# Ice and Climate

**About 80% of all the fresh water in the world is trapped as ice in the two polar regions. This ice is an exceptionally good environmental archive, containing invaluable clues to hundreds of thousands of years of climate history. Information on past climate can also be obtained from analyses of historical records of lake ice cover, such as those from the Lej da San Murezzan (the Lake of St. Moritz) in Switzerland and Lake Baikal in Siberia. A somewhat puzzling substance, which looks like ice, is methane hydrate. It normally lies buried in the deep-sea sediment, but slight changes in environmental conditions could cause it to rise to the sea surface, in which case it would be possible for large amounts of the greenhouse gas methane to enter the atmosphere, resulting in a serious acceleration of climate warming.**

Water conjures up images of babbling brooks and deep blue lakes reflecting snow-capped peaks. But water comes in other states, for example as a gas, when it is evaporated and transported from the sea onto the land, or as a solid, as snow and ice, when the temperature falls below zero. Considering all three states, most of us would be surprised to hear that most of the fresh water on the earth today is not found in rivers and lakes, but as ice (Fig. 1).

Almost all of this frozen water – 99.4% – is located in the polar regions; i.e., in Antarctica and Greenland. The Antarctic ice mass is in parts 5 km thick, while in Greenland the ice depth can reach 3 km. The amount of ice in glaciers at lower latitudes accounts for only 0.6% of the total, and this proportion is unfortunately continually decreasing.

Ice is, however, more than just frozen water. It provides us with a lot of invaluable information about current and past changes in the environment. Much of what was once trapped under the ice is just waiting to be brought out and investigated [1].

## Ice as an Archive

There is practically nothing that does not leave a long-term record in the ice. But how does ice become such an archive? Land ice derives from snow. Freshly fallen snow is quite soft and light and contains about 90% air (Fig. 2). Within just a few days the ice crystals condense to firn, which, under the pressure of new snow layers, becomes harder and denser, until at a certain depth the firn crystals fuse to form ice (Fig. 3).

Snow and ice, though, consist not just of water. As clouds form, atmospheric water vapor condenses most readily around aerosol particles, which can contain a wide variety of chemical substances. In addition, as a snow flake wafts down to earth, it can pick up a number of substances from the air. And finally, all sorts of things settle on freshly fallen snow: pollen and fine dust from volcanoes or deserts, for instance, as well as larger, more spectacular finds such as the stone-age man Ötzi or ice-age mammoths. The fact that all these environmental samples have been stored at very low temperatures is one of the main reasons that makes ice such an exceptional environmental archive [2].

## The GRIP Ice Core

Drilling in the polar ice sheet places high demands on both drilling techniques and logistics. Setting up a drill camp and conducting a drilling operation at 3000–4000 m above sea level more than a thousand kilometers from the nearest town during several summers is really only possible within the framework of an international operation. The first deep-drilling operations to reach the

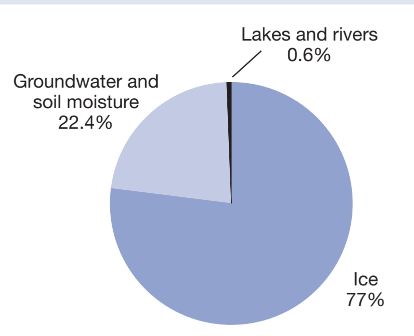


**Fig. 1: Distribution of global fresh water. Water vapor in the atmosphere, which accounts for only 0.04% of the total, is not included.**

