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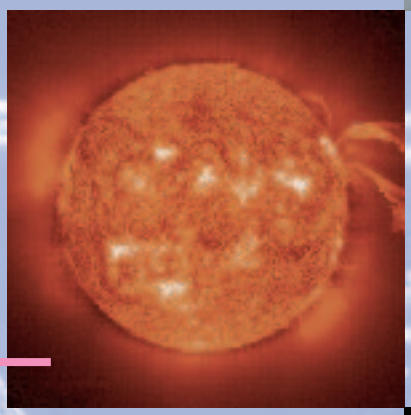
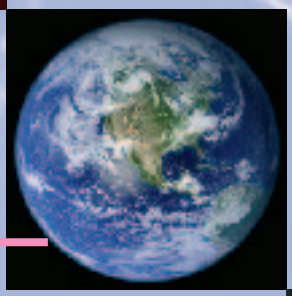
EAWAG news

58e July 2005
Swiss Federal Institute for Environmental Science and Technology (EAWAG),
A Research Institute of the ETH-Domain • CH-8600 Dübendorf

Icy Discoveries





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EAWAG news 58e • July 2005
Information Bulletin of the EAWAG

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Publisher Distribution and © by:
EAWAG, P.O. Box 611, CH-8600 Dübendorf
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http://www.eawag.ch

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Publication 2–3 times per year in English, German and French. Chinese edition in cooperation with INFOTERRA China National Focal Point.

Cover Photos M. Märki and J. Beer, EAWAG; NASA; Research Center Ocean Margins, Bremen

Design inform, 8005 Zurich

Layout Peter Nadler, 8700 Küsnacht

Printed on original recycled paper

Subscriptions and changes of address
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ISSN 1440-5289

An Icy Look Back to the Future

Martina Bauchrowitz, Editor

Imagine you have arranged to meet some friends at a cinema. You are delayed unexpectedly and don't arrive till an hour after the film has started. Just as you are getting comfortable in your seat and getting into the story, the film tears, and the screening has to be cancelled. You are very disappointed, since you would love to know how the film turns out. What can you do? You could perhaps try to guess how the story continues on the basis of the short snippet you have seen yourself, extended by what your friends can remember. Of course, the descriptions of your friends are nowhere near as detailed as your own experience, but have the advantage that they cover a far longer part of the film. In any case, your prediction of how the film continues is just a guess.

This is how it is for scientists when they attempt to piece together via computer models a picture of how the earth's climate might develop in the future. The more information that is available to put into the model, the more reliable the predictions will be. Climate researchers can fall back on databases of climate-relevant factors accumulated from a broad range of precise recent observations and instrumental measurements. These include air temperatures, the exact timing of the break-up of lake ice in spring, solar activity, and the degree of glaciation of the earth. Two articles in this edition of EAWAG news analyze historical records of lake ice cover, such as those that have been kept for the Lej da San Murezzan (the Lake of St. Moritz) since 1832. In terms of our film, these recent climate markers correspond to the part of the film you saw in person.

In addition, climate researchers also examine the various natural archives that have been left behind as silent witnesses to the beginnings of the history of our climate. In particular, the polar ice caps contain valuable information on thousands of years of past climate conditions. In the international "Greenland Ice Core Project", in which EAWAG participated, a 3-km-long ice core, 10 cm in diameter, was drilled out of the Arctic ice shield between 1990 and 1992. It contains precipitation from the last 100 000 years. Meter for meter and ice layer for ice layer, these ice cores have been carefully examined over the past 12 years. EAWAG alone has worked on thousands of ice core samples. Some of the results you will find in this current issue of EAWAG news.

A further factor which climate researchers might find relevant is the behavior of methane hydrate. This ice-like compound, which is found, for instance, in deep sea sediments, is composed of water and methane and is formed at low temperatures and high pressure. It is estimated that around 10 000 billion tonnes of methane in the form of this gas hydrate are sitting on the beds of the world's oceans. Given this enormous quantity, concern is growing that "frozen" methane will escape, enter the atmosphere, add to the greenhouse effect, and thereby accelerate climate change. An EAWAG research group is therefore also involved in investigating the behavior of methane hydrate on the seabed.

Ice in various forms therefore supplies much valuable information about present and past environmental conditions. Our only chance of obtaining reasonably reliable predictions of the climate of the future depends on our success in using this information to reconstruct the beginning of the climate film.

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

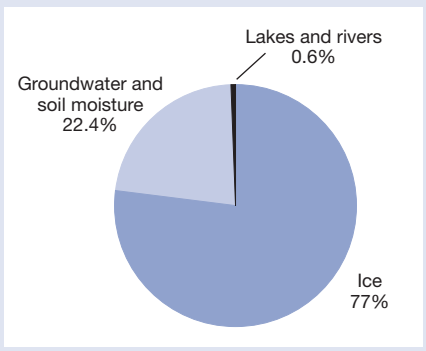

Fig. 1: Distribution of global fresh water. Water vapor in the atmosphere, which accounts for only 0.04% of the total, is not included.

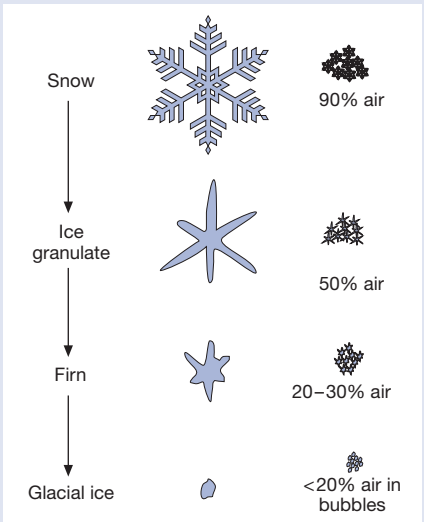

Fig. 2: Stages in the transformation of snow to glacial ice.

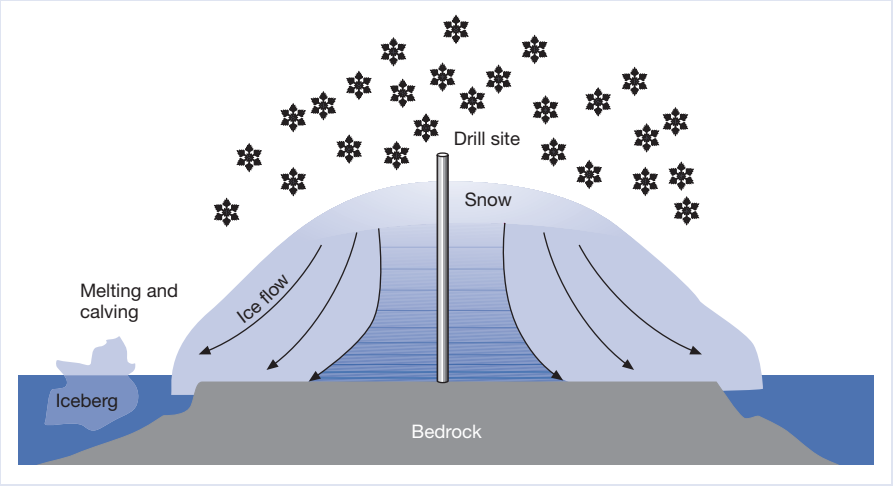

Fig. 3: Cross-section of the polar ice sheet. In the higher parts of the ice sheet, ice is being continually formed from snow. This ice flows slowly towards the coast, where it melts or floats off into the sea as icebergs (a process known as "calving"). This flow of ice means that the annual ice layers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

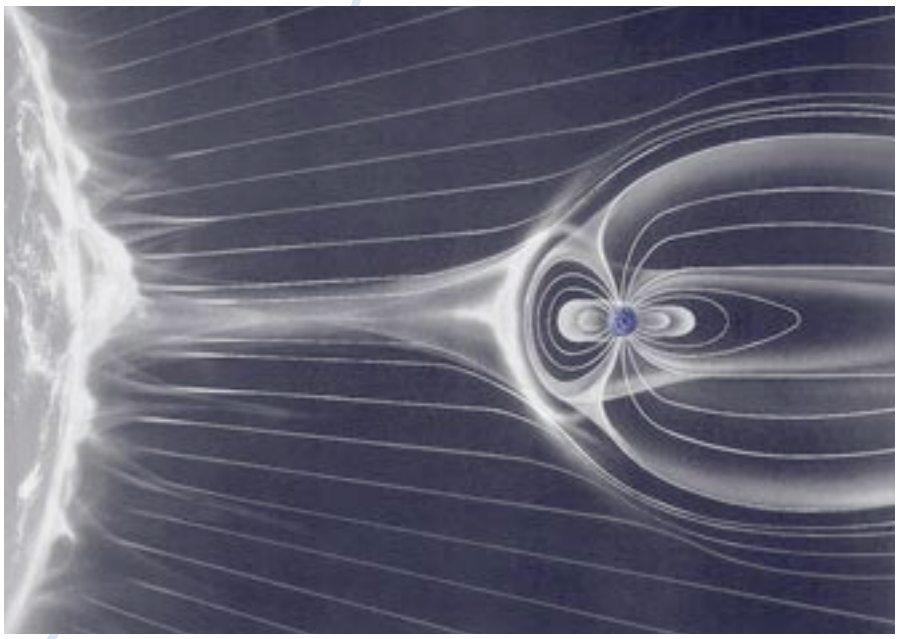

Fig. 4: The magnetic field of the solar wind interacts with the magnetic field of the earth. Together they form a natural protective shield which lowers the amount of cosmic radiation from outer space reaching the earth's atmosphere.

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.

Jürg Beer, physicist and leader of the Radioactive Tracers group in the Department of Surface Waters, is a titular professor at ETH Zurich. Research area: cosmogenic radionuclides; effect of solar activity on the climate.

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A Long Road: from Greenland to the Lab in Zurich

Conclusions can be drawn about past environmental changes from telltale footprints left in environmental records. We are following one such hot lead in our investigations of the 3-km-long Greenland ice core. Layer for layer, the ice is examined to determine the concentrations of the radionuclide beryllium-10 (^{10}Be). From such data it is possible to obtain information about past climate changes. About 10,000 ice samples have been prepared by the EAWAG laboratory in recent years for measurement in the ETHZ/PSI accelerator mass spectrometer.

Each year, rain and snow transport around 1 million atoms of the radionuclide beryllium-10 (^{10}Be) from the atmosphere on to each square cm of the earth's surface. Some of these ^{10}Be atoms are frozen, layer by layer, into the polar ice. Taking the global annual mean precipitation to be 1 m, this means that 1 kg of ice contains approximately 10 million ^{10}Be atoms. At first glance this would appear to be many. 10 million ^{10}Be atoms, though, weigh just 10^{-15} g, the equivalent of a single raindrop in Lake Constance. To detect such a low concentration is a challenge to analytical science. To keep pace with the development of the accelerator mass spectrometer, over the last 15 years EAWAG has developed an elegant sample preparation method (see box). This article provides an insight into the routine work carried out in our laboratory and describes how ^{10}Be atoms are extracted from the ice core and prepared for measurement in the ETHZ/PSI accelerator mass spectrometer at Hönggerberg, Zurich.

From the Arctic to the EAWAG Laboratory

The ice cores from Greenland (55-cm-long sections, maximum a quarter of the total cross section) are sealed in plastic bags and packed in styrofoam boxes before being sent to Dübendorf, where they are stored in a refrigerated room at –20 °C until required for preparation (Photo 1). Some of the ice samples are cut to smaller size with a bandsaw (Photo 2) to obtain a higher temporal resolution. Prior to the actual preparation procedure, each sample is washed with high purity water to remove any residual bore fluid and other external contaminants. Finally, the ice samples are placed in melting trays, weighed, and an exactly known amount of ^{9}Be carrier added (Photo 3). The ice is then melted in a conventional microwave oven (Photo 4) and afterwards passed drop by drop through a cation exchange column (Photo 5), which retains the beryllium ions. The cation resin with the beryllium ions can be easily stored for months till the next preparation stage.

In the next step, the beryllium ions are eluted out of the cation resin with acid, precipitated out with ammonia as beryllium hydroxide [$Be(OH)_2$], separated from the solution, and redissolved in acid. For Be to deliver negative ions to the ion source of the accelerator mass spectrometer, it needs to be laced with a conducting metal. We use silver, added as silver nitrate solution. Silver and beryllium now precipitate out together in hydroxide form. For the spectrometric measurement, the $Be(OH)_2$ must now be oxidized. For this, the samples are dried briefly under a UV lamp and put into a muffle kiln (Photo 6), where, at 850 °C, $Be(OH)_2$ oxidizes to BeO within 2 hours. Finally, the samples are pressed into a small hole of 1 mm diameter in the copper target (Photo 7). After about 24 hours, the beryllium samples are ready at last (Photo 8) for measurement in the accelerator mass spectrometer (Photos 9 and 10).

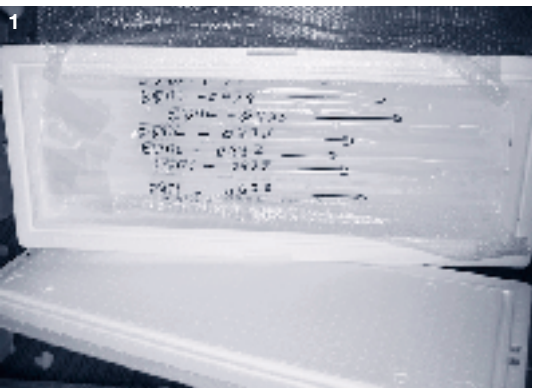
From EAWAG to the Lab at Hönggerberg

The isotope ratio in our samples is extremely low – on the order of 10^{-13}. This is outside the range of detection of a conventional

Extraction and Detection of ^{10}Be

Traditionally, radionuclides are detected by means of their radioactive decay. However, this method is only of use if the radionuclide being investigated has a sufficiently short half-life. Within a reasonable measuring period – several days to several weeks at most – enough atoms have to decay so that they can be detected without excessive measuring error. It is precisely here that the difficulty lies with ^{10}Be. Its half-life of 1.5 million years is far too long. Per year, only about 5 ^{10}Be atoms of the approximately 10 million atoms of ^{10}Be present in a kilogram of ice undergo radioactive decay. The detection of ^{10}Be by means of its radioactive decay is therefore not a viable technique.

The mass spectrometer offers an alternative method. This instrument exploits the fact that most elements are found in a range of isotopes of different masses. Beryllium is no exception. Along with the radioactive isotope ^{10}Be, with an atomic mass of 10, there is also the lighter, non-radioactive isotope ^{9}Be, with an atomic mass of 9. Mass spectrometry can determine the ratio of two isotopes – in our case ^{10}Be/^{9}Be – so that the number of ^{10}Be atoms can be calculated. Since the ice samples contain only tiny trace amounts of the ^{9}Be isotope, a known quantity of this isotope (typically 0.2 mg) must be added for the measurement. The added ^{9}Be acts as a so-called carrier and ensures that during the chemical extraction, the few ^{10}Be atoms present in the ice are also extracted.

