ICE AND GLACIERS

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Introduction

Ice forms when water in the liquid state freezes. Freezing temperature depends on the content of salt dissolved in the water: at normal atmospheric pressure, it is 0° C for pure water, not greatly different for fresh water and it drops to -1.8°C in the case of sea water. When temperatures drop below freezing point, water turns into the solid state. This is true for water that flows freely on the Earth's surface as also for stretches of water such as lakes, rivers, seas, and also for water trapped in wedges in rocks and in pores in the ground, where ice lenses and veins form. Running water, due to its movement, freezes more slowly than still water, for this reason it is easier in winter to see the formation of ice on the surface of small stretches of still water, while the waterways are not frozen.

Ice

How ice forms

Since most of the Earth's ice does not come from frozen pure water, the ice we see generally consists of ice crystals mixed with a number of impurities, including dissolved salts absorbed in the ice crystal network (like sea water salts in sea ice), fragments of debris, atmospheric dusts, fragments of rock or soil trapped among the crystals, and minute air bubbles imprisoned during the freezing phases or as the snow was transformed into ice. The study of these impurities enables us to obtain important information about the formation processes and about where the ice comes from and even about the composition and temperature of the atmosphere at the time of ice formation.

Snow transforms: glacier ice

The formation of the ice of a glacier begins with snow deposition. Snow, with its star or hexagon shaped crystals, contains a great quantity of air, and has a very low density (this is why we sink in so easily, furthermore because of this, snow has a great capacity to absorb sounds, a snowy landscape seems strangely "silent").

As soon as it falls to the ground, snow begins a **transformation** that leads to the modification of the shape and size of the crystals and a progressive decrease in the number and size of the empty spaces, increasing the density. This transformation is known to skiers, who well know the difference there is in skiing on powdery winter snow or in spring snow that is transformed and granular! The main factor responsible for the transformation of snow is **melting**, by which single crystals are enveloped in a film of water, which melts the sharp tips giving them a more rounded shape. The variations in the shape and the presence of water in the gaps between the crystals provoke a gradual decrease in the empty spaces between the snow grains, also favoured by the **compacting effect** of the weight of the overlying layers of snow. If there is a refreezing of the melted waters, the size of the pores decreases further and the larger crystals become bigger at the expense of the smaller ones, which disappear. The transformations are very rapid when the snow is subjected to many cycles of melting and freezing, they are slower if the temperatures remain low : in the latter case the transformations occur by effect of **sublimation**, a process that requires a longer time (this is why plentiful snowfall in winter can lead to a high risk of avalanches, as persisting low temperatures do not allow the transformation and stabilization of the snow layers). Therefore snow is transformed into a not very compact mass of rounded ice crystals called old snow, or more elegantly known as névé or ***Firn*** (German term) if it remains for more than a year. Firn is characterized by a density over 0.54 and porosity under 40%. The transformation of snow into Firn is more rapid when there are a greater number of freezing and thawing cycles: approximately 4 months in the Andes, one year in the Alps, 4 years in Southern Alaska, twenty years in Greenland (source: Smiraglia, 1992). The size of the grains and the density increase and the porosity decreases with age. The transformation of Firn into **glacier ice** takes place when the empty spaces that are present no longer intercommunicate: ice becomes impermeable and the air that is present remains trapped in bubbles between the crystals. When the mass of ice begins to flow, the air bubbles are further compressed and the density of the ice increases up to approximately 0.91 g/cm^3 (compared to 1 for water). The transformation of Firn into ice is even slower and always depends on temperatures.

The physical properties of ice

Ice has a singular property, which is apparently banal, but which has important repercussions on the life of the entire planet. While most substances decrease in volume when changing from the liquid state to the solid state, the property of water is that it is less dense in the solid state than in the liquid state: in fact, maximum density of water is reached at a temperature of 4°C.

This implies that ice is lighter than an equivalent quantity of liquid water, therefore ice floats on water: this can be seen when sipping a drink in a glass full of ice cubes. However, in nature, the same phenomenon can be seen in the icebergs and in the formation of sea and lake ice.

If ice did not have this property, ice formed on the surface of a sheet of water (a lake or a sea) would sink, accumulating on the bottom. This would finally form thick deposits of ice on the bottom of seas and lakes, which would soon be transformed into large masses of ice, and the summer heat would only produce a minor layer of liquid water near the surface. The consequences of this property on the life of our planet are therefore very easy to imagine.

As a result of this property, when water freezes its volume increases. This is easy to test, when we put a bottle of water in the freezer, the pressure of the ice can break the bottle – if the bottle is full, the ice does not have space to expand and the container cannot deform, as in the case of a glass bottle. In nature, this process is very important: the pressure of water freezing inside small cracks in a rock can be so great that the rock breaks into small fragments. This process, called cryoclastic weathering (from Greek cryo, kryos : cold and clast, klastos: broken), (freeze-thaw weathering or frost shattering) is responsible for mechanical weathering of rocks in the high mountains, and produces large stretches of sharp debris, which are a characteristic feature in mountain landscapes above the limit of arboreous vegetation (that mountain climbers and excursionists call “screes” – those who are familiar with the mountains know how tiring it is to walk on this large gravel!).

How much does ice weigh?