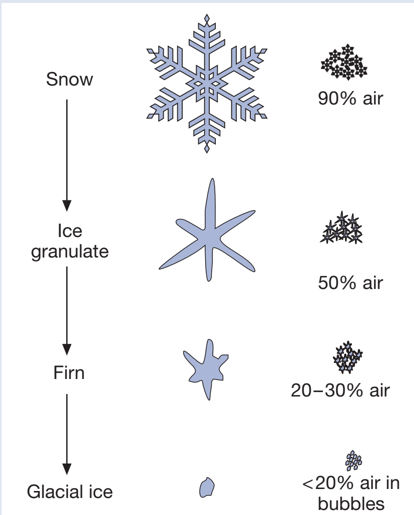


**Fig. 2: Stages in the transformation of snow to glacial ice.**

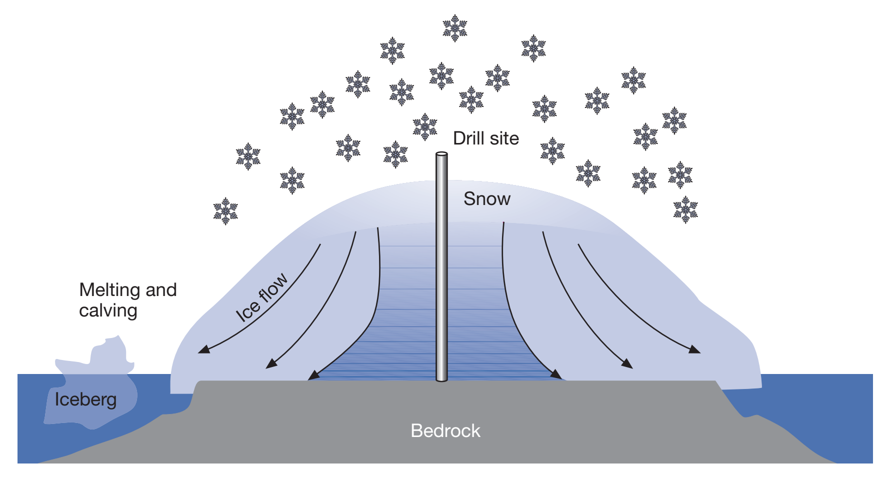


**Fig. 3: Cross-section of the polar ice sheet. In the higher parts of the ice sheet, ice is being continually formed from snow. This ice flows slowly towards the coast, where it melts or floats off into the sea as icebergs (a process known as "calving"). This flow of ice means that the annual ice layers become thinner with increasing depth.**

bedrock under the ice sheet were carried out as long as 40 years ago. Since then there have been about a dozen similar projects. One of the latest large drilling campaigns was the **Gr**eenland **I**ce Core **P**roject (GRIP) in central Greenland. From 1990 to 1992, scientists from Belgium, Denmark, Germany, the UK, France, Iceland, Italy and Switzerland drilled an ice core 3029 m long and 10 cm in diameter which contains precipitation from the last 100,000 years.

Lengthy discussions ensued to determine the best possible way of dividing up the ice between the various research groups in order to cover the up to 50 different parameters to be investigated, ranging from ice structures, isotopes, and various chemical substances, to dust and volcanic ash. This "squaring of the circle" was made all the harder since a certain part of the core had to be reserved for possible later verifications and additional parameters.

For the drilling operation, a custom-made electrically driven mechanical drill bit was used. Using a steel cable, this was lowered into the borehole, where it could drill a core section up to 2.5 m long. To prevent the borehole from slowly closing under the enormous pressure of the ice, it was filled with a liquid which does not freeze even at –30 °C (the annual mean temperature at the drill site), and has the same density as ice. The drill bit was then brought back to the surface and the core removed. After being measured and numbered, each piece was given a preliminary examination and the first samples were removed. Finally, the cores were cut with a bandsaw into sections 55 cm in length, packed into plastic bags in well-insulated styrofoam boxes, and prepared for the flight to Copenhagen. There they were cut up according to the distribution plan and forwarded to the respective research groups for analysis.