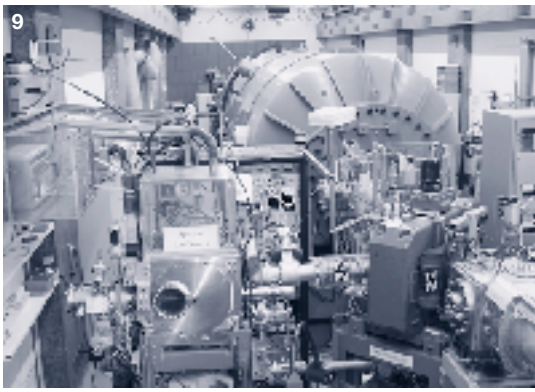


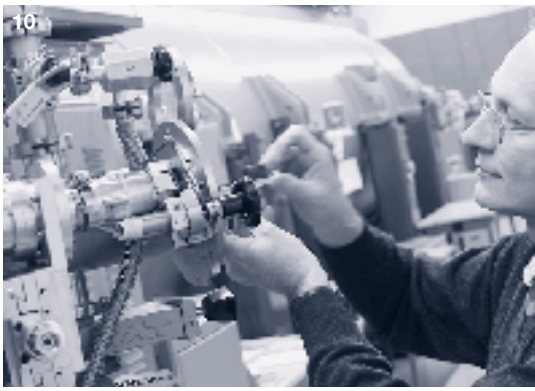
mass spectrometer, lying within the background noise level. Only by raising the acceleration voltage to several million volts instead of just the thousands of volts normally used in conventional mass spectrometers is it possible for the detector not only to count every individual atom, but also to identify it by its unique mass and charge. Only thus can the rare ^{10}Be atoms be distinguished from the more common atoms. The actual measurement lasts only about 15 minutes. Such high-energy mass spectrometers require an accelerator as their central unit, hence the name accelerator mass spectrometer. One of the world's first is in ETH Zurich at Hönggerberg, and is operated by ETH Zurich in conjunction with the Paul Scherrer Institute. The core piece, the tandem accelerator, which accelerates particles by up to 6 million volts, was built in the 1960s, and has served for all these years as a reliable fundamental research tool in nuclear and atomic physics.

Over the past 15 years, EAWAG has prepared around 10,000 samples and measured them with the accelerator mass spectrometer. Around 5 km of ice cores have been analyzed, and the ^{10}Be concentrations over approximately the past 100,000 years have been determined. Based on these raw ^{10}Be data, the following four articles (pp. 8–18) describe how changes in climate have occurred through time.

Silvia Bollhalder (left) and Irene Brunner (right) are technicians in the Radioactive Tracers group in the Department of Surface Waters. Part of their duties is the routine preparation of ice samples.

Co-authors: Maura Vonmoos and Jürg Beer





Sun and Climate: Hot History from Cool Ice

Paleoclimatic research has revealed that, far from being stable as previously assumed, the earth's climate underwent large fluctuations. Over the past 10,000 years, it has been influenced primarily by the sun, volcanic activity and internal system fluctuations. Only since the Industrial Revolution has humankind joined in efficiently – in the last 20 years actually becoming the greatest contributor to the phenomenon of rising global temperatures. In order to understand the complexity of the climate system better, and to get a clearer picture of the human influence on the climate, it is necessary to examine the individual natural climate factors more closely. EAWAG is therefore undertaking a study of how greatly solar activity has varied in the past.

The sun is by far the largest source of energy for the earth, and therefore the powerhouse of our climate system. It drives atmospheric circulation directly through its incident radiation, and indirectly through its effect on the composition of the atmosphere (e.g. ozone, water vapor).

The energy input from the sun has long been considered invariable, and consequently dubbed the "solar constant" by climatologists. Its value is about 1366 W/m^2. It refers to the intensity of the sun's radiation (= irradiance) at the outer limit of the atmosphere, at a distance from the sun of 1 astronomical unit (the average distance of the earth from the sun). Direct measurements of the irradiance via satellite have been possible only since 1978. Since then, it has become evident that the solar constant is far from being a constant. In actual fact, it exhibits cyclical fluctuations with an average period of 11 years (Fig. 1A) and an average amplitude of 0.1% [1]. This is a clear indication that the engine of our climate system is not constant in its energy output. These changes in the irradiance are connected with variations in solar activity. So what was the situation like prior to 1978, before direct measurements were possible? EAWAG has joined a number of international research groups in an attempt to answer the riddle of the history of solar activity, as far back in time as possible [2, 3].

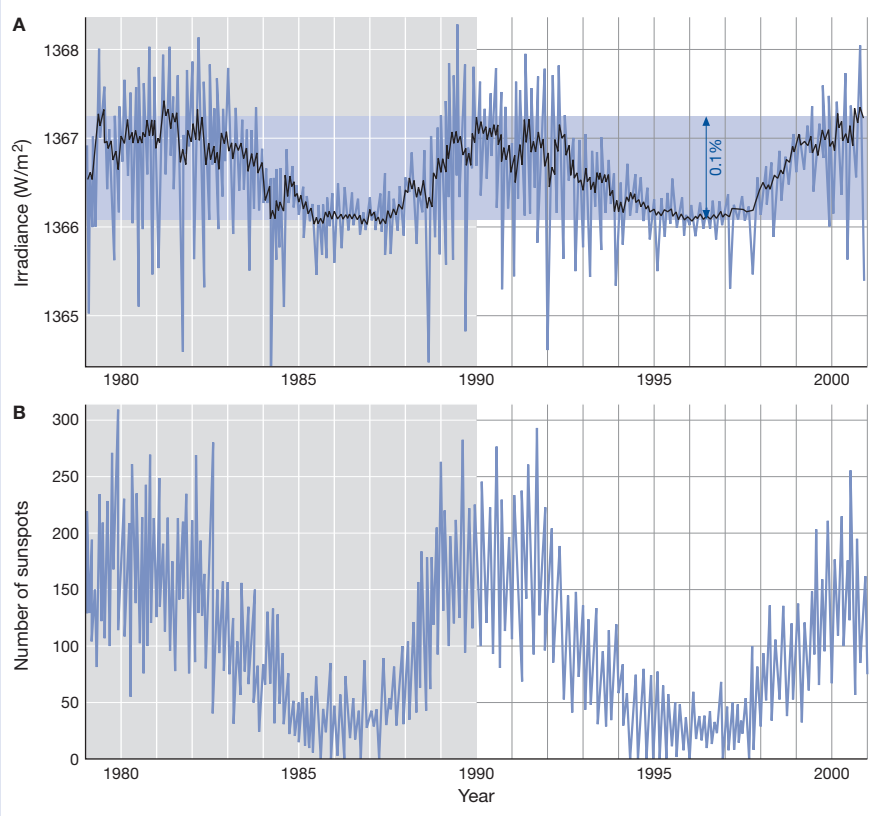


Fig. 1: Irradiance measured by satellites since 1978 (A) [1] compared to sunspot counts (B) in the same period [4].

Sunspots as an Indicator of Solar Activity

Astronomers first collected evidence of variations in solar activity as much as 400 years ago. Since the invention of the telescope, people have observed changes on the sun's surface and recorded them by the only means available – in handmade drawings [4]. It was soon realized that the number of dark sunspots varied between 0 and approximately 300 spots. Just like irradiance, the number of sunspots fluctuates in a cycle with a period of around 11 years (Fig. 1B + 2). The sunspots are an expression of magnetic processes and therefore a direct measure of solar activity. The more active the sun is, the more sunspots there are on the sun's surface. They appear dark since they have a relatively cool surface temperature of circa 4000 Kelvin (about 3700 °C), and, as a result, emit less energy locally than the normal surface areas at circa 5800 Kelvin (about 5500 °C). However, since the regions immediately surrounding the spots are hotter than the average, the

emission of radiation from a sun with many sunspots is on the whole greater.

This strict correlation between sunspot prevalence and irradiance measured by satellite can be seen clearly in Figure 1A + B, in which the two curves run parallel to each other. This has allowed scientists to use the number of sunspots as the basis for determining the irradiance arriving at the top of the earth's atmosphere, and thereby map changes in climatic events over the past 400 years.

400 Years of Strongly Fluctuating Solar Activity

If we look at the four hundred year-long sunspot record [4], they show that solar activity has fluctuated significantly more strongly and more irregularly than satellites have so far measured (Fig. 2). Practically no sunspots were recorded during the Maunder Minimum of 1645–1715, and only a few during the Dalton Minimum of 1795–1830, suggesting that the sun was relatively inactive during both periods. Since then there has been a steady increase in the number of sunspots. Lean and fellow researchers wanted more detailed information, and attempted to quantify the intensity of past solar radiation from the number of sunspots, concluding that irradiance has increased by 0.24% since the Maunder Minimum [2] (Fig. 3). This change is significantly outside the range of fluctuations measured to date. From observations of other solar systems, we know that stellar radiation can vary greatly – by much as 1% for stars showing similar characteristics to our sun. In addition, various climatic traces on the earth indicate that such fluctuations in the irradiance are not unrealistic. For example, the occurence of the so-called Little Ice Age from about 1400 to 1850 coincident with a period of reduced solar activity. During this period, large-scale glaciers advances occured in the Alps that resulted in large moraine deposits. Furthermore, from historical sources it is known that the River Thames froze over in winter during the Little Ice Age. The ice was particularly thick in the winter of 1683/84, neatly in the middle of the Maunder Minimum! Since the winter of 1813/14, the Thames has stopped freezing over, and the glaciers have been under continuous retreat, while the number of sunspots has been increasing continuously.

11,500 Years of the Sun's Activity Recorded in the Polar Ice Cap

How can we extend the historical research beyond 400 years into the past? EAWAG is currently engaged in a project with the ambitious aim of reconstructing solar activity over the entire Holocene epoch, which corresponds to the recent warm period stretching back about 11,500 years. Once again, we are dependent on indirect clues. To measure past solar activity, we are investigating the quantity of the cosmogenic radionuclide beryllium-10 (^{10}Be) that was formed in the past by cosmic radiation, and which can now be found in frozen precipitation in the polar ice caps (see lead article p. 4). Thanks to this thick ice record we can go very far back in time through relatively short vertical drill-cores, since the single annual deposits have been compressed into thin layers by the pressure of the subsequent ice layers and by the ice flow. The GRIP ice core from Greenland examined by EAWAG is about 3 km long and represents several hundreds of thousands of years. In a Sisyphean undertaking, the ^{10}Be concentration is determined painstakingly layer by layer (see article from S. Bollhalder and I. Brunner, p. 6). The ^{10}Be concentration will enable us to determine the solar activity, provided two important points are taken into consideration:

- The ^{10}Be production does not depend on the solar activity alone, but also on fluctuations in the earth's magnetic field. To reconstruct the solar activity, the influence of the magnetic field must also be determined.
- The ^{10}Be concentration measurable in the ice is affected not only by the ^{10}Be produced in the atmosphere, but also by the amount of precipitation – the greater the precipitation, the more the ^{10}Be is diluted. The measure of solar activity is therefore not simply the ^{10}Be concentration, but rather the ^{10}Be flux, which gives us the number of ^{10}Be atoms deposited per square meter and second in the ice.

Our investigations show that the ^{10}Be flux, and consequently the solar activity, was very irregular over the entire Holocene epoch (Fig. 4, blue curve). A low ^{10}Be flux indicates an active sun and a high ^{10}Be flux

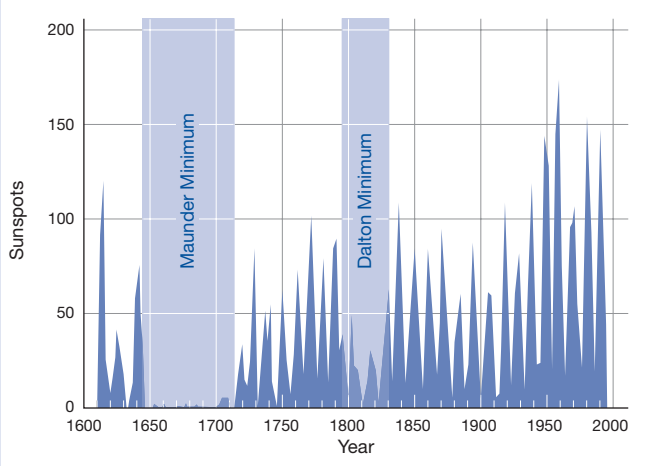


Fig. 2: The sunspot count since 1610 [4], given as an annual average. The more active the sun, the more sunspots appear on its surface. Along with the clear 11-year cycle an increasing activity since the beginning of the 18th century can be observed.

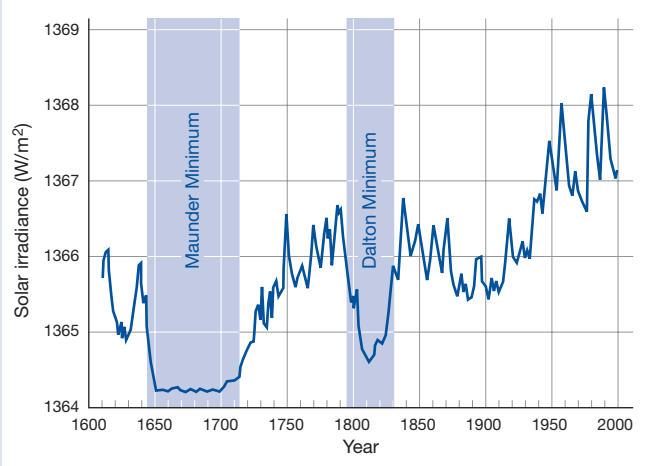


Fig. 3: Irradiance reconstructed back to 1610. The reconstruction is based on sunspot drawings and observations of stars similar to the sun. Accordingly, irradiance has increased by 0.24% since the Maunder Minimum. Adapted from [2].

a less active sun. We are currently working on expressing this relatively imprecise information on solar activity as irradiance values. In parallel to the reconstruction of the irradiance from the sunspots described previously, we are attempting to derive the irradiance from the ^{10}Be data.

Further Climate Clues from Drifting Icebergs

Further clues indicating the fluctuating influence of the sun during the Holocene come from other paleoclimate archives [3]. A number of sediment cores from deep-sea boreholes in the eastern North Atlantic, at about the latitude of Ireland, and in the western Atlantic, at about the latitude of Newfoundland, have revealed several pronounced deposits of coarse-grained material. Whereas normally only fine-grained clays and muds are deposited in deep-sea sediments so far from the coast, these deposits have grain sizes equivalent to, or even larger than, those of the sand fraction.

Where does this material come from? A very probable explanation is that they were transported there by icebergs. When an iceberg breaks away from a glacier into the water (calving), rock debris eroded by the glacier and frozen to its underside is carried to sea. When the iceberg melts, this debris sinks to the seabed. Based on its mode of transportation, this coarse particulate matter in the sediment is known as "ice-rafted debris" (= IRD).

Red Greenland Stone in Deep-Sea Sediment

Careful examination of the composition of IRD in the sediment cores reveals clues to the origin of the particles. Volcanic glass points to an origin in the volcanic island of Iceland. Other minerals acting as petrological tracers could only have originated in Greenland and Newfoundland. For example, a red coloring reveals the presence of a mineral from the "red beds", a typical rock formation of eastern Greenland.

The locations of these polar rock fragments reveal that icebergs have been able to travel far to the south during the Holocene. This was possible only when the melting of the icebergs was delayed by very low air and seawater temperatures. Therefore, such large-grain rock deposits are clear indicators for colder climatic periods. In an international joint research project, the proportion of the IRD in a number of sediment cores was determined (Fig. 4, white curve) [3] and the results were compared with the ^{10}Be data (Fig. 4, blue curve). Both curves show a quite closely matching pattern. A higher IRD fraction in the sediment indicates a cold period, in which icebergs could travel farther south. During warmer periods, the icebergs melted much further to the north, resulting in a lower proportion of IRD in the sediment samples investigated.

From our results we can derive the following two correlations:

- A "high proportion of IRD ≈ cold period" is associated with a "high ^{10}Be flux ≈ inactive sun".
- A "low proportion of IRD ≈ warm period" is associated with a "low ^{10}Be flux ≈ active sun".

This means that the drift behavior of the icebergs in the Holocene appears to have been controlled by the sun.

