mountain climbing are the tubular ice pitons, crampons and a short ice-axe, that facilitate vertical climbing and also movement when the bottom is reached. The risks are connected with water, which flows from outside with a remarkable flow into the active sinkholes and the stones that at times impend over the edges. For these reasons it is opportune to carefully choose the period of the year and the time of the day, when planning a descent, in order to minimize the risks and make this spectacular activity as safe as possible.

Studying ice caves

The entire glacier body moves continuously downstream and in this movement it drags whatever is on its surface and inside. Therefore also the ice cave systems move downward together with the glacier in which they have formed. By studying the mechanisms by which these cavities form, it has been possible to observe that a new sinkhole forms every year in the same point of the glacier, above a fixed point of the substratum. It is as if in that point there were particular conditions, due, for example, to the characteristics of the substratum, that determine the formation of a moulin in the ice that is in that point at that time. The same occurs in the case of whirlpools and eddies in the current of a stream of water: the shape of the whirlpool is always the same, and also the point in which it forms, but the water that forms the whirlpool is continually replaced. For this reason, even though they vary continuously, glacial caves are stable structures inside a glacier. The distance separating a new sinkhole from the one that formed the previous year, therefore, is equal to the speed of the glacier's downward movement: measuring the distance between aligned moulins is therefore an excellent and rapid system to evaluate the speed of a glacier. And by observing aligned moulins from the top of the mountain to the valley, it has been observed that the speed is not the same for the entire glacier, but it is as if within the body of the glacier there are areas flowing with different flows, that may be more or less rapid: the distances between moulins belonging to the same alignment enable a "visual" evaluation, and do not require complex measurements, the areas that are faster are where the moulins are further apart one from the other, and the slower areas are where the moulins are to be found closer together.

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