## Cosmogenic Radionuclides in Ice

Amongst other things, EAWAG is interested in the radionuclide beryllium-10 ($^{10}$Be) contained in the GRIP ice cores. This radioactive isotope of the element beryllium is formed continually in the atmosphere, and falls to the ground in precipitation (see box). Nonetheless, the rate of production of these cosmogenic radionuclides in the atmosphere is relatively low: on average, only around 1 million $^{10}$Be atoms per year fall on each cm$^2$ of the earth's surface. It is therefore not surprising that extremely sensitive instruments, called accelerator mass spectrometers, are required for their detection. This instrument is capable of detecting and counting individual atoms (see article by S. Bollhalder and I. Brunner on p. 6).

## Reconstruction of the Past Climate

Why go to such expense just to count a few $^{10}$Be atoms? The main reason is that by doing this we can learn something about past variations in solar activity and in the strength of the earth's magnetic field. The rate of production of $^{10}$Be atoms in the atmosphere is not constant and depends, for instance, on the solar activity [3]. The cosmic radiation that is responsible for the production of $^{10}$Be in the atmosphere originates from our galaxy, which consists of around 100 billion stars similar to our sun. When the cosmic radiation approaches our solar system, it first encounters the heliosphere, a spherically shaped region around the sun with a radius of about 15 billion kilometers. The heliosphere consists of ionized gas, known as the solar wind, which streams away from the sun at high speed. The solar wind carries with it the sun's magnetic field, and because of this it shields the earth's atmosphere to a certain extent from the cosmic radiation (Fig. 4), thus reducing the production rate of $^{10}$Be. In other words, the more active the sun is, the lower the $^{10}$Be count. This provides us with a complicated but unique method of learning about the history of the sun and its variability (see articles by M. Vonmoos on p. 8 and R. Muscheler on p. 11). The $^{10}$Be data also allowed us to test a hypothesis proposed by Danish scientists at the end of the 1990s which asserts that the cosmic radiation influences the climate (see article by J. Beer on p. 16).

In addition, the rate of production of $^{10}$Be is influenced by the earth's magnetic field. The

## Origin of Cosmogenic Radionuclides

**Cosmogenic radionuclides originate through processes which the alchemists in the Middle Ages tried in vain to imitate: namely through the transmutation of elements; e.g., from nitrogen to beryllium or from argon to chlorine. What the alchemists did not manage to do, nature does at will. Cosmic radiation, consisting of high-energy particles (protons and helium nuclei), penetrate the earth's atmosphere, colliding there with the oxygen, nitrogen and argon atoms of the air. This results in whole cascades of new particles, including neutrons, which likewise collide with other atoms, breaking them in turn into smaller particles. Most of the collision products are unstable and are immediately transformed into stable isotopes which can no longer be distinguished from those present beforehand. However, $^{10}$Be and $^{36}$Cl remain unchanged for long periods, due to their long half-lives of 1.5 million and 301,000 years, respectively. After an average residence time in the atmosphere of about 1 year, most of these isotopes are transported to earth in the precipitation. If a $^{10}$Be atom found a snowflake for this journey, it is possible that it could end up in a glacier or in a polar ice sheet.**