All these observations reveal the important role the sun plays in our climatic system. Many questions still remain unanswered: How does our climate system react to changes in the irradiance? What are the processes responsible? Do small changes in solar activity become amplified in the earth's internal climate system, e.g. in the atmosphere? Current research is attempting to answer these questions, and the search is on for further clues.

Maura Vonmoos, earth scientist, reconstructed Holocene solar activity as part of her doctorate in the department "Surface Water".

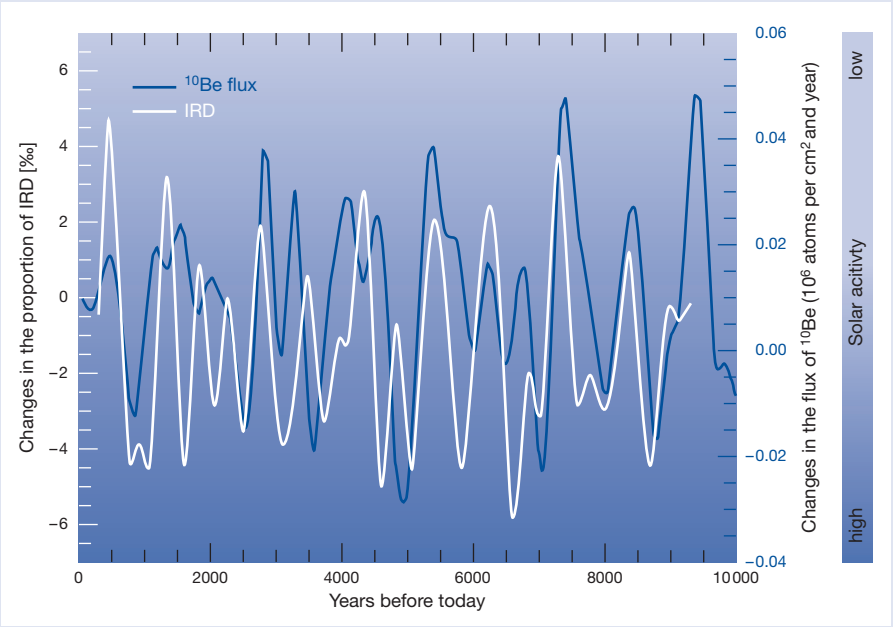


Fig. 4: Changes in the ^{10}Be flux in the GRIP ice core (blue curve) and changes in the IRD proportion in the sediment (white curve). Simplified from [3].

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Why Did a Cold Period Follow on the Heels of the Last Ice Age?

Large-scale climate changes in the northern Atlantic region were often associated with changes in ocean currents. That is also the case for the last cold phase of the Würm Ice Age, known as the Younger Dryas. At this time, a new cold period occurred and the northern Atlantic region relapsed from a moderate climate back to glacial conditions in the course of just a few decades. Climate indicators provide nevertheless contradictory information concerning the origins of this cold phase. EAWAG is on the trail of additional clues in an ice core from Greenland.

The Würm Ice Age is the most recent ice age in the course of earth's history. It lasted approximately 100,000 years and ended only about 10,000 years ago. This ice age was characterized by rapid climate changes in the North Atlantic region. The last cold phase of the Würm Ice Age is known as the Younger Dryas. It started very suddenly about 12,700 years ago and lasted circa 1200 years. In this period the mean annual temperature in Greenland fell by an amount on the order of 10 °C (Fig. 1A) [1]. A common hypothesis is that this climate change was caused by changes in the ocean currents. If the transport of warm water from the south to the north is interrupted, this would result in a sudden temperature fall in the northern regions. This hypothesis is supported by a number of observations. However, the reconstruction of the atmospheric ^{14}C provides contradictory evidence. EAWAG wanted to know more and pursued this contradiction.

Contradictory Evidence

The radioactive carbon isotope ^{14}C (see box) is a natural trace element of enormous importance for climate research. It is produced continuously in the atmosphere by the action of cosmic radiation, and, after oxidation to $^{14}CO_2$, takes part in the global carbon cycle.

Oceans continuously exchange air and CO_2, including radioactive ^{14}C, with the atmosphere. Within the oceans the distribution of ^{14}C is governed by oceanic ventilation: the better the oceans mix globally, the more ^{14}C is transported down to the deeper water layers, and the more ^{14}C poor water is transported from the deep sea to the surface. This process has the consequence that when ocean mixing is stronger the proportion of ^{14}C in the atmosphere sinks. If we assume that the oceanic mixing in the North Atlantic during the Younger Dryas was in fact reduced, one would expect to see for this period, along with the above-described temperature fall, an accompanying increase in atmospheric ^{14}C.

By measuring the ^{14}C concentration in sediments, it was possible to reconstruct the ^{14}C concentration in the atmosphere during the Younger Dryas [3]. As expected, the ^{14}C concentration increased at the beginning of the Younger Dryas, which confirms the hypothesis of a reduced oceanic mixing. However, the ^{14}C atmospheric concentration fell again long before it became significantly warmer in the North Atlantic (Fig. 1B). This contradicts the predicted association between heat transfer, deepwater formation and ^{14}C content of the atmosphere. We wondered therefore what other factors could have played a role.

Nuclide Production Effect on the ^{14}C Concentration

The ^{14}C concentration in the atmosphere is not only determined by oceanic circulation, but is also influenced by the rate of production. During a period of weak solar activity, more ^{14}C is produced in the atmosphere, which results in an increase in the atmospheric ^{14}C concentration. Such an increase in ^{14}C occurred, for example, during the Maunder Minimum between 1645–1715 [4].

The Radiocarbon Dating Method

Along with the two stable carbon isotopes, ^{12}C and ^{13}C, there is the radioactive isotope ^{14}C. It has a half-life of 5730 years; i.e. after 5730 years half of the original ^{14}C in any sample has decayed. This convenient fact is exploited in the ^{14}C dating method. All living organisms continuously exchange ^{14}C with their environment. This exchange stops when the organism dies. In the course of time, the radioactive ^{14}C decays in the organism and the ^{14}C concentration decreases continuously. By measuring the ^{14}C concentration in a sample, it is therefore possible to estimate the age, or more precisely expressed, the point in time when the ^{14}C exchange with the environment was interrupted.

This is, however, only possible precisely when the history of the atmospheric ^{14}C concentration is known. The reason is simple: if in the past the ^{14}C concentration was higher, then it would have taken correspondingly longer for the decay to reduce ^{14}C to a specific concentration. Without knowing the original ^{14}C concentration in the air, one would draw the conclusion that the sample is younger than it actually is, or over-estimate its age in the opposite case.

For this reason, scientists are developing a ^{14}C calibration curve, which for the past 11,500 years was accurately dated within ±1 year [2]. This research involves above all fossil tree remains and sediments with known ages. The measurement of the ^{14}C concentrations in individual tree rings and sediment layers can then be used to infer the past changes in the atmospheric ^{14}C concentration.

At that time the climate in Europe was significantly colder than today. From astronomical observations with the recently invented telescope, it was observed that the sun had hardly any sunspots on its surface in this period (Fig. 2; see also the article by M. Vonmoos, p. 8). The absence of sunspots shows that the sun at this time was a lot less active than it is today. In the case of the Maunder Minimum, the observations of sunspots allowed us to draw a clear association between the increase in ^{14}C and solar activity. However, we need another source of information if we want to infer possible causes for changes in atmospheric ^{14}C concentration which occurred further in the past.

^{10}Be as a Measure of Atmospheric Radionuclide Production

An additional and exceedingly interesting source of information is available through measurements of the radioactive isotope Beryllium-10 (^{10}Be). Like ^{14}C, ^{10}Be is produced by the effect of cosmic radiation on atmospheric atoms (see lead article p. 3). However, thereafter its terrestrial cycle takes an entirely different form to that of carbon: ^{10}Be is deposited relatively directly onto the earth by being washed out of the atmosphere, and does not, as is the case for ^{14}C, enter a biogeochemical cycle. The history of the ^{10}Be production rate can be reconstructed thanks to paleo records. Particularly successful have been measurements

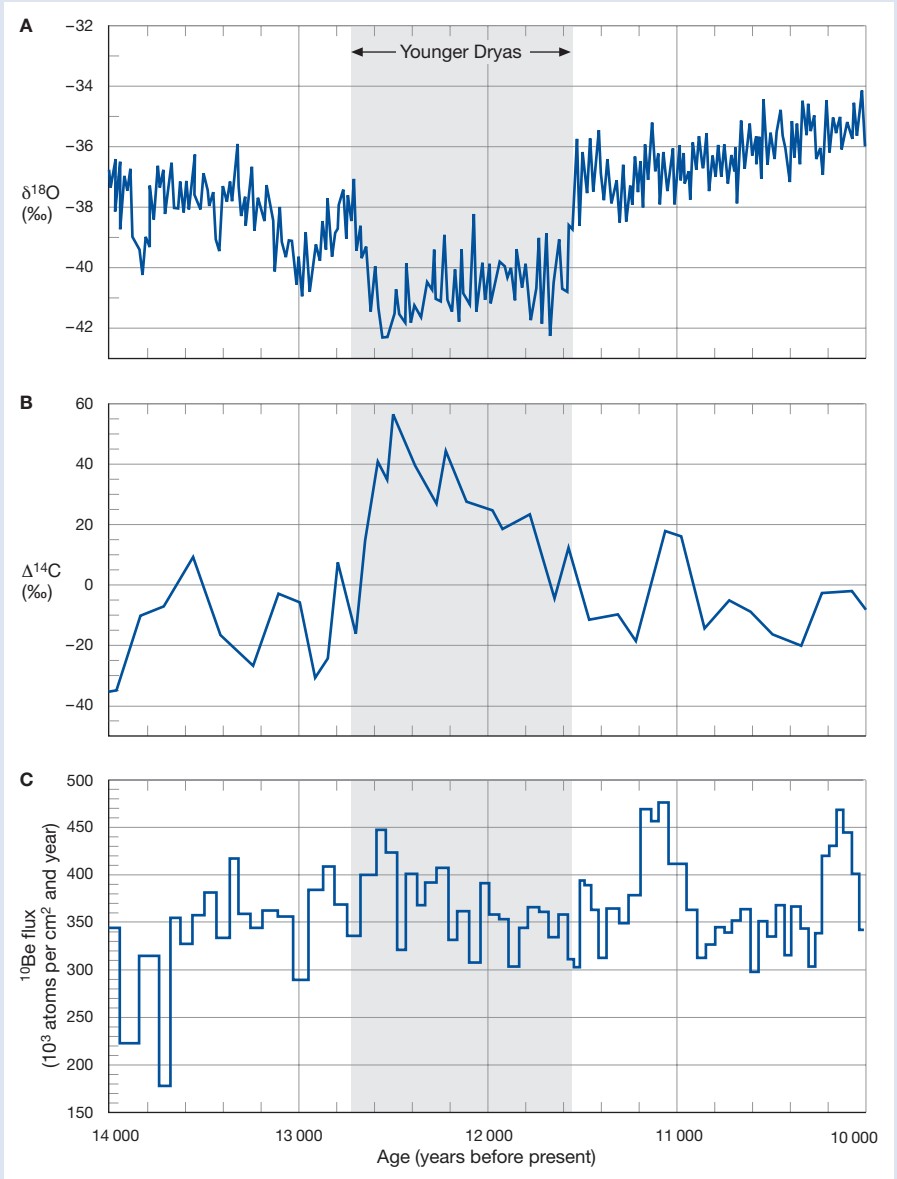

Fig. 1: Temperature, atmospheric ^{14}C concentration and ^{10}Be flux during the Younger Dryas.
A) $\delta^{18}O$ as a measure of the temperature in Greenland (see also lead article).
B) Reconstruction of the atmospheric ^{14}C concentration expressed as $\Delta^{14}C$ based on the sediment investigations in the Cariaco Basin off the north coast of Venezuela. $\Delta^{14}C$ shows the variation in atmospheric ^{14}C concentration with respect to a standard (unit: per mil).
C) ^{10}Be flux indicating the past radionuclide production.

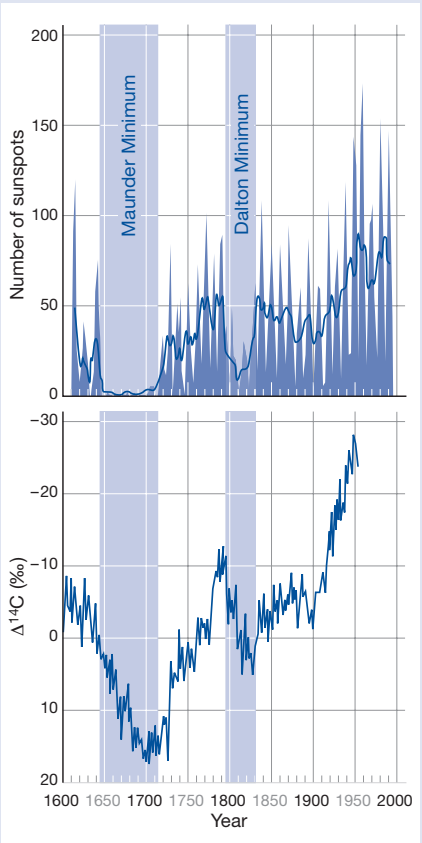

Fig. 2: Comparison of the number of sunspot groups with the changes in atmospheric ^{14}C concentration. In phases of reduced solar activity, such as during the Maunder and Dalton Minima, the atmospheric ^{14}C concentration increased ($\Delta^{14}C$ is shown inverted).

of ^{10}Be in ice cores from central Greenland, in which ^{10}Be has been deposited from the atmosphere by precipitation, year by year and ice layer by ice layer.

If the ^{14}C concentration is dependent only on one variable, ocean mixing, then we should find constant deposition of ^{10}Be in the Younger Dryas ice. If, however, also changes in the nuclide production rate are involved during the Younger Dryas, we should expect a variable ^{10}Be concentration in the respective ice layers similar to the variations observed for ^{14}C.

Variable Production of ^{10}Be Isotopes

It has in fact been possible to show through the analysis of ^{10}Be data [5] that the radionuclide production rate, and, therefore, most probably also the solar activity during the Younger Dryas, was indeed variable (Fig. 1C). If one converts the ^{10}Be data to ^{14}C values, it appears that a large part of the atmospheric ^{14}C variation can be explained by this variable rate of production (Fig. 3A). However, the ^{14}C variations observed during the Younger Dryas can only be explained satisfactorily by including in addition the effects of a 30 % reduction in ocean circulation (Fig. 3B) [6]. Our analyses confirm, therefore, that the Younger Dryas is in fact associated with a reduced deepwater formation. The trigger for this abrupt climate change is still unclear. It is apparent, though, that the radionuclide production at the start of the cold phase was higher. This clue suggests that a reduced solar activity could have been the cause for the onset of the cold spell.

With the example of the Younger Dryas, we have been able for the first time by comparison of ^{10}Be and ^{14}C data to distinguish between changes in the production rates and changes in the carbon cycle. This process is usable for the whole time period covered by the ^{14}C method (i.e. the last 50,000 years), and will play an important role in future investigations concerning the global changes in the carbon cycle.