Like an object that floats on water, analogously the Earth's crust "floats" in equilibrium on the viscous plastic rocks of the underlying mantle. A decrease in the weight of the crust, caused, for example by the removal of rocks due to erosion, makes the rocks lighter and the crust rises, while an increase in the weight makes the crust sink even deeper into the "soft" and viscous mantle, by a process called isostasy. The formation of thick layers of ice, (as in the glaciations of the past), causes an overload on the ice covered crust, and the result is that it sinks into the mantle, various hundreds of metres, in some cases even below sea level. Knowing the average density of ice and its thickness, it is easy to calculate its weight at the base. At present, due to the weight of the ice-sheet, which reaches 4.5 km in some parts, the Antarctic has sunk over 900 m. Radar measurements carried out in Greenland show that one third of the rock base is below sea level and the weight of the accumulated ice has pushed the rock downwards by over 600 m in some parts. As the large ice-sheets retreat after the last glaciation, the territories that are freed of the weight of the ice have started to rise. For example, the region around the Hudson Bay has risen over 300 m in a little over 10,000 years after the Laurentide ice-sheet retreat. This rise is not over as the territory still has not reached its height before the last glaciation. Also the Scandinavian peninsula is still rising at a rhythm that reaches 9 mm per year in the middle of the Gulf of Bothnia. The delay in the response to the removal of the load is due to the viscosity of the material of the mantle, which has a certain amount of inertia. The rise after the end of the last glaciation is greatly camouflaged by the rise in the sea level as a consequence of the melting of large quantities of continental ice.

What glaciers are

How does a glacier work?

The mass of ice that forms a glacier is not a static and homogeneous mass: the ice has different characteristics in various points of the glacier, and behaves differently depending on the compactness, density, temperature within and at the base of the glacier, and the characteristics of the bedrock the glacier rests on. On the surface of every glacier, therefore, it is possible to identify different areas, where different processes are taking place, which mould the shape of the glacier and determine its behaviour. In every glacier it is possible to identify two fundamental areas : the accumulation area where the snow that falls in winter is preserved during the hot season, which is the area where the glacier receives the supply of snow that is necessary for its survival, and the ablation area, where, instead, there is a loss of ice, mainly due to the melting of the snow that fell during the previous winter season, and the ice left bare after snow melting, but also due to collapse and detachment of material from the glacier body, as in the case, for example, of the formation of icebergs. Therefore there are areas of the glacier where ice is produced, and areas where, on the contrary, ice is destroyed and moved away. The two areas are easy to recognize in summer : the accumulation area in fact has a white surface covered with snow and firn, while the ablation area shows weathered ice, whose appearance is generally "dirty" due to the presence of rock debris that appear on the surface of the ice. The extension and importance of these two areas characterize every glacier and condition their behaviour. The extension of the two areas is not fixed in time – in fact they are separated by an equilibrium line that coincides, approximately, with the perennial snow limit. Since this limit varies greatly depending on the climatic conditions, short term and long term variations in the climate greatly influence its position, and consequently the magnitude of the accumulation and ablation area. The body of a mountain glacier is usually confined by the rocky mountain slopes surrounding it, generally on almost all the sides, however there usually is a non-confined side, where the glacier is free to expand or retreat. This is the glacier front, that indicates the limit beyond which the glacier cannot exist, because here, simply, ablation destroys all the ice. One of the most evident characteristics of a glacier, which differentiates it from a snow deposit, is that ice moves, sliding toward the valley, under the pressure of its own weight. In this manner the ice lost in the ablation area is continually replaced by new ice that forms in the accumulation area and is transported downstream by glacier movement.

Glacier movement

Glacier movement is not uniform throughout its mass and it is not even constant in time. The speed of the movement is slower near the walls and the base, where the glacier is slowed down by friction with the bedrock, and maximum in the central zones, where friction is minimum and ice thickness is maximum. Different speeds may be noted also at the confluence of two ice snouts, usually marked by a “floating” medial moraine, a long strip of debris on the sides of the glacier snouts along the entire length of the ablation area. If there is melted water at the base, the glacier moves more rapidly. Therefore, temperate glaciers are the ones that “shift” more, while those with a cold base may remain “anchored” to the frozen bedrock and move very little, or in “jerks”, as along a fault. Glacier speed varies greatly depending on the characteristics of the ice and the bedrock: from a few metres a year to many hundreds of metres per year. One of the fastest glaciers is the Columbia Glacier in North America that, since the Seventies, has been moving at a speed of 24 metres per day. Intuitively one may think that this unrestrainable movement pushes the glacier front more and more downstrem – the faster the ice is, the more it should move forward. Therefore continuous observation of the position and shape of the glacier front in time should give us reliable indications on its state of advance and retreat. But actually the situation is much more complex. Even when the front is stable, apparently still, the glacier continues to move downstream: the fact that the front does not move means that the ice lost by ablation is continually replaced by new ice coming from the accumulation area, at the same rhythm at which it is being lost. In case of the Columbia Glacier, its high speed would lead us to think of its rapid advancement, however the large losses on the front make it a glacier with an overall retreat – since 1982 its retreat has been 14 km.

The delicate equilibrium of glaciers

Therefore in order to evaluate the “state” of a glacier, in particular if the glacier shows an advance or a retreat, it is not sufficient to evaluate the variations in the position of the front, but the delicate equilibrium of the snow supply, i.e. the formation of new ice, and the loss of ice in the ablation area must be considered. In other words, it is necessary to evaluate the variations in the volume of the glacier, studying the "balance" of these two factors, calculating what researchers call "mass balance". Practically this means measuring supply and loss, as in a company balance-sheet, and to find, from the difference, if the volume of the glacier is increasing or decreasing. If the balance is positive and supply is greater than loss, the glacier will tend to expand, shifting the position of the front more downstream, while, if the balance is negative, the ice will decrease, its thickness will diminish and the front will retreat progressively upstrem. A stable front in time on the contrary indicates a stationary situation of equilibrium between supply and losses (however this does not mean that the glacier is still at all). The glacier's response, however, is not immediate. Generally the glacier responds with a certain inertia, that also depends on its size, and it takes a few years of positive balances in order to see a glacier advance, and vice versa. Many glaciers in the Alps have been studied for decades, some for over a century, and researchers therefore have numerous series of measurements of the variations of the front and mass balance records, over long periods of time: this has enabled, through a comparison of the glaciers' advance and retreat, together with the climatic and meteorology data, to understand how glaciers have reacted to the more recent climatic variations, thus enabling the formulation of hypotheses on the future of our glaciers.