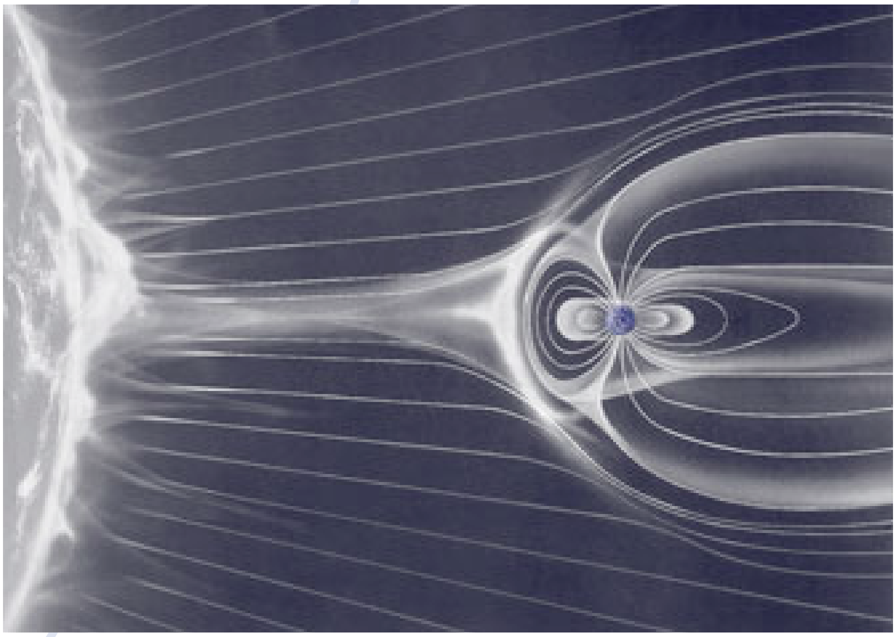

**Fig. 4: The magnetic field of the solar wind interacts with the magnetic field of the earth. Together they form a natural protective shield which lowers the amount of cosmic radiation from outer space reaching the earth's atmosphere.**

magnetic field lines, which span the earth from pole to pole, only permit the charged particles of the cosmic radiation to enter the earth's atmosphere when these have sufficient energy (more precisely, momentum per unit charge). The stronger the magnetic field, the more effectively it shields the earth from cosmic radiation, resulting in lower rates of production of $^{10}Be$. Analyses of volcanic rock and sediments show that the earth's magnetic field has clearly varied over the past millennia. As expected, these fluctuations were recorded in the ice and can be reconstructed (see article by J. Beer on p. 14).

## Ice Cover as a Climate Parameter

Ice provides not only a valuable record of solar activity and the magnetic field. Further information about the climate can be gleaned from historical records of lake ice cover (see article by D. Livingstone on p. 19). For example, the calendar date of freeze-up of Lake Suwa in Japan has been documented almost continuously since 1443. This unique data set has been used in many historical climatological studies of the North Pacific region. The longest data set from a Swiss lake is that of the calendar date of ice break-up on Lej da San Murezzan, which dates back to 1832. A further investigation pursued the question of whether there is a connection between the ice cover of lakes and the North Atlantic Oscillation (see article by D. Livingstone on p. 23). The North Atlantic Oscillation is a "see-saw" in surface atmospheric pressure between the Azores High and the Iceland Low. In winter, it results in variations in the strength of the westerly winds that transport relatively warm, moist, maritime air eastwards over Europe. These variations result in corresponding variations in the severity of winter in Europe and much of central Asia, which are reflected in the timing of thawing of ice on lakes in these regions [4].

## Ice from Methane Hydrate

And lastly, we leave ice as a tracer of past climate and turn to methane hydrate. This is a compound of ice (i.e., water) and methane. It is formed at low temperatures and high pressure – e.g., in deep sea sediments – and is stable only under such conditions. The joint project CRIMEA involves an international group of scientists, including scientists from EAWAG, who are attempting to answer the question of whether this methane hydrate represents a danger to our environment (see article by C. Schubert on p. 26). Even a minor change in environmental conditions – such as a slight increase in the temperature of the deep-sea water or a shift in pressure due to sea level variations – could lead to methane hydrate being released and decomposing. This could result in large quantities of methane reaching the atmosphere. Since methane is one of the most important greenhouse gases after carbon dioxide, the consequences for the climate could be severe [5].

## Looking Back to the Future

To predict the future has always been a dream of mankind. While earlier prophets were not particularly successful with reading cards and tea leaves, scientists today attempt to divine the future climate using sophisticated computer models. Such computer models only provide reliable results if all of the significant processes and their interactions are correctly parameterized. In addition, they have to be studied on a sufficiently long timescale. We can only hope to foresee future climate change if we are able to understand past climate changes. A good prophet therefore takes a long hard look at the past.

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