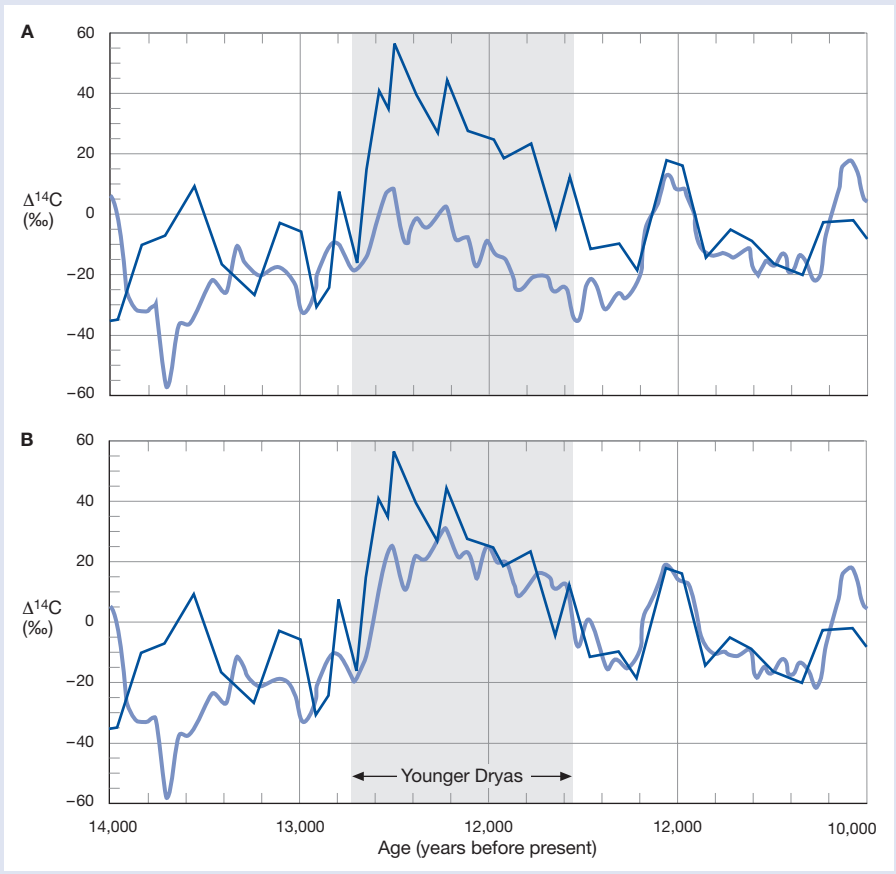

Fig. 3: Model of the atmospheric ^{14}C concentration (light-blue curves):
A) taking only into account radionuclide production,
B) taking into account both radionuclide production and ocean circulation.
For comparison the actual reconstructed ^{14}C concentration is again represented (dark-blue curve from Fig. 1B).

Raimund Muscheler worked on this project as part of his doctorate in the "Surface Waters" department. Since 2003 he has been working as a post-doctorate fellow at the University of Lund in Sweden.

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The Compass in the Ice

Everyone knows that a freely-moving magnetic needle will align itself to north, making it rather useful for finding one's way in unknown areas or when visibility is poor. The principle of the magnetic compass has been known for more than a thousand years, and has been of inestimable value to navigators. Even migratory birds and other animals seem to have an inbuilt compass which permits them to home in on their destinations with uncanny precision. However, a compass several thousand years ago would not have pointed to the north pole; throughout the earth's history, the geomagnetic field has reversed its polarity again and again.

Even though the earth's magnetic field, or geomagnetic field (Fig. 1) has been investigated in detail for more than 300 years, Einstein referred to it as one of the greatest unsolved mysteries of science. Since then many outstanding questions regarding the origin and alignment of the geomagnetic field (Fig. 2) have been answered (see box). However, the reason why the polarity of the magnetic field has reversed itself on a number of occasions throughout earth's history is still a riddle (Fig. 3). Before an answer to this riddle can be found, the polarity and strength of the magnetic field must be reconstructed as far back in time as possible. EAWAG has been able to show that the measurement of radioisotopes in ice cores represents a new method of calculating the geomagnetic field.

Paleo Records Reveal the Earth's Magnetic Field

Traditionally, paleomagnetists use sediments and volcanic rock to reconstruct the geomagnetic field. In sediments, it is the magnetic particles which have been deposited layer by layer throughout the past that are of interest. As long as these particles remained mobile within the sediment, they would align themselves with the magnetic field like a compass needle. The stronger the magnetic field, the more they display this characteristic. This allows the direction and intensity of the earth's past magnetic field to be determined from sediment cores. Similarly, volcanic rock reveals the past through the outpouring of high temperature rock mass from deep within the earth's interior during a volcanic eruption. So long as the lava is fluid, it is not magnetizable. Only during cooling do ferro-magnetic particles align themselves with the geomagnetic field.

These methods of geomagnetic field reconstruction are most applicable when the magnetic field was strong, the sediment homogeneous and rich in magnetic particles, and the recorded magnetic field not disturbed subsequently by other processes.

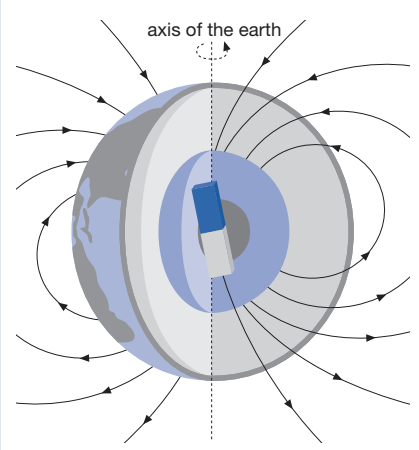

Fig. 1: The geomagnetic field can be depicted in simplified form as a dipole field produced by an imaginary bar magnet located at the earth's center. This bar magnet is slightly askew with respect to the earth's axis of rotation.

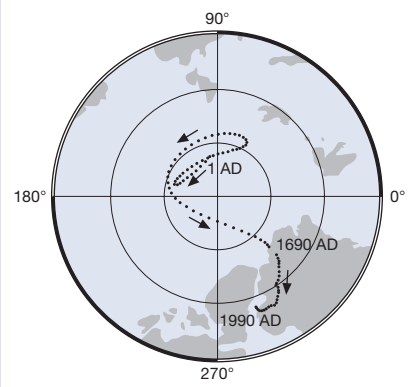

Fig. 2: Migration of the magnetic north pole through the Arctic during the last 2000 years [1]. The migration continues.

Origin, Orientation and Strength of the Geomagnetic Field

The earth is surrounded by a magnetic field (Fig. 1). The origin of this magnetic field lies in the convection fluxes of fluid iron in the earth's center: as in the case of water, hot iron rises to the outside and cold iron sinks to the center.

The direction of the axis of the magnetic field does not correspond to the earth's axis; i.e. the magnetic poles do not coincide with the geographic poles (Fig. 1). In addition, the magnetic poles are continually migrating. In the last 2000 years, the magnetic north pole has shifted thousands of kilometers over the Arctic (Fig. 2). About 300 years ago it reached Greenland. Today it lies in Canada, and it is unclear where it will go in the future.

Not only has the orientation of the magnetic field varied over time, its strength has done likewise. Of particular interest is when the field strength approaches zero. In this case, when the field intensity increases again, a reversal of polarity can occur, meaning that the magnetic north pole is suddenly in the southern hemisphere, where it usually remains for several hundred thousand years before flipping back again to the northern hemisphere. The timing of a reversal does not appear to follow any particular pattern, and is, therefore, impossible to foresee. The last reversal of polarity, the so-called Brunhes-Matuyama polarity reversal, occurred some 780,000 years ago (Fig. 3).

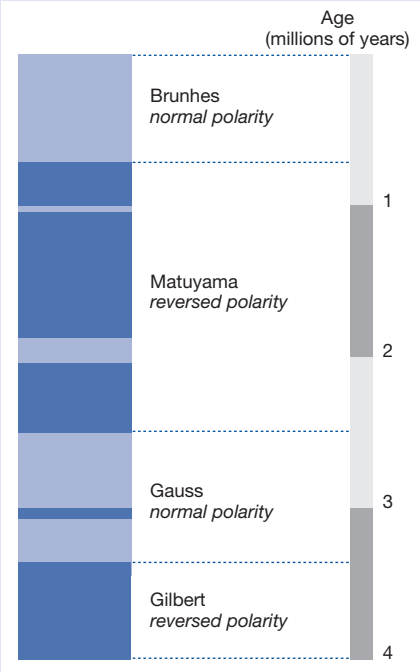

Fig. 3: Reversals of the polarity of the geomagnetic field over the past 4 million years. In the light-blue time periods the polarity was the same as today; in the dark-blue periods the polarity was reversed. Some epochs are named after researchers dedicated to solving the riddles of the geomagnetic field.

The Radioisotope Method

The new radioisotope method is based on the analysis of polar ice cores. Although this ice consists almost entirely of only the purest of water, and contains effectively no magnetic particles, it can nevertheless reveal invaluable information concerning the history of the geomagnetic field. This information can be read from the trace amounts of radioisotopes, such as beryllium-10 (^{10}Be) and chlorine-36 (^{36}Cl), found in the ice. A strong geomagnetic field shields the earth from cosmic radiation, reducing the production of radionuclides. When the magnetic shield is “switched off”, however, the global nuclide production rate more than doubles. If we assume that the slow change in ^{10}Be and ^{36}Cl found in the ice is caused by the magnetic field, and that the faster solar variations are averaged out, then we have at our disposal a new, completely different method of reconstructing the historical strength of the geomagnetic field. It differs from the traditional methods in that its sensitivity actually increases with decreasing field strength. Another advantage of this new method is that it is hardly affected at all by local variations in the magnetic field.

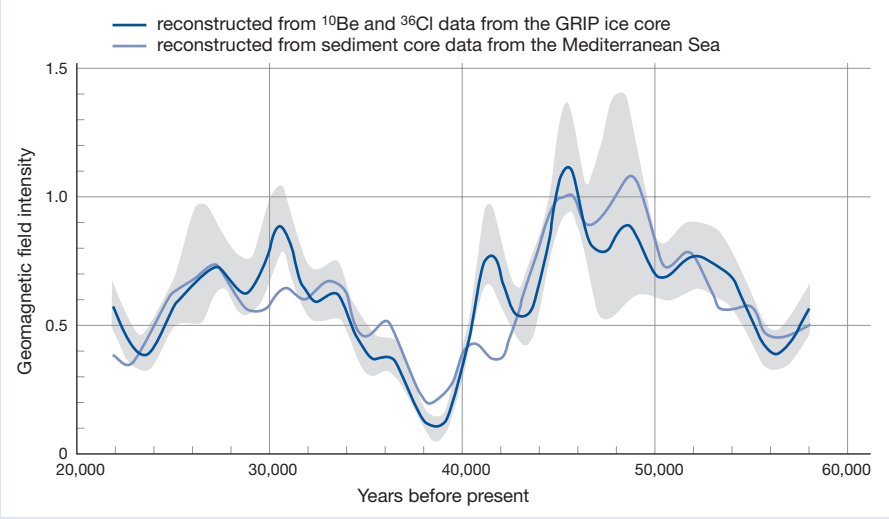

Fig. 4: Reconstruction of the geomagnetic field strength over the time period 20,000–60,000 years before present. Comparison of the radioisotope method (dark-blue curve: combined ^{10}Be and ^{36}Cl data from the GRIP ice core [2]) with traditional methods (light-blue curve: orientation of magnetic particles in a sediment core from the Mediterranean Sea [3]). The gray band represents the range of uncertainty of the radioisotope method. The range of uncertainty of the traditional method is not shown.

Is the Radioisotope Method Reliable?

In order to assess whether the radioisotope method does in fact produce reliable results, we have made a direct comparison of the two methods. Figure 4 shows the magnetic field strengths as reconstructed from ^{10}Be and ^{36}Cl concentrations in the GRIP ice core from Greenland [2], and from traditional measurements of Mediterranean Sea sediment cores [3]. Apart from a few digressions, the results of the two methods agree well. The radionuclide measurements, for example, confirm that the earth’s magnetic field weakened about 40,000 years ago to around 10 % of its current strength. However, just before a reversal of polarity could occur, it returned to its old state.

The radioisotope method has therefore passed its baptism of fire. In the future, it can be used to analyze the entire time range covered by ice cores and sediment cores, thereby making it possible to reconstruct the geomagnetic field back to about one million years ago.

And what about the future? When can we expect a new reversal of polarity? For about 2000 years the magnetic field strength has decreased continuously, so if the rate remains constant we will experience another magnetic polarity reversal within about another 2000 years. We humans will not notice this, but for migratory birds, which rely on the geomagnetic field for orientation, it is unclear what effect this will have on their ability to find their destinations.

Jürg Beer, portrait on page 5.

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Cosmic Radiation and Clouds

Ice cores provide abundant information about past climate changes. They can also provide answers to very specific questions and the means of testing hypotheses. One such hypothesis proposes that climate changes are caused primarily by changes in the intensity of cosmic radiation. If this is correct, it relegates the enhanced greenhouse effect to a secondary role – a politically explosive hypothesis which demands closer analysis.

In 1997, Danish scientists came before the press and announced, not without some pride, that they had found the explanation for the global climate warming that has occurred over the past 150 years [1]. According to them, the decisive role was played neither by the greenhouse effect nor by the solar constant (see lead article on p. 3), but rather by global cloud cover (see box). Their work suggested that cloud formation is affected by cosmic radiation, which underwent a significant decrease during the 20th century. This work found wide public appeal. Newspaper, magazine, and television reports followed the debate blow by blow, and a book on the subject, "The Manic Sun" [2], also appeared. Since the Danish hypothesis presents global climate warming as a natural process, and therefore exonerates humans of any responsibility for it, it was particularly welcome in those circles of industry and politics which are keen to avoid the necessity of implementing any measures to reduce the emission of greenhouse gases. Here, science was challenged, and also EAWAG entered into the fray [3]. Once again climate change demonstrated itself to be a very complex process which resists explanation in terms of a single process. The major potential causes of climate changes are greenhouse gases, solar irradiance, aerosols, volcanic eruptions and internal variations within the climate system. In the following discussion, we focus on the first two of these.

Greenhouse Gases and Solar Radiation

Since about 1850, the temperature in the northern hemisphere has undergone an almost continuous increase (Fig. 1) [4–6]. Among the possible causal factors under discussion for this climate change are the increase in the concentrations of greenhouse gases present in the atmosphere, and variations in solar activity:

- If we look, for example, at the behaviour of CO_2, a major greenhouse gas, an exponential increase in its concentration has indeed occurred over the past 150 years. This increase has been particularly steep since the middle of the 20th century (Fig. 1). The cause of the exponential increase is generally acknowledged to be the increasing consumption of fossil fuels. Air temperature, on the other hand, fluctuates greatly. Particularly noteworthy are two temperature rises from 1910 to 1940 and from 1970 to the present. Between 1940 and 1970 there was in fact a slight cooling. These fluctuations do not correspond to the exponentially growing CO_2 concentration.
- As regards solar radiation, satellite measurements made since 1980 show that the radiation intensity is not constant, but rather fluctuates through an 11-year sunspot cycle (see Fig. 1, p. 8). Looking more closely, however, it can be seen that the solar constant of 1366 W/m^2 varies by less than 2 W/m^2 over a sunspot cycle, which is just 0.15% – too low to explain the observed temperature fluctuations.

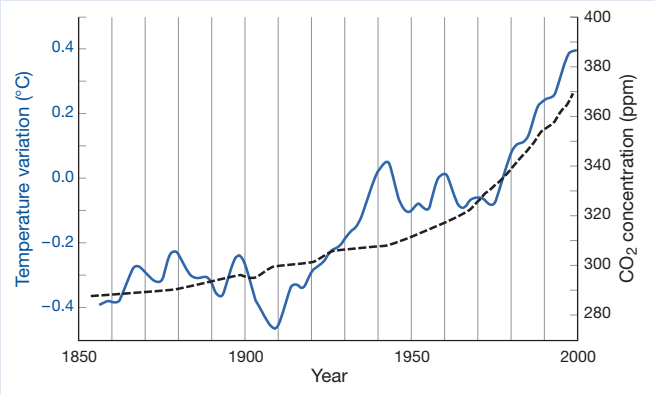

Fig. 1: Comparison of global temperature variations since 1850 (relative to the period 1961–1990) with the concentration of CO_2 in the atmosphere. Temperature curve: average of innumerable measurements from different weather stations [4]. CO_2 curve: data up to 1953 from analyses of air bubbles in the Siple ice core [5]; since 1958 direct CO_2 measurements at Mauna Loa [6]. ppm = parts per million.