The "material" ice

Ice has singular physical properties that condition all the processes that take place on the surface and within a glacier. At ambient pressure, ice is a very fragile material. If it is subjected to mechanical stress such as compression or distortions it reacts and it forms fractures and breaks in a fragile manner (to verify this try dropping an ice cube: it will break into a myriad of splinters that will melt rapidly on your kitchen floor). In high pressure conditions, as for example within a glacier, or as a result of stress applied very slowly, on the contrary, ice is plastic, and deforms and twists continuously, without forming any fractures (as with a packet of plasticine), in order to prove this, try the classic experiment of stretching a thread with two weights on each end, on an ice cube – slowly the thread will penetrate the ice cube, and the borders where the thread passes will weld together as the thread progresses downward, crossing the ice cube completely without leaving any traces of its passage. Therefore ice in a glacier behaves very differently on the surface and deeper under. This may seem of little importance, but it is fundamental for water to circulate and for storage of water reserves within the glacier. Ice, in fact, is an impermeable material, that does not allow water to pass: however it becomes permeable, enabling water circulation, when it is fractured. The fragility of the superficial layers is also responsible for the better known morphologies of the surface of a glacier: crevasses and seracs, immense fractures that at times make it very difficult and dangerous to cross glaciers. Often described as "bottomless abysses", actually due to the physical characteristics described above they rarely reach a depth over 40-50 m (not much in a glacier where the ice thickness is over 800 m, as in the case of the Aletsch Glacier, but sufficient to cause reverent fear). Direction of crevasses and fractures depends on tensions originated in the ice in response to irregularities in the bedrock and friction along the walls, and can be useful to reconstruct the trend of the underlying rock and to evaluate the ice thickness. For example, fields of seracs, large "cascades" of blocks of ice that are intensely crevassed may indicate a sudden variation in the inclination of the bedrock, or a rocky "threshold", that may indicate the presence of subglacier lakes, which could be extremely dangerous due to their instability.

A large conveyor belt

Glacier movement, friction with the rock along the sides and on the bottom, falling material from the surrounding sides, dust brought by wind, animal carcasses, waste left by man, including war relics and the bodies of unfortunate soldiers or mountain climbers: everything can be "captured" and swallowed by the ice of a glacier, on the surface or within. The movement of a glacier, described before as a sliding downstream movement, is actually more complex and it contributes to letting debris penetrate deeply in the accumulation area, and to bringing them out in the ablation area, where also melting process collaborates in uncovering them.

When a glacier moves forward, like a gigantic scraper, it pushes incoherent debris and rocks below and in front of itself; when it retreats, it abandons all the material it was carrying, forming glacial deposits also known as till, from a Scottish term. These deposits have different names, depending on how the glacier arranged them (e.g. "spreading" them on the sides and on the bottom, crushing and pressing them with its weight, as in the case of "lodgement tills", or accumulating them as the ice containing them slowly melts, as in the case of "ablation tills"). Ice deposits have unique unmistakable characteristics (for example the contemporary presence of large size blocks, very coarse particles and a very fine matrix, rounded gravel that is striped due to the enormous pressures and the reciprocal friction it is subjected to during transportation), so that it is easy to recognise them even when the ice that produced them disappeared a long time ago. Thanks to the discovery of deposits of glacial origin, it is possible to reconstruct the succession of various glaciation episodes over the years: at times the locations in which ice deposits have been found were truly extraordinary, as for example, recent findings in the desert in Namibia or in the Sahara Desert, proofs of a glaciation of over 400 million years ago.

Younger deposits often also mantain particular features, as moraines, which enable the reconstruction not only of the presence of ice, but also the shape of the front and the height of the sides. Glaciers can be tens or hundreds of kilometres long, in the past there were even more wide-ranging ice bodies. Also the study of the type of rocks that form the ice deposits provides important information, enabling us to reconstruct the course of ancient glaciers that are now extinct. For example, in the territories to the north of Milan, there are rock cobbles originating from the Valtellina and Valchiavenna valleys, which enables the reconstruction of the course of an ancient glacier that in various spurts, flowed down the valley of the Adda river, occupying the area that now is Lake Como. Detailed studies in this area, enabled the reconstruction of the exact course of the various tongues the main glacier divided into, avoiding various nunataks, till it reached the plain. The study of glacier sediments is therefore fundamental in order to understand the variations in the expanse and shape of glaciers in the past, but this can be done in an efficient manner only if the processes regulating the behaviour of glaciers today are known very well.