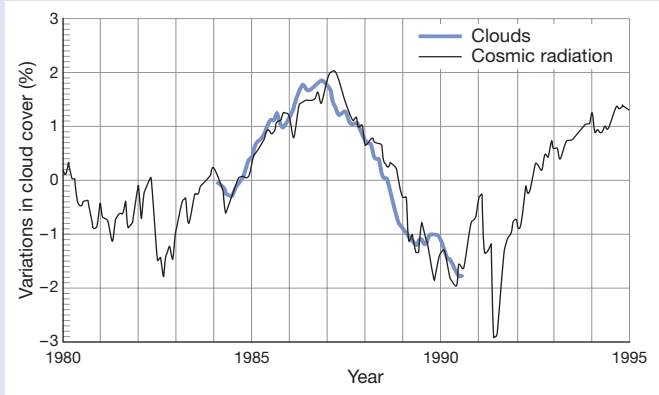

Fig. 2: Cloud cover variations from1980 to 1995, which exceed 2%, follow the variations in cosmic radiation very well [1]. On the same scale, the 12-month running mean cloud cover (expressed as a percentage change) is plotted against normalized monthly mean measurements of cosmic radiation in Colorado (USA).

Therefore neither of these two factors alone can explain the climate warming. So much for the level of understanding today, with which the Danes are in agreement. But how do the Danes argue further?

Influence of Clouds

The Danish scientists wondered whether the cosmic radiation could have an effect on our climate. According to their idea (see box), the more cosmic radiation that reaches the earth from space, the greater the global cloud cover should be. To test this hypothesis, they examined satellite pictures of the cloud cover from the years 1980 to 1995, and compared them to the intensity of the cosmic radiation. They found that the cloud cover in this period varied by about 2% and followed the variation in cosmic radiation exactly (Fig. 2). Their hypothesis appears to be fundamentally able to explain past observed climate fluctuations. Nevertheless, the work of the Danes stands on wobbly legs, since their data analysis is limited to a tiny time window of only 15 years. To strengthen their hypothesis, it would be necessary to obtain further data on cosmic radiation and climate over the past few hundred or even thousand years. EAWAG has found such additional information in the Greenland ice core.

Weak Cosmic Radiation in the Past 300 Years

If we look back over the past 300 years, we see that the cosmic radiation has in general decreased. On the one hand, we know this from direct measurements of cosmic radiation by neutron monitors which have been operating since the 1950s; on the other hand, we can use radionuclides such as beryllium-10 (^{10}Be) and chlorine-36 (^{36}Cl), which are deposited in Greenland, as indirect parameters for the reconstruction of the cosmic radiation in the past. The reduction in cosmic radiation would seem to be due to increased solar activity (see Figs. 2 and 3, p. 9). According to the Danish hypothesis, one would expect for this period,

David Parker

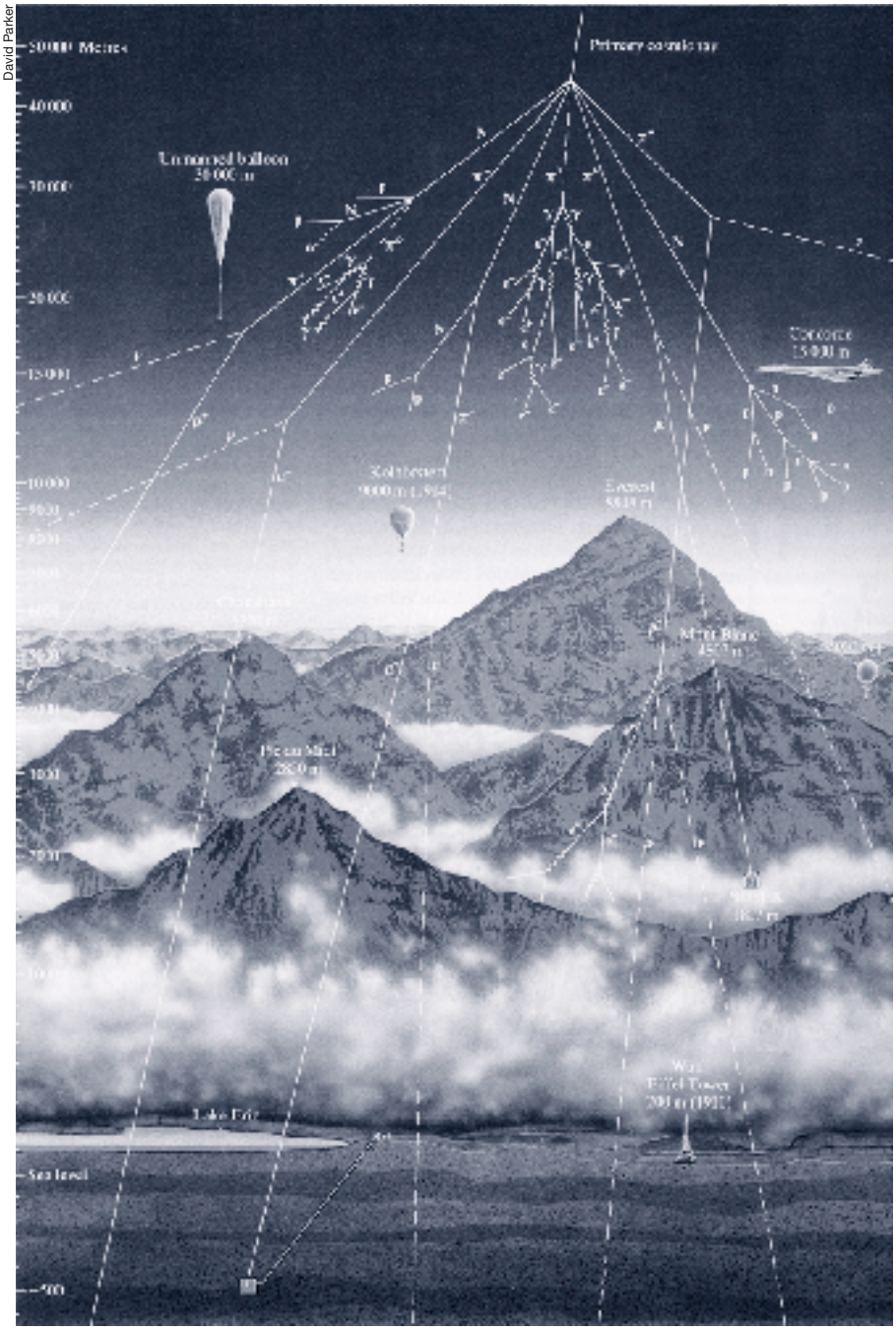

Fig 3: Cosmic radiation arrives with high energy from outer space and penetrates the atmosphere, where it collides with the atoms in the air. This produces secondary particles, which in turn collide with other air atoms, splitting them into cosmogenic radionuclides. At the same time the primary and secondary particles ionize the air, so that – according to the Danish hypothesis – more clouds are formed. The above illustration is a montage. It shows at which height in the atmosphere the various processes occur.

The Cloud Hypothesis

The hypothesis of the Danish scientists Svensmark and Friis-Christensen [1] appears simple and enlightening: cosmic radiation – high-energy particles from deep space – penetrates the atmosphere and ionizes the air (Fig. 3). Moisture in the air condenses on these ions to form small water droplets, resulting in cloud formation. The more clouds that are present, the less solar radiation reaches the earth's surface, and temperatures fall. As a corollary to this, it gets warmer if there are fewer clouds in the sky and the sun's rays can reach the earth's surface unhindered.

How much cosmic radiation can reach the earth's atmosphere depends on the interplay of two factors: solar activity and the earth's magnetic field. The sun is continually spewing out glowing gas into space. This gas expands to form the so-called solar wind, and in the process carries with it the sun's magnetic field. The solar magnetic field forms an external protective shield around the earth, which prevents the cosmic radiation from entering the earth's atmosphere (see Fig. 4 on page 5). In addition, the earth's magnetic field provides an internal protective shield, reinforcing the external shield. The more active the sun is and the stronger the magnetic field, the less cosmic radiation enters the earth's atmosphere.

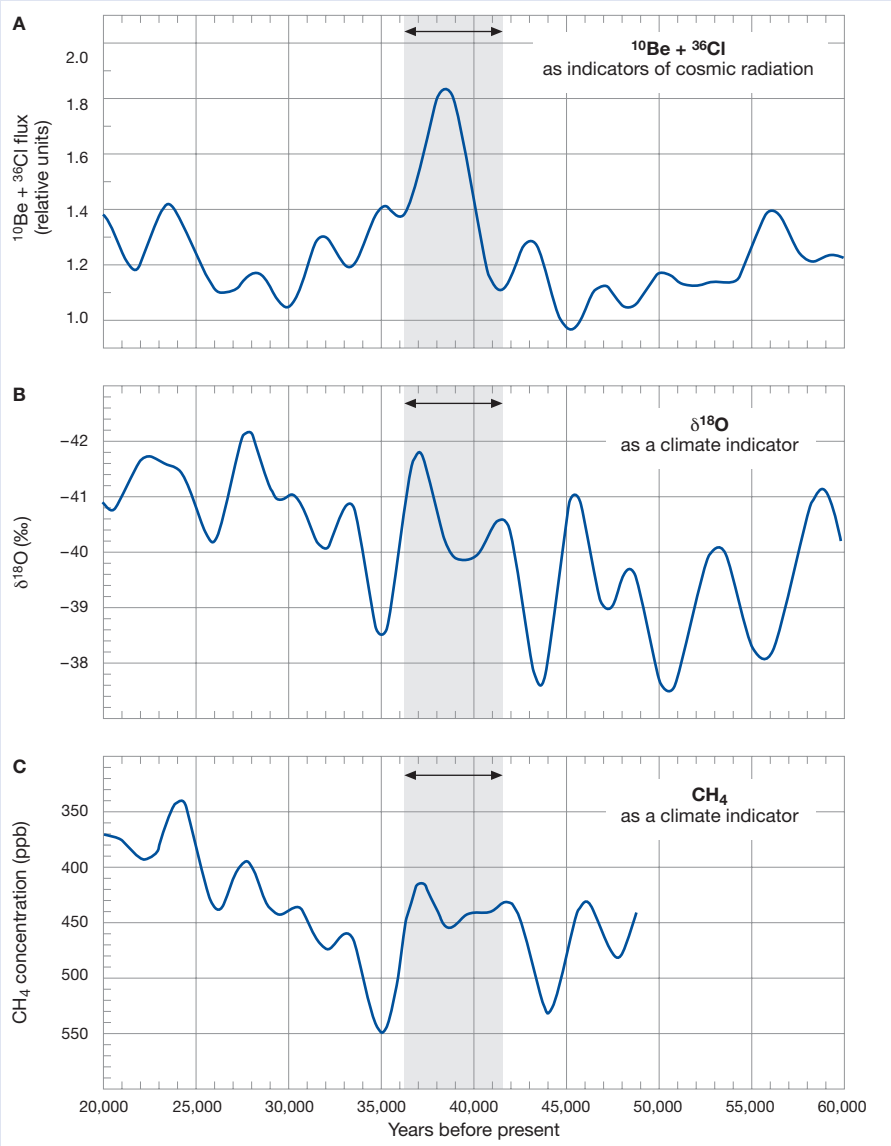

Fig. 4: Comparison of combined ^{10}Be and ^{36}Cl data (A) with the two climate parameters δ^{18}O (B) and CH_4 (C) in the GRIP ice core. Resulting from a weakening of the earth's magnetic field around 40,000 years before present (grey area), the intensity of the cosmic radiation increased, and more ^{10}Be and ^{36}Cl was formed. Contradicting the Danish theory, neither of the climate parameters shows any indication of a climate cooling. The calculated correlation coefficients approach zero. ppb = parts per billion.

with its decreasing intensity of cosmic radiation, a matching decrease in cloud cover, and thereby climate warming. So far so good for the cloud hypothesis.

Strong Cosmic Radiation 40,000 years ago

If we go even further into the past, the situation changes. About 40,000 years ago we find a period of about 3000 years during which the cosmic radiation was relatively strong. During this period the earth suddenly lost its protective shield, and the cosmic radiation penetrated the earth's atmosphere with a considerably increased intensity. The cause lay in the earth's magnetic field, whose intensity at that time had sunk to about 10% of today's value. If the Danish hypothesis is true, the cloud cover in this period should have increased, resulting in a significant climate cooling [3].

Once again the Greenland ice core provides ample information to test this hypothesis. Fig. 4A shows the combined ^{10}Be and ^{36}Cl data. In this figure, a peak around 40,000 years ago springs to the eye. This radionuclide peak meets our expectations exactly, since stronger cosmic radiation increases radionuclide production. At the same time, two climate parameters, δ^{18}O and methane, were measured in the ice core. According to the cloud hypothesis, it should have become significantly colder, so we would expect a clear reduction in δ^{18}O and methane to have occurred during this same period. This is, however, not the case (Figs. 4B and C). The two climate parameters δ^{18}O and methane correspond well with each other, but do not match the ^{10}Be/^{36}Cl curve. Our results clearly contradict the cloud hypothesis. Since all the parameters are measured in the same ice core, this important result does not depend on how well the ice core is dated.

Too Ambitious Interpretations

In the meantime, further disagreements have arisen, in particular with regard to the analysis of the latest cloud data, which no longer follow the cosmic radiation data. At the moment it looks bad for the cloud hypothesis, although the last word has not yet been uttered. Once again it has been made apparent that climate is a complex beast, and that changes in climate cannot be explained in terms of a single, simple mechanism. On the other hand, evidence is mounting that prior to 1970 the sun played a very central role, not in terms of cosmic radiation, but directly, through variations in the intensity of solar radiation (see article by M. Vonmoos, p. 8). The strong warming that has occurred over the past 30 years can nevertheless not be explained by the sun. There is every indication that it is the result of increases in anthropogenic emissions of greenhouse gases. In a few years we will know with certainty, but with no possibility of avoiding the consequences.

Jürg Beer, portrait on p. 5.

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Ice Cover on Lakes and Rivers

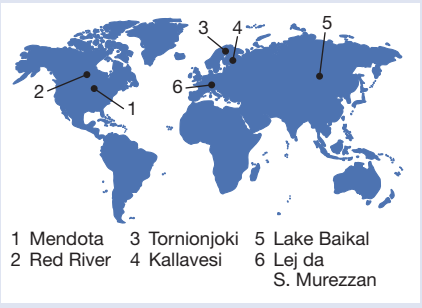
Climate Trends Inferred from Historical Records

The longer and colder a winter is, the earlier lakes freeze and the later they thaw. This is obvious intuitively even if we ignore the underlying meteorological complexities. EAWAG decided to take a closer look at this phenomenon by analyzing long series of historical observations of the timing of freeze-up and break-up of lakes such as the Lej da San Murezzan in Switzerland and Lake Baikal in Siberia. From these data, conclusions can be drawn about past and future climate forcing.