White and black glaciers

The amount of debris inside and on the surface of a glacier is very variable and depends on glacier movement, on the type of bedrock it moves on, and on the shape and geological characteristics of the walls overlooking the glacier. Particular types of rocks, sensitive to weathering processes such as cryoclast weathering freeze-thaw weathering, or where the sides are subjected to frequent landslides and falling and flowing of debris, can provide large amounts of detrital material, which then cover the glacier surface. The glacier surface normally appears to be white, and consists of snow in the accumulation area, and it is characterized by ice scattered with debris in the ablation area. However, when the supply of detrital materials from the sides is great, the surface of the glacier may be completely covered with rock debris of various sizes, and the ice becomes practically invisible, in this specific case the glaciers are called black glaciers, as opposed to white glaciers. Examples of this type are several glaciers in the Himalayas or Karakorum. In Italy, a beautiful example is the Miage Glacier in the Valle d'Aosta region, also famous for its terminal lake. The presence of debris protects the ice from melting: black glaciers are therefore more protected than their counterparts, which are white and bare, and are not protected from solar radiation.

Who went this way?

All glaciers leave traces of their passage, traces that may remain even for thousands or millions of years. By studying present day glaciers, geologists are able to easily recognize the evidence of the existence of ancient glaciers. A glacier, moving and sliding on the bedrock leaves two different types of traces: it may deposit material carried inside and on its surface, thus giving rise to ice deposits accumulated in characteristic features that are easy to recognize, or it may erode the rocks it is moving on, leaving smooth and polished surfaces.

Ice deposits are generally characterized by a granulometry that includes very fine material deriving from crushed grains and debris due to friction with other grains and with the bedrock, and also very coarse material, including blocks that are several metres in diameter. This derives from the viscous property of ice, due to which a load of materials of very different weights and densities can be taken up, unlike other agents of transportation that are much more selective, (as for example the wind, that can only transport sand, or running water that can transport materials of different sizes depending on the speed of the current). The larger boulders are known as "glacial erratics" and are a good method for understanding up to what heights and for what distance the glaciers of the past moved. If the morphology of ice deposits is preserved, this also provides evidence regarding the shape of the front, the characteristics of the transportation and movement of the glacier, its advance and retreat, and many other aspects. The more characteristic and well known forms are surely moraines, which can be lateral moraines, on the sides, formed between the glacier edge and the slope, or frontal or terminal moraines, which are deposited in front of the glacier, generally forming concentric arcs. Other less known forms in the Alpine glaciers originate at the base of the glacier, due to the effect of deformations caused by the weight of the ice, as in the case of fluted moraines or drumlins, and due to the effect of the water circulating at the base, as in the case of eskers. Other forms originate from the contact of the glacier and the slopes; in ice contact deposits like kame terraces, depressions are formed between the lateral moraine and the slope, which can lodge small lakes and are filled with debris coming from the slopes, such as landslides or avalanches deposits. The study of deposits and morphology enables a detailed reconstruction of the morphology and characteristics of ancient glaciers and is fundamental in order to reconstruct environments and climates of the past.

Erosion or exaration features are also excellent evidence of the passage of a glacier and can at times be the only type of trace remaining. These can be very large scale features, as entire valleys with the characteristic U shaped profile, ice cirques separated by narrow crests (forming the so-called glacial horn, as in the case of the Matterhorn), or they can be seen in the form of specific rocky protrusions, the roches moutonnées also known as whale-back rocks, due to the elongated and rounded form. Roches moutonnées are smooth and polished due to the abrasive action of the ice containg a lot of debris, and they are often characterised by stripes and grooves in the rock due to a scraping process on the bedrock, and these enable to reconstruct both the passage and the direction of the glacier flow. By the study of morphology and deposits left by the glaciers, the reconstruction of the maximum limit reached by glaciers during the Quaternary glaciations, is very important. The acronym MEG (Maximum Extension Glacier) indicates the maximum height reached by Pliocene and Quaternary glaciers, while the term LGM (Last Glacial Maximum) indicates the maximum height reached by the glaciers during the last glaciation: the two levels are not the same, especially in plains, as the glaciers did not reach their maximum expansion during the last glaciation. The age of the more recent glacial deposits has been calculated by observing the state of weathering of the rocks forming them, the level of soil development, that determines a different amount of vegetation, the age of vegetation (dendrochronology) and lichens (lichenometry) covering the rocks.

Ice tales

Changes in the glaciers

Observations of the front variations include monitoring changes in shape and position of the front of a glacier. Once, this operation used to be carried out “by hand”, patiently drawing the profiles of the front, more recently photographing them from fixed positions, and measuring their retreat with mechanical instruments. Today, these operations are carried out generally using the GPS and aerial or satellite photographs, which enable a comparison of the variations year by year. Every year, the Comitato Glaciologico Italiano (Italian Glaciology Committee) promotes campaigns to measure the frontal variations of all the glaciers of the Alps and organizes interesting courses for those who wish to become glaciology operators.

Glacier Mass Balance

Calculation of the Glacier Mass Balance is a more complex operation – in fact a series of measurements and surveys must be carried out. First of all, the quantification of the additional constituents, measuring the amount of precipitations on the ice, also bearing in mind the so-called “hidden precipitations”, such as hoarfrost, or ice formed by sublimation, and contribution by avalanches. In order to do this, the height of snow precipitation, during winter and spring, in fixed, special points of the glacier, is measured. Usually this is carried out by fixing special long, thin rods, only a couple of centimetres in diameter, called “stakes” into the glacier in summer and inferring the thickness of the sheet of snow from the height of the protruding stoke. Since for the balance, snowfall must be transformed into equivalent millimetres of water, also the density of the snow must be known. For this purpose, special trenches are dug into the layer of snow, and its density is measured at various depths. These operations must be carried out in different points of the glacier, at different depths, so as to have a representative picture of the entire glacier.