Causally, the formation of an ice cover on lakes and rivers in winter and its disappearance in the following spring are the end results of complex series of mixing, freezing and thawing processes driven ultimately by many meteorological forcing factors. By far the most important of these factors is air temperature, so that the formation or disappearance of ice on a lake or river can often be viewed in an empirical sense simply as a temporally integrated response to the seasonal variability in air temperature. The reverse is also true, allowing conclusions about the air temperatures that prevailed in the vicinity of a water body at some time in the past to be drawn from historical observations of the timing of freeze-up and break-up. Since air temperature is a very spatially coherent meteorological variable – air temperatures are usually well correlated over several hundred kilometers – historical variations in the timing of break-up do not merely reflect variations in local weather, but – much more usefully – variations in regional or even supraregional climate.

Shorter and Thinner Ice Cover – A Response to Climate Change?

Historical observations of the calendar dates of freeze-up (defined as the first day of total ice cover) and break-up (defined as the first completely ice-free day) of lakes and rivers in Canada, the USA, Finland, Switzerland, Russia and Japan provide consistent evidence that lakes and rivers around the Northern Hemisphere have been freezing later and thawing earlier since at least the middle of the 19th century (Fig. 1) [1]. These long-term historical freezing and thawing trends average around 6 days per 100 years, which corresponds to an air temperature increase of 1.2 °C per 100 years. Thus historical cryophenological data from lakes and rivers lend support to the hypothesis of past and current global warming, but



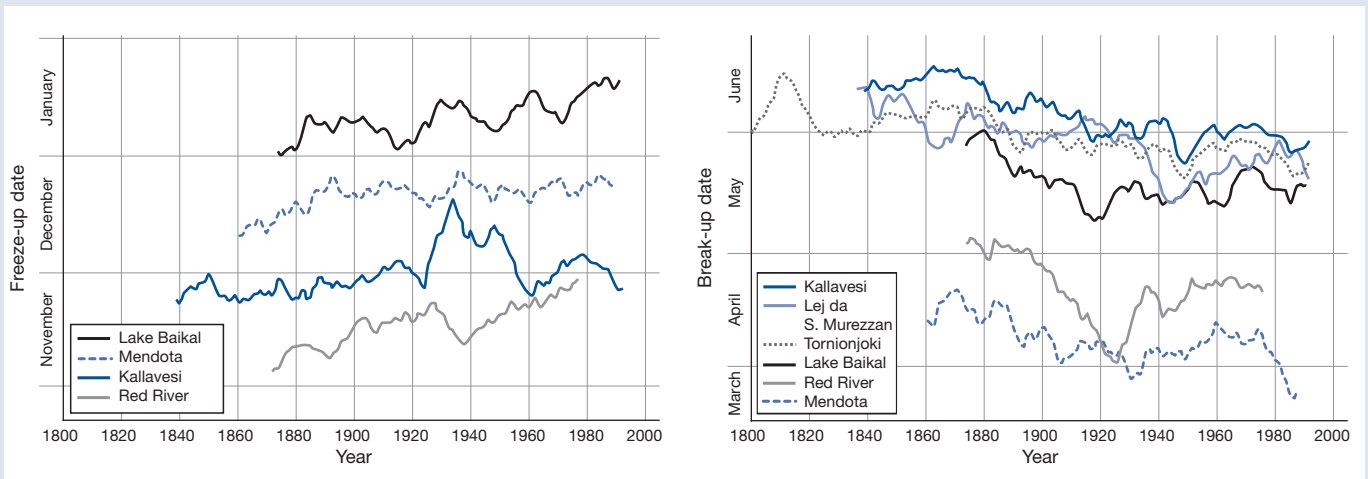


Fig. 1: Time-series of the calendar dates of freeze-up (left) and break-up (right) for a small but representative selection of lakes and rivers distributed around the northern hemisphere. Data presented as a 10-year running mean, from [1].

Tourist Office St. Moritz

Fig. 2: The annual horse race on the frozen Lej da San Murezzan, Switzerland.

also make it clear that global warming will have a substantial effect on the timing and duration of ice cover on lakes and rivers in the future. This is likely to have socio-economic and ecological impacts with both negative and positive aspects. At high latitudes, for instance, the transport of people and goods across large lakes (e.g., Lake Baikal) and wide rivers (e.g., the Yukon River) in winter will on the one hand be made more difficult and more costly by a diminution of the thickness of the ice cover and a shortening of the ice season. On the other hand, an increase in the duration of the open-water season will benefit transport by ships and barges (e.g., on Lake Superior). Ecologically, a shortening of the ice season will result in better oxygen conditions in lakes that are normally under ice for much of the winter [2], so that the danger of winter fish-kills due to prolonged anoxia will be lessened. However, a shift towards earlier break-up will generally result in a corresponding shift towards earlier spring turnover, and hence to an earlier spring phytoplankton bloom, but at lower light intensities. This change in environmental conditions at such an important time of the year is likely to result in a shift in the species composition of the phytoplankton community, with potentially wide-ranging ecological ramifications for the lake concerned.

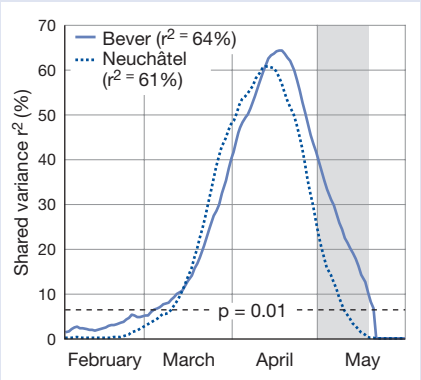


Fig. 3: Proportion of variance shared (r^2) between the timing of break-up of Lej da San Murezzan (Upper Engadine, Switzerland) and integrated air temperatures at Bever, 7 km from the lake, and in Neuchâtel, 230 km west of the lake. The air temperatures were integrated over 51 days. Each curve consists of 120 r^2 values which occur in the middle of each of 120 51-day periods. The shaded area represents the usual range of break-up date (mean break-up date ± one standard deviation). The p = 0.01 significance level is shown as a horizontal dotted line. Adapted from [3].

Ice Data from the Lej da San Murezzan

In Switzerland, the longest available series of ice observations is that of the break-up date of the Lej da San Murezzan, the "Lake of St. Moritz", located at 1768 m a.s.l. in the mountains of the Upper Engadine (Fig. 2). This valuable data series, which begins in 1832 and continues without interruption up to the present (Fig. 1), is unique in central Europe. Because of its length and because reliable instrumental air temperature measurements beginning in the second half of the 19th century are available from various meteorological stations in Europe, this series is particularly suited to investigating the relationship between break-up date and air temperature on various spatial scales.

Supraregional Climate Influences Ice Cover

The Lej da San Murezzan thaws, on average, on 12 May. Our analysis (Fig. 3) shows that the timing of break-up is highly correlated with the local air temperature, with a maximum shared variance (r^2) of 64% [3]; i.e., 64% of the variability in the timing of break-up can be explained statistically by the variability of the air temperature. Consequently, the mean local air temperature over a time period of 4–8 weeks in spring can be estimated quite well from the calendar date of break-up of the lake (Fig. 3). Air temperatures measured quite far from the lake, however, also correlate well with the Lej da San Murezzan break-up dates [3, 4]. For instance, correlations with the air temperature at Neuchâtel, about 230 km from the lake, yield a maximum shared variance of 61%, only slightly lower than the value obtained from the correlation with the local air temperature at Bever (Fig. 3). This implies that the thawing of Lej da San Murezzan – and, by analogy, of other alpine lakes – is primarily a response to climatic forcing on a regional scale rather than to local meteorological idiosyncrasies.

Extending the analysis even further afield, statistically significant relationships were found with air temperatures measured in the Netherlands and the United Kingdom, but not with mean Northern Hemisphere air temperatures, implying that interannual variability in lake ice break-up is more the result of climatic forcing on a synoptic scale than on a global scale. A companion article on p. 23 of this issue of EAWAG news describes the relationship between the timing of ice break-up on Northern Hemisphere lakes and the large-scale climatic phenomenon known as the North Atlantic Oscillation (NAO).

Ice Data from Lake Baikal

The world's deepest (1650 m) and largest (23,000 km^3) freshwater lake is Lake Baikal, situated in the Baikal Rift Zone of eastern Siberia (Fig. 4). It is over 600 km long, has a

Beat Müller, EAWAG

Fig. 4: In winter people and goods are transported over the ice of Lake Baikal.

mean breadth of about 50 km, and contains no less than 20% of all liquid fresh water on the surface of the planet. The lake is estimated to be over 25 million years old, has the highest biodiversity of any lake now existing, and supports a unique ecological system with about 1500 floral and more than 3500 faunal species and subspecies.

Lake Baikal is frozen over during 4 to 5 months of the year, but because of the difference in climate along the lake, there is a north-south gradient in both the timing of freeze-up and the timing of break-up. Freezing begins in late October, and most of the northern basin is usually frozen over by early December; the southern basin, however, does not freeze over until about a month later. Ice decay in the southern part of the lake begins in late March or early April, and by the middle of May the southern basin is generally ice-free. Break-up in the northern basin occurs 2–3 weeks later. Because of these north-south differences, ice observations on Lake Baikal can only refer to a specific part of the lake. Fortunately, the date of break-up at the same point of observation, the Listvyanka limnological station on southern Lake Baikal, has been registered continuously since 1869.

Another Influencing Factor: the Annual Minimum Air Temperature

As in the case of the Lej da San Murezzan, the timing of break-up of Lake Baikal correlates strongly with the local air temperature (right-hand peak in Fig. 5A). However, the existence of a further important correlation (left-hand peak in Fig. 5A) implies that the situation at Lake Baikal is more complex [5]. The timing of break-up of Lake Baikal is determined not only by the air temperature prevailing during the spring thaw, but also by the minimum air temperature prevailing in February during the coldest period of the Siberian winter (Fig. 5B). The air temperature at this time of year determines the maximum thickness of the ice layer (the lower the minimum air temperature, the thicker the ice layer becomes), and also influences the thickness of the insulating snow layer (the lower the minimum air temperature, the less snow falls). Air temperatures in March, just before the snow begins to melt, normally lie below zero but above the annual minimum, and so influence neither the processes of thawing nor those of ice growth (Fig. 5B). The air temperatures prevailing in March are hence much less relevant for the timing of break-up than those prevailing in February and April.

As in the case of the Lej da San Murezzan, the timing of break-up of Lake Baikal is strongly related not only to local air temperatures, but also to air temperatures measured at large distances from the lake – in this case, throughout northern Asia. This is the case especially in February and April (Fig. 6).

Effect of Climate Warming on Ice Cover

In a further project, we analyzed a uniquely comprehensive set of 4 decades of observations of the timing of break-up of 196 Swedish lakes. These lakes are distributed along a north-south gradient, covering 13 degrees of latitude [6, 7]. The analysis showed that the relationship between the timing of lake ice break-up and air temperature is nonlinear, resulting in marked differences in how the timing of lake ice break-up responds to changes in air temperature between colder and warmer geographical regions, or between colder and warmer time periods. This implies that lakes in warmer

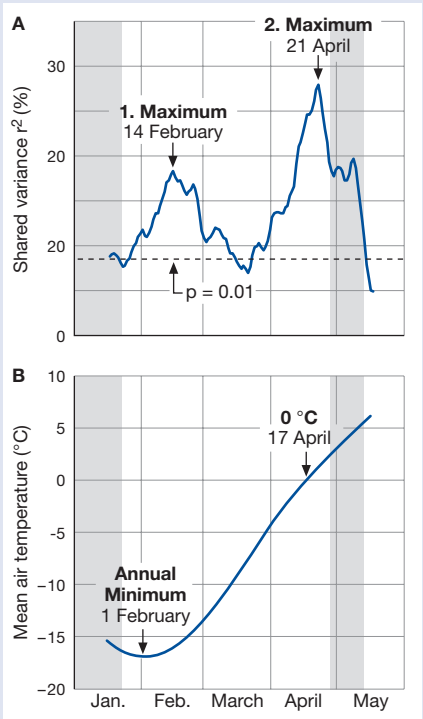


Fig. 5: (A) Proportion of variance shared (r^2) between the observed date of break-up at Listvyanka on southern Lake Baikal and the mean air temperature at the Babushkin meteorological station for an integrating time of 31 days.
(B) Seasonal progression of the 31-day mean air temperature at Babushkin (based on data from 1931–1994).
The r^2 value exhibits two maxima, viz. on 14 February and 21 April (A). These two days closely follow the dates of occurrence of the annual minimum air temperature (1 February) and the intersection of the air temperature curve with the 0 °C line (17 April), respectively (B). Shaded areas represent the usual ranges of freeze-up date and break-up date of southern Lake Baikal (mean date ± one standard deviation). The p = 0.01 significance level is shown as a dashed line. Adapted from [5].

regions (e.g., southern Sweden) will respond more strongly to global warming than lakes in colder regions (e.g., northern Sweden). In other words: the further global warming advances, the greater its effect will be on the timing of break-up, and consequently on the ecological processes within each individual lake.

Ice Phenology Time-Series as Historical Archives for Climate Prediction

Historical observations of the timing of freeze-up and break-up of lakes and rivers thus provide a valuable store of information on past changes in large-scale climate – both century-long trends and variability on interannual and interdecadal time-scales. Additionally, the fact that the timing and duration of ice cover are determined more by large-scale climatic forcing than by local deviations from the large-scale pattern implies that prediction of the effects of any future climate change on lake and river ice does not require climate models of high spatial resolution (which at present are not available). Because of the importance of the timing and duration of ice cover for the ecology and water quality of high-latitude and high-altitude lakes and rivers, predictions of the timing and duration of ice cover will be necessary in any investigation of the potential effects of climate change on our future water resources on a global scale.

The research described here was carried out within the framework of the European Union projects MOLAR, EMERGE, CLIME, REFLECT, and Euro-limpacs.

David M. Livingstone is a physicist and data analyst in the Department "Water Resources and Drinking Water", working on the past, current and potential future effects of climatic change on water resources on a European scale.

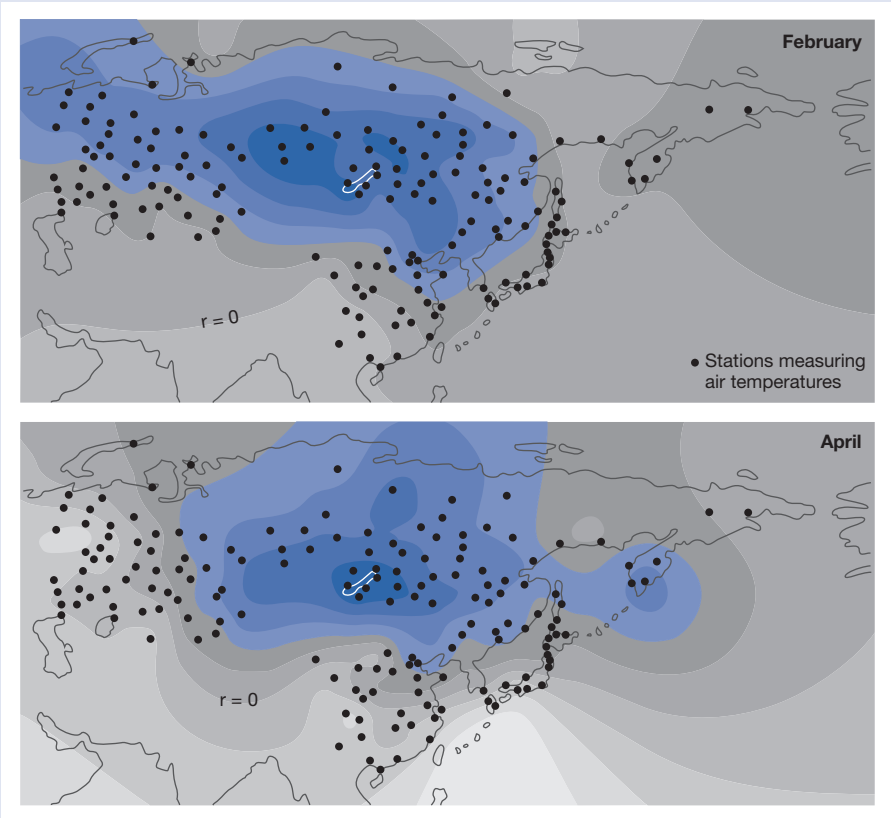


Fig. 6: Contour plots of the correlation coefficient (r) between the calendar date of break-up on southern Lake Baikal and monthly mean air temperatures at 170 stations distributed over Russia, Kazakhstan, China and Japan (1936–1989) in February and April. The correlation is best within the blue shaded area (r <–0.2 is significant at the p <0.1 level) The contour interval is 0.1. Lake Baikal is outlined in white. Adapted from [5].