Secondly, it is necessary to determine the quantification of losses, determining the amount of ice removed by ablation. Most of the ablation, in the case of Alpine glaciers, is due to ice melting. In order to measure this parameter, series of stakes (which are usually the same used to measure the thickness of the snow layer), numbered and labelled, are positioned on the surface of the glacier with the help of special drills, up to a given depth. Periodically, during the summer period even daily, the height of the stake getting free as ice melts is measured. It is therefore possible to measure the thickness of ice that is lost in a determined period of time, and from this, with repeated measurements, to estimate the overall quantity of ice that is lost during the course of summer. On the Forni glacier, in the Ortles-Cevedale Massif, for example, during the summer period, approximately 3-3.5 m of ice are removed by ablation, and between mid July and mid August melting reaches peaks of 4-5 cm a day (source of data: Smiraglia). The same stakes can also be used, measuring their movements vis-à-vis fixed points outside the glacier, to quantify the speed of the glacier movement downstream.

Since a large quantity of ice also melts at the glacier base, where it collects forming sub-glacial lakes and streams, in the glacier mass balance it is important to include the measurement of the outflow of the streams springing out of the glacier front. The amount of water produced by surface ablation should be subtracted, in order to obtain overall basal melting.

The determination of Glacier Mass Balance is a complex operation, and in Italy recordings are carried out systematically every year only of a very limited number of glaciers, among which Careser (since 1966), Sforzellina (since 1986) in the Cevedale range, Chardonay (since 1992) in the Gran Paradiso range. A general indication can also be obtained from observations, using aerial photographs, of the ratio between accumulation areas, covered with snow, and ablation areas at the end of the summer, or of the snow-limit: if this is at a low altitude, the balance will be probably positive even it is not possible to obtain specific quantitative indications. Observation of the characteristics of the glacier front can also be indicative: at a similar altitude, a high and swollen front generally indicates a positive balance, while a “depressed” thinner front indicates the opposite.

Measurement of the speed

The measurement of the speed at which a glacier is moving was certainly one of the first operations carried out by the first glaciologists in the 19th century, along with the observation of the front variations. In order to measure the speed at which the ice is moving, it is necessary to determine a fixed point on the glacier, easy to recognize thanks to some particular feature (e.g. a large boulder on the surface), or else marking it with one or more stakes, and constantly taking measurements (a number of times a year for a number of consecutive years) of the glacier movement vis-à-vis a fixed observation point outside the glacier.

Today, the use of aerial photographs and satellite images, together with use of particular instruments such as GPS, make this operation much easier, rapid and precise than in the past when operators had to take measurements directly on the glacier, often having to face a number of difficulties in reaching the measurement points. By means of more complex observations, made by aligning masses or glacier sinkhole systems, it has been possible to identify different areas moving at different speeds in the glacier. The speed at which glaciers move varies greatly in different glacier structures. The speed can vary during the year (usually slowing down in winter) and also from one year to another.

Measurement of the thickness

The thickness of a glacier can be obtained, with special formulae, once the speed, inclination and width are known along with some characteristics of the ice such as its density and viscosity. However, since these parameters are difficult to evaluate and vary in different parts of the glacier, it is a very rough estimate.

The oldest and most direct method of measuring the thickness of a glacier consists in digging a hole that reaches the rock substratum. However, this method is very expensive, it requires heavy machinery difficult to transport, especially in the mountains and gives the thickness only at a fixed point and not along the entire glacier. The ice is extracted by perforation in the form of long and thin cylinders called “cores” and can be studied to obtain a lot of information.

An indirect method of measuring the thickness of a glacier is by using geophysics, a special branch of geology that studies anomalies in the Earth’s gravitational field and the propagation of seismic and electromagnetic waves in order to obtain information about the substances that compose the Earth’s crust, including the ice of the glaciers. Seismic reflection profiling is the most commonly used technique for glaciers: blasting an explosive charge or ramming a heavy hammer on the surface of the ice generate waves that travel in the ice and are reflected by the underlying bedrock. By studying the course of the waves and knowing the speed at which they travel in different materials it is possible to calculate the thickness of the ice. Electric profiling, instead, is based on the study of the difference in potential created by the passage of electric current between two measuring points inserted in the ice, utilising the different conduction properties of ice and rock. A recent technique, that is very fast and efficient, is based on the reaction of ice to radar waves passing through it as if it were transparent. The novelty of this technique is that the required instruments can be placed on airplanes that can fly over vast areas: in this way, in fact, it has been possible to reconstruct the morphology of the bedrock and ice-sheet thickness in Antarctica and Greenland. This innovative technique was discovered by chance by some pilots who noticed the ‘anomalous’ behaviour of the radar altimeters on board their planes while they were flying over the Antarctic.

Cores and perforations

The presence of solid impurities and air bubbles trapped within the ice provide vital information about the chemical composition of the atmosphere and the temperature at the time of ice formation. It is of course essential that the ice should not have undergone melting processes, which would disperse the air bubbles: therefore, for these kinds of studies, one has to work on cold glaciers in polar regions. In some parts of the Earth, ice can be very old, like at the base of the great ice-sheets of Antarctica and Greenland, where ice can be older than 300,000 – 500,000 years. From the study of ice in these places it is therefore possible to reconstruct in detail the variations in temperature and in chemical composition of the atmosphere over a very long lapse of time, enabling us to gain access to a precious source of data regarding the climate in the past. For these studies drillings are carried out that extract long cylindrical ice samples which must not have any interruptions or missing parts from the surface up to the depth reached: in Antarctica, drilling reached a depth of over 2,000 m, as in Dome C (a project in which Italy participated) or in the Vostok perforation (Soviet), where the longest core, covering a time span of 420,000 years, was obtained.