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The North Atlantic Oscillation

Does it Affect the Timing of Break-up of Northern Hemisphere Lakes?

The North Atlantic Oscillation is a large-scale climate phenomenon that affects the climate of much of the northern hemisphere in winter and spring. EAWAG found that it also affects the timing of ice break-up on northern hemisphere lakes. The area of influence of the North Atlantic Oscillation has shifted over the past 130 years, with an increase in its influence in Siberia and a decrease in North America.

Climate over the North Atlantic is generally dominated by the simultaneous existence of an area of low surface air pressure centered on Iceland (the Iceland Low) and an area of high surface air pressure extending approximately from the Azores to the Iberian peninsula (the Azores High) (Fig. 1). The resulting large-scale north-south gradient in surface air pressure between these two pressure centers is of course not constant, but varies according to their strength. This variation in the meridional pressure gradient over the North Atlantic is known as the North Atlantic Oscillation (NAO). The NAO is directly responsible for a great deal of the interannual variability in climate experienced by the land areas bordering the North Atlantic, but is also associated with the climate variability occurring over a large part of the rest of the Northern Hemisphere, especially at high latitudes [1]. The mean air temperature of the northern hemisphere, for instance, is linked to the NAO, and almost a third of the interannual variance in the mean air temperature can be explained statistically by the NAO. The influence of the NAO on the northern hemisphere climate is especially strong in winter and spring.

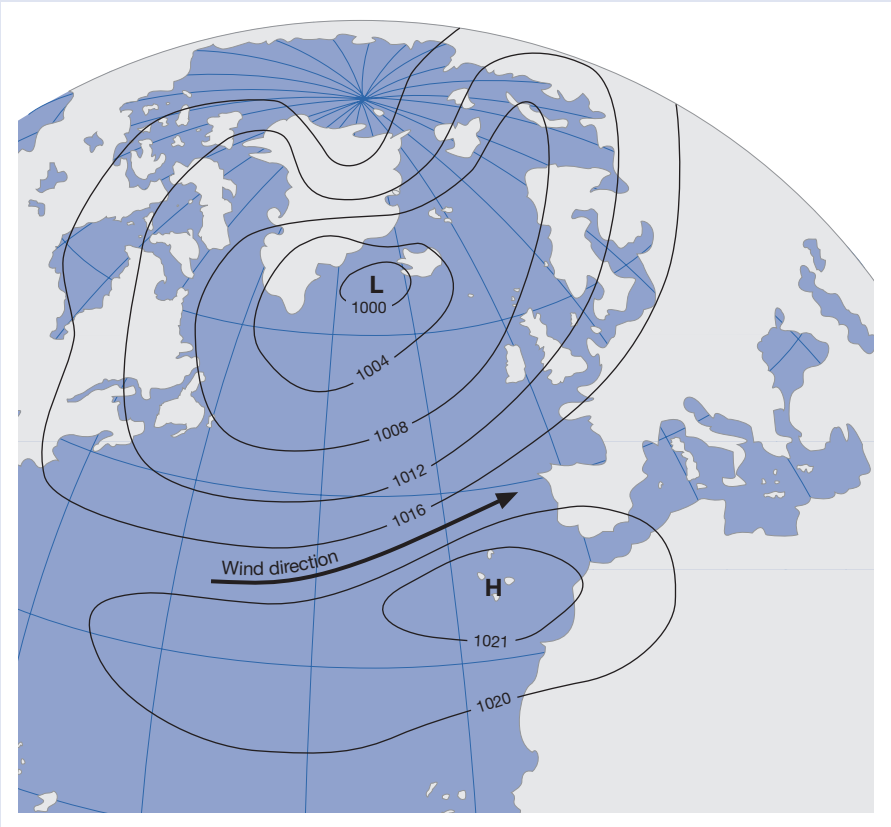

Fig. 1: The mean sea-level air pressure distribution over the North Atlantic in January (1941–1970), showing the Iceland Low, the Azores High and the prevailing direction of the winds blowing across Europe from the North Atlantic. Adapted from [2].

The Meteorological Significance of the NAO

The NAO is commonly represented in terms of an index (Fig. 2) based on the difference of the sea-level air pressure measured at a meteorological station close to the center of the Azores High and that measured at a station in Iceland [1]. A high pressure difference results in a positive index and a low pressure difference in a negative index.

High winter NAO indices indicate a steep meridional (i.e., north-south) pressure gradient over the North Atlantic. This results in strong westerly winds that transport warm, moist maritime air eastwards across Europe (Fig. 1), giving rise to mild, wet winters in Europe and much of central Asia. Low winter NAO indices indicate a relatively weak meridional pressure gradient with correspondingly weak westerlies over the North Atlantic and colder, drier winters in Europe. In eastern Canada the situation is the opposite, with high NAO indices being associated with strong northerly winds and cold winters, and low NAO indices being associated with weaker northerly winds and warmer winters. Rare winter reversals of the normal pressure distribution over the North Atlantic (i.e., high pressure over Iceland and low

pressure over the Azores) cause polar air to be transported southward over Europe, resulting in extremely cold winters there [2]. This occurred, for instance, in January 1963, when both the Lake of Zurich and Lake Constance froze over – a very rare event indeed.

Analyses of historical data records

The timing of break-up of ice on lakes is highly dependent on the air temperatures prevailing during winter and spring (see also article on p. 19 of this issue). Since this is when the climatic influence of the NAO is at its greatest, it is likely that the NAO will determine to some extent the interannual variability in the timing of break-up of the lakes that lie within its extensive geographic range of influence. This hypothesis was investigated for various lakes distributed throughout the Northern Hemisphere for which long series of observations of the timing of break-up exist [3–6]. Here we will look at four representative lakes: Kallavesi (Finland), Lej da San Murezzan (or Lake of St. Moritz, Switzerland), Lake Baikal (Siberia) and Lake Mendota (Wisconsin, USA). Whether there really is an association between the NAO and the timing of break-up of these four lakes was investigated by correlating the time series of the calendar dates of their break-up with seasonal NAO indices. In general, any correlation obtained would be expected to be negative, since high NAO indices are associated with mild winters, presumably resulting in early break-up, and vice-versa. To find out additionally how the degree of influence of the NAO has varied through time, correlations were computed for a series of overlapping 50-year historical data windows, beginning with 1865–1914 and ending with 1947–1996.

The correlation coefficients obtained are illustrated in the form of two-dimensional contour plots in Fig. 3. In each plot, the correlation coefficient is shown as a function both of the season for which the NAO index was computed and of the historical data window. Significant negative correlations are shown as dark-blue areas in the plots. They indicate a high probability that the NAO influences the timing of break-up.

Beat Müller, EAWAG

Lake Baikal in Siberia is frozen over during 4–5 months of the year.

Has the Area of Influence of the NAO Shifted?

The influence of the NAO on air temperature is known to be extremely strong in Finland [1], so a consistently strong NAO signal might therefore be expected to manifest itself in the timing of break-up of Kallavesi. This is indeed the case: throughout the entire record, there is a significant negative correlation between the calendar date of break-up of Kallavesi and the NAO indices from the previous winter and spring (Fig. 3). The maximum correlation obtained for

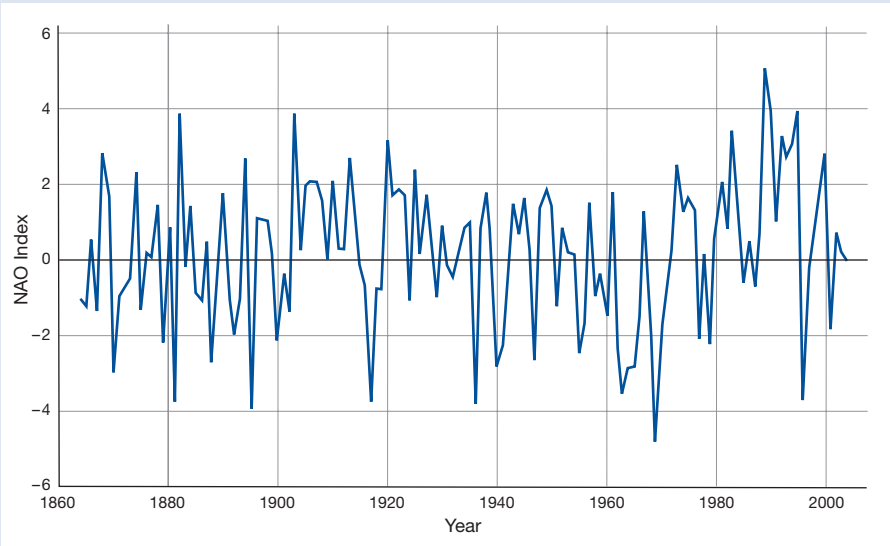

Fig. 2: The variation in the North Atlantic Oscillation (NAO) in winter (December to March) since 1864, expressed in terms of the NAO index. Adapted from [1].

Kallavesi corresponds to 43% shared variance; i.e., 43% of the variability in the break-up date can be explained statistically by the variability of the NAO index. This is a surprisingly high figure in view of the simplicity of the NAO index as a representation of the complex climatic effects operating on the lake.

The Lej da San Murezzan, in the Swiss Alps, is situated in a region where air temperature is much less influenced by the NAO than it is in Finland. Thus, only slight indications of a weak association between break-up and the winter NAO during the latter part of the series are apparent (Fig. 3). Nevertheless, there is still up to 11% shared variance.

In the case of Lake Baikal, the influence of the winter NAO on break-up has increased substantially during the period covered by the data [5]. Prior to the 1918–1967 data window, the winter NAO had no detectable effect on the timing of break-up (Fig. 3); subsequently, up to 16% of the variance in break-up date can be explained in terms of the winter NAO indices.

The most surprising results are those from Lake Mendota (Fig. 3). During the last half of the 20th century, air temperatures in central North America are known to have been affected relatively little by the NAO, and the low correlations found between the break-up date of Lake Mendota and the winter NAO during the latter part of the series is in agreement with this. However, going back further in time, the magnitude of the (negative) correlation coefficient increases to the point where almost as much variance is explained as in the case of Kallavesi now. In combination with the apparent shift in the reverse direction in the case of Lake Baikal, and possibly also in Lej da San Murezzan, this suggests that the geographical area of influence of the NAO may have changed during the last 130 years. Previously, the NAO may have had a greater influence on the climate in North America than it does today, coupled with a weaker influence on the climate in Siberia.

To support these results, we are carrying out investigations into a number of other lakes in various regions of the Northern Hemisphere. Preliminary results indicate that these lakes are also influenced by the NAO. Furthermore, the Arctic Oscillation, which is strongly associated with the NAO, apparently also plays a role in determining the timing of break-up of these lakes.

The research described here was carried out within the framework of the European Union projects REFLECT, CLIME and Eurolimpacs.

David M. Livingstone, portrait on p. 22.

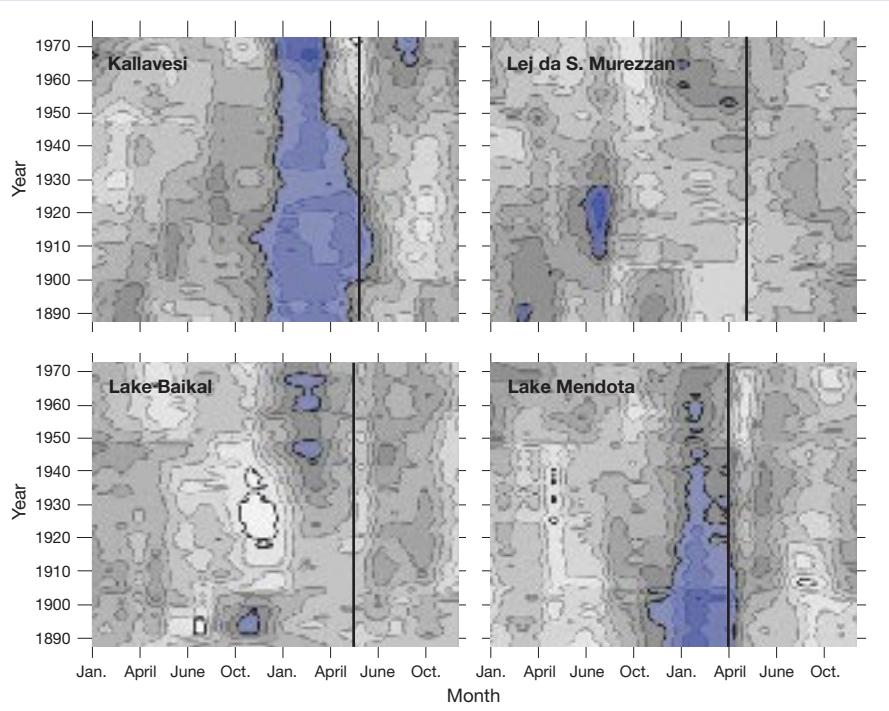

Fig. 3: Contour plot of correlation coefficients (r) between the calendar date of break-up and seasonal indices of the North Atlantic Oscillation (NAO) for 4 lakes in various parts of the northern hemisphere: Kallavesi, Finland; Lej da San Murezzan, Switzerland; Lake Baikal, Siberia; and Lake Mendota, Wisconsin, USA. The seasonal NAO indices (horizontal axis) in each case refer to a 3-month period (e.g., January to March). All correlations were calculated over a 50-year time window (vertical axis) (e.g., 1871 to 1920). To simplify the representation only the middle month of each season and the middle year of each time period are plotted. The blue areas represent significant negative correlation coefficients. The contour interval is 0.1. The thicker solid contour lines round the blue and white areas represent r = -0.3 and r = +0.3, respectively. Values of r = ±0.28 are statistically significant at the p = 0.05 level, and values of r = ±0.36 at the p = 0.01 level. The mean date of break-up for each lake is denoted by the vertical line. Adapted from [3].

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Ice On Fire – Methane Emissions to the Atmosphere

Is There a Hazard Lurking on the Sea Floor?

The stories told by seafarers over the centuries about burning icebergs were long considered superstition until they were finally confirmed near the end of the last century. The "burning icebergs" are caused by pieces of methane hydrate, a compound of ice and methane deposited in the sediments of the seabed, occasionally floating to the sea surface. All it takes is for them to be struck by lightning and we really can see burning ice. Around 10,000 billion tonnes of methane are bound in the form of gas hydrates in the sediments of the world's oceans. In the EU project CRIMEA, EAWAG is investigating the occurrence of methane in the Black Sea.