Bubbles in the ice

Temperature of the trapped atmosphere can be obtained by studying the ratio between the heavy isotopes of oxygen, such as ^{18}O, and the more commonly found one ^{16}O. The ratio $^{16}O/^{18}O$ is then compared to the composition of a standard sample of sea water, the so-called SMOW (Standard Mean Oceanic Water), and the difference is calculated ($\delta^{18}O$‰).

Ice formed in a cold period has a lower content of heavy isotopes, such as ^{18}O, therefore $\delta^{18}O$‰ is negative compared to ice formed at higher temperatures. Specific tables allow us to calculate the average temperature of the air on the basis of the value of $\delta^{18}O$‰. This type of analysis, carried out on different cores in Antarctica and Greenland have permitted us to establish, for example, going back in time, the end of the last glaciation, around 13,000 years ago and its beginning, around 75,000 years ago; the interglacial period between the latter and older glacial episodes (120,000-140,000 years ago) had a warm climate and temperature was over 2°C higher than present, according to the reconstruction that was made using the Vostok core.

The analysis of the chemical composition of trapped air takes into account mainly the greenhouse gases, such as carbon dioxide and methane, considered the main cause of global warming. In fact, the analysis of the core shows that the content of these gases is naturally lower during the cold periods, corresponding to glacial periods, and increases when temperature increases. By studying numerous cores, it has been possible to reconstruct the trend in time of the two main greenhouse gases, and to identify different cold and hot periods.

The most significant result of this analysis is, however, the dramatic increase of these gases in the last 200 years – starting from the development of industrial activities – an increase that has no comparison with any other in the last 160,000 years. From the end of the last glacial episode to the beginning of the Holocene (a period of time of about 2-3,000 years), the carbon dioxide concentration in the atmosphere has increased by 70 ppm, and the same increase has been recorded from pre-industrial times until today (less than 200 years)! Data inferred from the study of glaciers thus allow us to reconstruct with great detail information on the climate and on the atmosphere of the past – essential in order to understand how the climatic system of our planet works and at the same time it rings a warning bell that should make us reflect and take necessary measures. Will we be able to make good use of the ‘advice’ our glaciers give us?

“Dirty” ice

During its formation, glacier ice traps air bubbles and numerous solid impurities, that can be opportunely studied and provide important and precious data on the history of our planet. The coarser debris usually come from the mountain slopes closer to the glacier or to its base: the examination of glacial deposits is very important to reconstruct glaciers that are now extinct however they do not usually supply interesting information regarding present-day glaciers (which we already have information about with regard to expanse and position).
Smaller fragments, fine dusts that may come from far away carried by the wind, are more interesting. Observing their distribution one can, for example, reconstruct the direction of winds, while an analysis of the dust composition can occasionally lead to some surprises: grains of sand from the Sahara Desert are wide-spread on Alpine glaciers, and it is not improbable to find traces of particularly violent volcanic eruptions in the form of great amounts of volcanic ash. The study of the composition of these ashes often allows us to identify the volcano from which they derive, and this provides us with information on the winds that carried them and on the strength of the explosion. If the ashes comes from historic volcanic events it is also possible to date the level of ice in which these were found. On the other hand, the possibility of dating the different levels of ice makes it possible to assess the time of very ancient volcanic events.
The study of dust in Antarctica and in Greenland, for example, shows that the concentration during the last glacial episode is much higher than today: this fact makes us infer that during glaciation, atmospheric circulation along the meridians was more ‘energetic’ due to greater differences in temperature between the tropical and polar zones and that the arid and desert zones were more wide-spread. The discovery of pollutants of industrial origin in cores of glaciers very far from anthropic settlements, such as those of the Himalayas or of the Karakorum, enable us to study how these substances are propagated in the atmosphere and, in some cases, to establish who is the “culprit”.

The age of ice

Glacier ice is far from being a homogenous material and is usually stratified in layers, due to the progressive annual accumulation of layers of snow of various thicknesses: the older parts can be found at the base and the younger ones closer to the surface. Usually summer ice has a glassier appearance, often full of dark dusts and it is less thick, while winter ice is white and thicker. In a way similar to that used to measure the yearly growth in trees by the number of rings, it is possible to ‘count’ the different layers and therefore infer the number of years. This method, however, can be used only until the growing pressure within the glacier cancels the ice stratigraphy. For the old and deep ice, indirect and more complex methods are used, taking into consideration the air bubbles trapped in ice. The radiocarbon method utilizes carbon 14C contained in trapped carbon dioxide in a way similar to that used to date handicrafts and organic material, but this method is rarely utilized due to the great quantity of material required. The most frequently utilized method analyses the heavy isotopes of oxygen present in the air bubbles. For the older and deeper layers other methods must be used based on mathematical models of the ice flow. The finding of levels rich in dust, particularly volcanic ashes, is important: when it is possible to associate them with a known volcanic eruption , it is possible to give a precise age to the layer level at which they have been found.

Glaciations

Glaciers of the past

Glaciations, periods of cold climate in which the glaciers all over the planet are characterized by a great expansion, and in particular, the formation of large ice-sheets are studied and are well known, with regard to the more recent period, the Quaternary period, but the entire history of the Earth is studied with climatic oscillations, with alternating hot and cold periods, and episodes of glacier advance and retreat. The study of very ancient ice deposits in North America, Africa, Australia enabled the discovery of the traces of the most ancient glaciation, over 2 billion years ago. Very ancient ice deposits were found in Africa and in Australia and can be dated back to 900, 750 and 600 million years ago, as evidence of the same number of glaciations: the extension and duration of these glaciations, however, are not known precisely, as such ancient deposits are preserved only in small discontinuous slivers, and do not enable a reconstruction on a vast scale.

Other glaciations took place in the upper Ordovician period, 450 million years ago, ice deposits and roches moutonnées have been found in the Sahara desert where once there must have been a vast ice-sheet, twice as large as Antarctica at present and, at the time of the Permian-Carboniferous passage, approximately 300 million years ago, with glacial deposits reaching a thickness of 900 m in South Africa, there is evidence of a large ice-sheet that not only covered the Antarctic but also Southern Africa, Madagascar and most of India and Australia (naturally, to study these ancient deposits, it must be borne in mind that the positions of lands above sea level were very different from the present, and so were the positions of the poles). No traces of glaciations have been found during the Mesozoic age, however there is evidence of cold periods during the Cenozoic Era, 65 to 22 million years ago. The Antarctic ice-sheet started to form approximately 15 million years ago, reaching its maximum expansion, which was more extended than at present, 7 to 4.4 million years ago. The Arctic Ice Sheet instead, started forming only 2.6 million years ago, date of the start of the last "ice age", often called "Quaternary", but actually starting in the Pliocene period and continues during Quaternary (beginning 1.8 million years ago).

The Quaternary period

The Quaternary period is divided into two periods. Pleistocene, characterized by numerous glaciations, ended 10,000 years ago with the end of the last glaciation. Each glaciation is separated from the previous and subsequent ones by warm periods known as interglacial periods, with climates similar to the present-day climate, and even hotter. In the subsequent period, the Holocene, even though there was an alternation of warmer and colder periods, there were no real glaciations at a global scale but only small episodes of glacier advance and retreat in the higher latitudes and higher altitudes. In the past 4 Quaternary glaciations were classified and named: starting with the most ancient, these are named Gunz, Mindel, Riss and Würm from the names of the locations in which they were recognized and studied for the first time. However today we know that there were many more glacial episodes, with great differences in the number of stages and the surface area occupied in the different parts of the Earth. For example, in the Alps, in the Lake Como-Lake Maggiore amphitheatre, at least 13 advance and retreat episodes have been noted instead of the 4 traditional ones. The last glaciation began approximately 75,000 years ago after a long hot interglacial period, and reached its maximum expansion during the period 30,000 to 18,000 years ago, covering approximately 30% of the land above sea level. The Laurentian Ice Sheet covered most of North America and a vast ice-sheet also covered North Europe, while the Alpine glaciers moved Southward occupying part of the plain of the Po river. In the Alps, the retreat began 14,000-15,000 years ago; a study of the moraine ridges enables the reconstruction of the stages of the retreat and shows that it was not a regular and progressive retreat, but there were many small advances and subsequent retreats, the so-called tardiglacial pulsations.

At the beginning of the Holocene there was a period of climatic oscillations that was followed, around 8,000 years ago, by a hot period called Climatic Optimum, with much smaller glaciers than the present ones. It was the period, for example, of the mummified Similaun man, evidence of the fact that in those times many mountain passes in the Alps could be crossed and were used. Various studies enabled the reconstruction, for the Italian Alps, of a series of events, with local advances between 1300 and 1400 B.C and 900-300 B.C., followed by a warm period between 400 and 750 A.D., that coincides with the expansion of the Roman Empire, which is then followed by a short medieval advance, between 1150 and 1350 A.D. and what is called the Little Ice Age between 1150 and 1860, the maximum ice advance after the end of the Pleistocene glaciations. Many of the large moraines that are visible near the glaciers today date back to the Little Ice Age (as for example the Engadine Morteratsch Glacier in Switzerland, over 40 m high).

Evidence of the expansion of the Little Ice Age is also to be found in many reproductions, paintings and, more recently, photographs of great historical value. Evidence of the great retreat at the end of the LIA can be seen in numerous man-made structures, initially these were built near the fronts and now are very far from them, such as the Albergo dei Forni hotel, that is now over 2 km from the front near to which it was built. The retreat was also accompanied by a great decrease in the ice thickness, as the trenches of World War I and the Alpine shelters testify, at times these now can be seen hanging various dozens of metres above the surface of the glaciers, as for example the Konkordia Hostel on the Aletsch glacier, in the Jungfrau Group of mountains, that can now be reached climbing 100 m up a rocky cliff. Also the Aletsch Glacier retreated approximately 3 km since 1860, the year in which the LIA ended. Small pulsations were recorded in the subsequent years, between 1880 and 1890, in 1920 and more recently, between 1960 and 1980, following a period of lower temperatures, in the Fifties and Seventies. Presently all the Alpine glaciers show a retreat and a negative mass balance. In the past years, the only year with a positive balance was 2000-2001, with plentiful snowfall in winter and spring, but this has not led, at present, to any positive oscillation. The study of the climatic oscillations and the advance and retreat of the glaciers of the past enables us to better understand the mechanisms regulating the existence and “state of health” of the present glaciers, and we realize that glaciers are sensitive indicators of variations in the climate, and in particular of the temperature and precipitation.