Methane hydrate looks like ordinary ice, but when it comes into contact with air, it decomposes, separating into methane gas and water. This compound of frozen water and methane belongs to what are known collectively as gas hydrates (see box and Fig. 1), and is found mainly in marine sediments and polar permafrost. There are particularly large methane hydrate fields on the continental shelves of the oceans, where the water is between 500 and 2000 m deep [1]. The methane hydrate could be shaken free of its bonds by an undersea earth tremor, resulting in enormous amounts of methane escaping into the atmosphere. Since methane, along with carbon dioxide, is one of the major greenhouse gases (see box), the consequences of this for the climate could be serious. There is a lot of evidence to suggest that such a catastrophe has occurred once already, 55 million years ago, resulting in a dramatic global warming event [2].

Methane Sources in the Black Sea

Even small changes in environmental conditions – such as a slight rise in the deep-water temperature, or a variation in sea level causing a pressure change – can result in methane being released from methane hydrate. This process should not be underestimated, considering that the concentration of methane in the atmosphere has doubled over the past 150 years, and is now 1.7 ppm (ppm = parts per million), i.e., 1.7 parts methane per million parts air. Along with methane hydrate, there are also other undersea methane sources which, through microbial and geochemical processes, cause methane to be released from the sediments, increasing the methane concentration in the atmosphere.

Thousands of active methane sources have already been located in the northwestern part of the Black Sea, where plumes of bubbles rising from them have been detected by hydro-acoustic techniques. During our CRIMEA research expeditions alone, we have discovered approximately 2800 new sources. Measurements of the methane flux through the water surface over the Georgian Shelf of the Black Sea have shown that between 1.7 and 7.0 liters of methane per m^2 are being released there per day. Extrapolating this over the entire Black Sea, we estimate that around 70,000 tonnes of methane are escaping annually into the atmosphere. However, it is still unclear what happens to the methane on its journey through the water column.

Gas Hydrates

Definition, Deposits, Origin

Gas hydrates are non-stoichiometric, crystalline substances consisting of gas and water. Water molecules form cage structures in which the gas molecules are enclosed (Fig. 1). Gas hydrates are therefore also called inclusion compounds, or clathrates (Latin: clatratus = cage). All in all, there are five different cage structures known. About 90% of the naturally occurring gas hydrates contain methane. In addition, there are hydrates of carbon dioxide and hydrogen sulfide. Methane hydrate is formed at low temperatures and high pressures, and the methane gas necessary for its formation originates from the anaerobic decomposition of organic material by bacteria. Given long periods of time, this continuous process can result in surprisingly large quantities of methane hydrate.

A Future Source of Energy?

Gas hydrates contain much more energy than all the reserves of natural gas, coal, and oil put together, and therefore represent a potential future energy source. The technical problems involved in exploring for methane from gas hydrates have not been solved yet and will occupy technologists for some years to come. Should it come to an industrial exploitation of methane, we must bear in mind that the burning of methane leads to the emission of carbon dioxide, the most important greenhouse gas (after water vapor).

Greenhouse Gases

Greenhouse gases are those gases which absorb the infrared radiation that the earth re-radiates into the atmosphere. This process is also known as the Greenhouse Effect, and is the cause of global warming. The major greenhouse gases in addition to methane are water vapor, carbon dioxide, nitrous oxides, and ozone. The effect of the various greenhouse gases varies greatly and depends on their specific warming potential. Although methane occurs only in very small concentrations in the atmosphere, its role should not be underestimated, as it is about twenty times more potent as a greenhouse gas than carbon dioxide. Without greenhouse gases, the earth would be uninhabitable, as the mean temperature of its surface would be –18 °C instead of today's 15 °C.


EAWAG

To obtain the water samples we used a rosette sampler with 12 sampling bottles which could be closed off at different depths by a signal from the ship.

The CRIMEA Project

This is one of the questions researchers from ten European research institutes and universities – including EAWAG – are seeking to answer within the framework of the CRIMEA project (Contribution of high intensity gas seeps in the Black Sea to methane emission to the atmosphere). CRIMEA specifically aims to:

- map the methane sources in the Black Sea,
- quantify the escaping fluids and gases,
- describe the active methane-decomposing bacteria on the seabed and in the water column,
- quantify the methane turnover, and
- characterize the physical, biological, and chemical processes involved during the rise of the methane to the sea surface.

The First Black Sea Expedition

In June 2003, we undertook the first Black Sea expedition on the Ukrainian ship "Prof. Vodyanitsky". Our objectives included investigating two different methane sources, one at a depth of 90 m and the other at 1980 m. The existence of these sources could be identified using what is known as gas bubble imaging. For comparison purposes, measurements were also conducted at two reference sites with no methane sources. The Black Sea is 80 m deep at the shallower of the two reference sites, and 1660 m deep at the other.

The Path of Methane through the Water Column

The first step involved finding answers to two questions [3]: how high are the methane concentrations immediately above the emission sites, and how does the methane behave during its rise through the water columns of differing lengths? To answer these questions, a special probe, a rosette sampler, was used to take water samples above the two methane sources and at the two reference sites. The rosette is comprised of 12 10-liter sampling bottles which can be closed off by a signal from the ship at different depths.

Preliminary results show that the methane concentrations are highest directly above the two emission sites (Fig. 2A + B). The concentrations change very little during the first 40 m above the shallow site, and during the first 1500 m above the deeper site. At the deep methane source, a significant decrease in methane concentration only occurs in the upper 500 m of the water column.

We had expected to find much lower methane concentrations at the reference sites than at the emission sites. In the shallow zone this is in fact the case: there the methane concentrations at the reference site were on average 10 times lower than in the water column above the methane source (Fig. 2A). The methane concentrations found over the deep emission site, however, do not differ significantly from those found over the corresponding reference site. This was surprising, and we wondered whether our measuring technique, which involved the detection of methane using a gas chromatograph with a flame ionization detector, was capable of distinguishing such a low concentration difference.

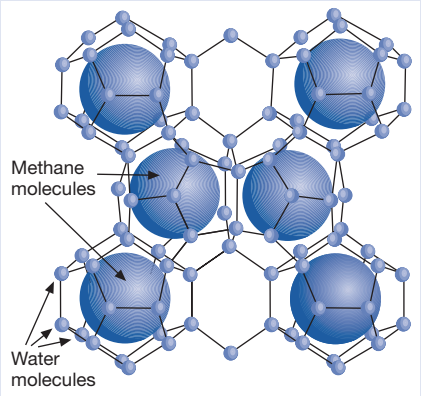


Fig. 1: Structure of methane hydrate.

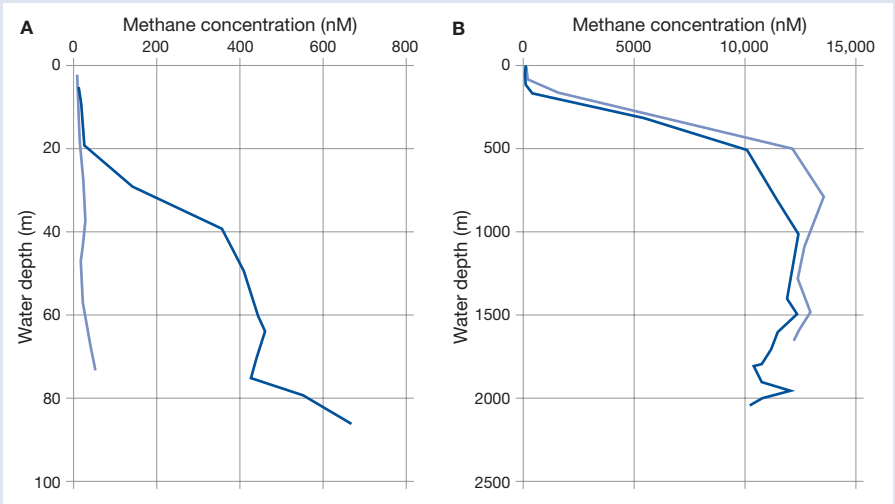
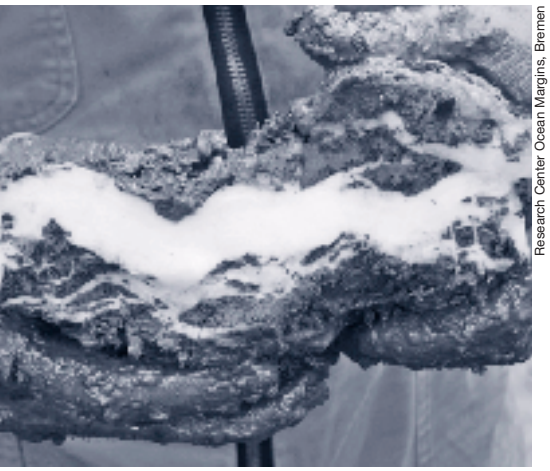


Fig. 2: Methane concentrations in the water columns above two methane sources (dark-blue curves) and the respective reference sites with no methane emission (light-blue curves). (A) in the shallow zone, (B) in the deep-water zone.



Research Center Ocean Margins, Bremen

Methane hydrate in a sediment sample.

We therefore used a second measuring technique that involves determining the distribution of the noble gas neon in the water column (see box). Normally, we would expect the neon concentration to be approximately the same throughout the deep water of the Black Sea. An anomalously low neon concentration in the water above a methane source would therefore suggest the occurrence of gas exchange between the rising methane bubbles and the water column. The concentration differential between the gas bubbles and the water column would cause some of the neon dissolved in the water to diffuse into the gas bubbles, and a corresponding amount of methane to diffuse out of the gas bubbles into the water column (Fig. 3). We did indeed find a lower neon concentration in the water column above the deep methane emission site than at the reference site, which, integrated over time, corresponds to a 20 % higher methane concentration above the methane emission site.

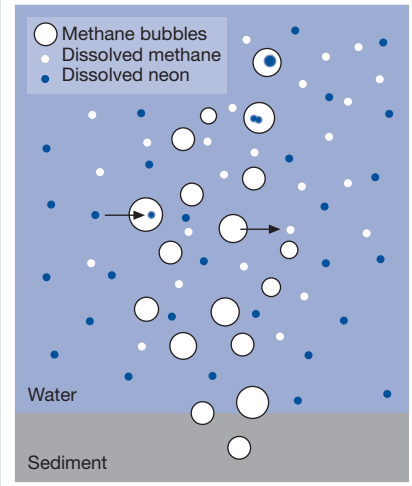


Fig. 3: Gas exchange between methane bubbles rising from a methane source and the surrounding deep water. Some of the neon dissolved in the water diffuses into the gas bubbles because of the concentration difference, and a corresponding amount of methane diffuses from the gas bubbles into the water.

Are Bacteria Decomposing the Methane?

A second step involved determining whether the methane is being decomposed by bacteria on its journey through the water column [4]. The continuous decrease in the methane concentration from the seabed to the water surface (Fig. 2A + B) suggests that this may be the case. Methane-oxidizing bacteria belong to the euryarchaeota, one of the two subgroups of the archaea bacteria. In the upper water layers, methane is oxidized to carbon dioxide by aerobic methane-oxidizing bacteria using oxygen. In the anaerobic conditions prevailing in the deep water, however, methane is oxidized using sulfate. This process is carried out by a specially adapted bacterial community: sulfate-reducing bacteria reduce sulfate to sulfide, and archaea oxidize methane to carbon dioxide.

Molecular biological methods make it possible to identify individual groups of bacteria, and to calculate the proportions of the total number of bacteria in the water samples belonging to each of these groups. We counted on average 25 % more archaea cells at the emission sites than at the reference sites. This result shows that methane-oxidizing bacteria are present above both the deep and shallow methane sources, and convert methane to carbon dioxide. Whether the methane from the sources we analyzed reaches the sea surface, and from there is able to get into the atmosphere, still needs to be investigated. The latest model calculations indicate that little or no methane from sources deeper than 100 m below the sea surface escape to the atmosphere [5]. We are currently processing the samples that have been brought back from the Black Sea expedition in 2004. The CRIMEA project runs until the beginning of 2006; by then we hope to have built up a comprehensive picture of the fate of this methane.

The CRIMEA project is funded by the European Union and the Swiss Federal Office of Education and Science.

The Neon Method

Neon gas is present in air. In addition, neon is able to dissolve in water by gas exchange at the air-water interface. The neon concentration in the water depends on its equilibrium concentration, which is determined by the environmental conditions, such as water temperature and salinity, that prevail at the time of gas exchange. Since the Black Sea is stably stratified and neon is chemically inert, the concentration of neon in the deep water is constant. Any deviation from this constant concentration indicates that some additional physical process is at work.

Carsten Schubert is a geologist and heads the "Biochemistry" group in the Department of Surface Waters. His chief areas of research are the anaerobic oxidation of methane and ammonia in marine and limnetic systems, and the decomposition of organic carbon in sediments.

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IN BRIEF

Environment Prize for EAWAG

The EAWAG research group “Water and Sanitation in Developing Countries” (Sandec) has been awarded the Energy Globe Special Prize 2004. Martin Wegelin received the prize on 27 April 2005 at EXPO 05 – the world exhibition in Aichi/Japan. The prize was awarded for the SODIS Project, a simple but ingenious method of solar disinfection using common PET bottles. The Energy Globe is one of the world’s most prestigious environment prizes and, thanks to the high level of media attention, will help greatly in spreading the SODIS method.

EAWAG

Greater security of drinking water supplies

High quality drinking water is taken for granted in Switzerland. However, bacteriological contamination of water supplies still represents a hazard to consumers. A new method has been developed at EAWAG to test the microbial quality of drinking water faster, more reliably and more cheaply than has been previously possible. Instead of waiting up to 12 days for the growth of cell cultures, the first results are available within 6–24 hours using the EAWAG technique. EAWAG has taken out patent protection on this invention and is looking for a manufacturer for the new instrument. Since the components are already being used in other applications, no costly development is required. The marketing potential worldwide is enormous. Along with drinking water management, the EAWAG method is also interesting for mineral water manufacturers.

EAWAG

RUMBA: Promoting Sustainability

In 1999 the Swiss Federal Parliament decided to introduce RUMBA Resource and Environmental Management in all federal administration, including the ETH domain. Under the guidance of the appointed EAWAG environmental manager, Herbert Güttinger, this four-year project is coming to a close. Already since April 2003 RUMBA is in use at EAWAG. The project involved the formulation of a new environmental policy, adaptation of management procedures, allocation of responsibilities and the definition of targets. EAWAG is attempting to reduce the consumption of non-renewable energy by 80 % in the period between 1990 and 2025. A large step has been made towards achieving this target with the decision to construct a new building, Forum Chriesbach, a “MinergieP” House.
The final project report “RUMBA and the ETH domain” (only in German) and further information can be obtained from www.ethrat.ch (link Environment Management) and www.umwelt.eawag.ch.

The construction of “Forum Chriesbach” is advancing

Following the laying of the foundation stone in October of last year, on 2 June 2005 the topping-out ceremony was held for the new EAWAG building “Forum Chriesbach”. The building, to house around 120 EAWAG staff, sets new benchmarks for sustainable development and will be completed in 2006. In the foundation stone were placed architectural designs, a daily newspaper, an EAWAG Annual Report, a microsensor for the detection of arsenic in water, as well as a water sample from the Greifen Lake from 16 August 1999 (the day of the great whitefish kill) for later generations to find.

EAWAG

Swiss Fishery Advisory Office FIBER opened

Since July 2004, the Swiss Fishery Advisory Office (FIBER) is active to answer the needs of fishermen. This office continues the valuable information platform for all matters concerning fish and waters established during the “Fishnet” project. FIBER is the outcome of a collaboration between EAWAG, FOEFL and the Swiss Fisheries Association (SFA). Susanne Haertel-Borer and Guy Périat are managing the advisory office located at EAWAG in Kastanienbaum.
www.fischereiberatung.ch