Oceans of ice

When, during the course of a glaciation, large quantities of ice are trapped in the ice-sheets and in the continental ice, the oceans and seas are depleted of large quantities of water. During the course of the glaciations this provoked a general drop in the sea level in the entire planet. During the last glaciation, for example, the sea level dropped approximately 100 m below the present level. Therefore much land that is now submerged, was above sea level. For example, a bridge of land united Alaska and Siberia, and what is the port of New York today was 160 km from the coast. Also the coasts in Italy must have been very different in appearance, specially the Adriatic coasts, where the shallow sea-bottom increased the extension of the land above sea level. As the continental ice melted, at the end of the last glaciation, the level of the oceans and seas once again rose to the levels it reached before the glacier expanded.
These oscillations in the coast lines and in the sea levels have been reconstructed studying the morphology of the coasts: for example, ancient beaches above the present sea level are a proof of levels higher than the today sea level. Very precious information may be obtained studying sea caves, which can be found in large numbers in the Mediterranean Sea; in these caves, at depths of even 100 m, forms that are typical “landmarks” such as concretions and speleothemes, can be found, and their isotopic analysis and dating enables the reconstruction of the temperature variations in the past, variations that show a surprising coincidence with the reconstructions obtained from studies of ice cores.

Why glaciation?

The debate is still open with regard to the cause of the glaciations. There are many factors and processes that determine them, none of which probably acts alone, but the most important glaciation episodes are surely the result of the sum of different causes. Among the various elements that are “imputed”, a classification can be made of terrestrial factors and astronomical factors that are external to the planet. Among the latter, an important role is played by the variations in the Earth’s orbit around the Sun according to the well-known theory of Milankovic. Among the terrestrial factors, surely the distribution of the land above sea level is the most important factor, the shape and position of the continents in fact influence the sea currents and the circulation of masses of air which in their turn are responsible for heat exchange in the entire planet. Plate tectonics therefore have a very important role in triggering climatic modifications. The Quaternary glaciations, in particular, according to the more recent theories, were apparently triggered by the separation of the continents, in particular by the detachment of Antarctica, and the consequent stabilization of the Circumantarctic Current, that prevents heat exchange with the warmer equatorial and tropical areas.

Glaciers, a resource

A water resource

Glaciers in dry temperate regions supply a source of water which is very important for the economy of local rural communities. The most systematic use of glacier water is to irrigate fields while the use for drinking purposes is often limited by the great amount of solid particles carried by water as these often have a greyish colour and a milky look. In the high Karakorum valleys, which are real high-altitude deserts, where rainfall varies from 200 to 80 nm per year, agriculture depends exclusively from melting of glacier water. To use this water are built canal systems that can be even several kilometres long: often the canals are built on unstable glacial deposits that need constant maintenance and continuous fixing to adapt them to glacier front variations. Also in the Alps, in Val d’Aosta or in the Rhone Valley, in the past existed a network of irrigation canals, called “bisse” or “ru”, that employed glacier melting water. In Polar regions, instead, populations in the far North, such as Inuits, for a long time have used icebergs as a drinking water source. As these are constituted by ice from glaciers, coming hence from the transformation of snow, icebergs are made mostly of fresh water. Even in these days are periodically presented projects to exploit these precious resources, for example towing icebergs close to the coasts of countries characterised by drinking water shortages, although the costs of these operations for the time being are still higher than the benefits.

An energy source

Hydroelectric energy production represents an important revenue for mountainous regions in many countries, including Italy. Melting glacier water guarantees a supply of great amounts of water even during summer and a great number of tanks and hydroelectric plants are supplied directly from glacier streams. Many examples can be on the Italian Alps, in northern mountainous regions such as Piedmont, Valle d’Aosta, Trentino-Alto Adige and Lombardy. On some glaciers, water is collected directly from inside the glaciers. Among the most famous, we can mention the Engabreen, in Norway, where in the water collection tunnels is installed an important glacial laboratory that allows to make observations on the inside of the glacier. Even on the Argentière Glacier, which descends on the French side of the Mount Blanc, in the Sixties were dug tunnels in the ice to harness melting glacier water but due to unforeseen variations in the direction of subglacial streams, the project didn’t have the expected success and the galleries have now been closed and converted into an underground laboratory for the study of basal erosion.

Water within the glacier

The study of glacial cave systems is very important even from a hydro-geological point of view, because it allows us to understand how the water contained in a glacier works and behaves when it is part of a glacial aquifer. The behaviour of glacial aquifers is very similar to that of karstic aquifers and are therefore studied with the same methods. First and foremost, it is necessary to cover the greatest number of accessible caves, plotting a topographical survey, so as to understand how the network of galleries stretches and in which direction waters flow. For those areas that cannot be explored by man (because they are flooded or too narrow for a human to enter inside) detailed studies are carried out on the flow of the glacier recharge system, which is the source of the glacial cave systems. In particular, it is important to observe the balance between output and input flow (in this case melt water or rainfall) and how the "springs" respond to external supply. To help out in this kind of a survey, water-tracing techniques are used. A given quantity of tracing substances (generally fluorescent dyes) is introduced into the caves through their sinkholes, and how these are returned at the springs is observed. By analyzing the time taken by the tracer to flow out and the dilution it has undergone, it is possible to understand the stretching and diameter of glacial galleries, to establish if water runs along narrow joints or large galleries, to estimate the volume of water stored within the glacier and to establish for how long waters remain within the glacier. In other words, it is possible to estimate the behaviour of the aquifer and the volume of its water reservoirs. This is very important, because in many parts of the world glaciers supply an abundant source of water, for both agricultural, as in many arid regions (e.g. the Karakorum) and hydroelectric uses, as in a great number of Alpine glaciers. To be able to understand how much water is stored and in what way it flows out of the glacier is of fundamental importance to be able to design water-tapping systems and to prevent possible risks. The presence of great quantities of water stored in a medium that moves and gets deformed continually, in fact, can be a great danger: the collapsing of the walls supporting these lakes within the glaciers can lead to sudden outburst of great quantities of water, provoking the so-called glacial outbursts, one of the most destructive and impressive phenomena that glaciers can be subjected to.

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