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Sun and Climate

Editorial

Man's early ancestors were wise enough not to call themselves *homo sapiens.* They were also wise enough not to exploit their habitat to an extent which could cause the climate to change. But the change occurred all the same: droughts entailed the jungles to retreat, leaving wide-open space for savannas. In order to survive in such radically different surroundings, the hominids had to adapt their behaviour appropriately. They were successful: they were able to propagate all over the Earth.

Much later, their descendents coined the term *homo sapiens,* the wise man, for themselves. They were wise enough to invent machines that burn huge amounts of fossil fuel. They did so to such an extent that the Earth's atmosphere increasingly became a greenhouse: letting the warmth of the Sun enter but not radiate back to space. The wise man has got now the chance to prove his wisdom adapting his behaviour appropriately.

Scientific research must have the goal of augmenting collective wisdom. Climate research is needed to increase our knowledge of the properties of that thin layer around Earth where life can exist. But the term *wisdom* is appropriate only if knowledge turns into action, with a full awareness of responsibility.

The present issue of *Spatium* is devoted to a general overview of the Earth's climate system, with special emphasis on the role of the Sun, because it is by far the most important forcing factor of the climate system. Since the Industrial Revolution some 150 years ago, however, the anthropogenic influence can no longer be neglected. Climate research provides the knowledge required for mankind to act in awareness of responsibility towards its future generations.

We are very grateful to Dr. Jürg Beer, head of the Radioactive Tracers Group at the Swiss Federal Institute for Environmental Science and Technology in Dübendorf (ZH) for his kind permission to publish herewith a summary of his fascinating lecture on climate research given at our association's meeting in late autumn 2000.

Hansjörg Schlaepfer
Bern, November 2001

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Sun-set over the Thyrrenian Sea.
(Photo: H. Schlaepfer)

Sun and Climate *)

Jürg Beer, Swiss Federal Institute for Environmental Science and Technology (EAWAG)

Introduction: Setting the Scene

The Sun is by far the most important driving force of the Earth's climate system. However, only little is known how variably this force acts on time scales ranging from minutes to millennia and how the climate system reacts to changes in this forcing.

In the core of the Sun nuclear fusion processes generate energy, which is then transported towards the solar surface. The total solar radiation that arrives at the top of the Earth's atmosphere depends on several factors: the energy production in the core of the Sun, the energy transport through the Sun's radiative and convective zone, the emission of radiation from the photosphere and the distance between Sun and Earth.

Satellite-based measurements over the past two decades have revealed a clear correlation between the solar irradiance and the 11-year sunspot cycle. The observed changes in total solar irradiance between solar maximum and solar minimum of an 11-year cycle amount to about 0.1% (annual average). This is too small a change to significantly affect the climate. However, there is growing evidence that, on longer time scales, solar variability is much more pronounced and the climate system is much more sensitive to solar forcing due to feedback mechanisms.

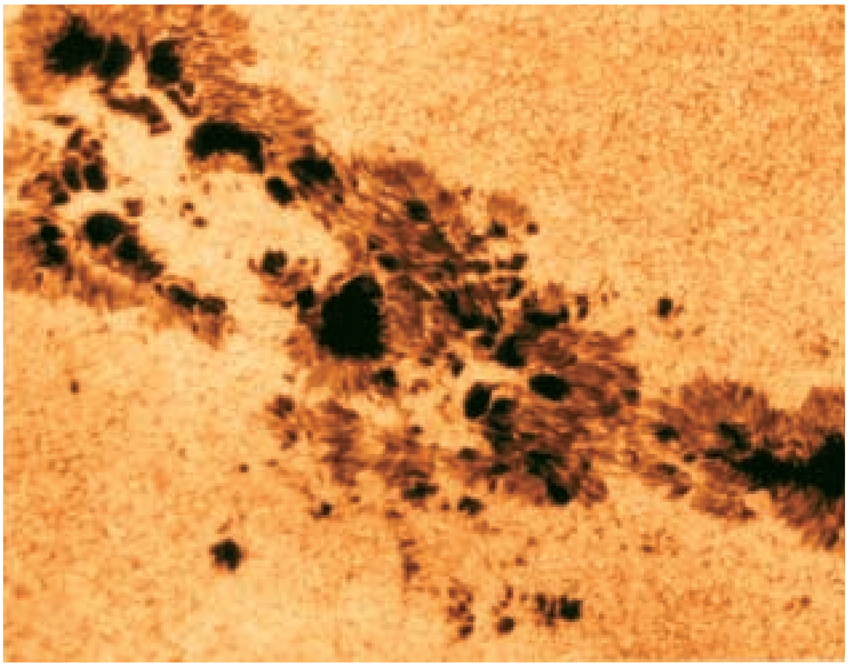

Figure 1
Sunspots represent areas where dense magnetic flux tubes cross the solar surface. As a consequence of the intense magnetic fields, the local convective heat transport is reduced and the surface temperature lowered by 1,000 to 2,000 K. In spite of the still very high temperatures of ca. 4,000 K, a sunspot looks dark compared to the temperature of 6,000 K of the surrounding area. The number of spots waxes and wanes with a periodicity of about 11 years (Schwabe cycle).

The response of the climate system to changes in solar forcing depends not only on the intensity of the radiation, but also on its spectral composition, seasonal distribution over the globe and on feedback mechanisms connected with clouds, atmospheric water vapour, ice cover, atmospheric and oceanic transport of heat and other terrestrial processes. It is therefore impossible to establish a simple quantitative relationship between reconstructed climate changes in the past and reconstructed solar variability. There is, however, growing evidence that periods of low solar activity coincide with the advance of glaciers, changes in lake levels and other significant environmental changes. These findings indicate that the Sun played an active role in past climate changes in concert with other geophysical climate forcing factors such as volcanic eruptions, greenhouse gases and internal variability of the climate system.

To study the climate in the past one has to rely on archives. The last few hundred years are quite well documented. The sunspots recorded by many observers tell us about solar activity and meteorological stations provide information about local air temperatures.

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*) Pro ISSI lecture, Bern, October 31st, 2000

Unfortunately, these stations are not equally distributed around the globe. This instrumental time span, however, is too short to document slow climate changes and does not allow us to study the underlying long-term processes. We need archives that record climate changes over much longer periods of time. Glaciers and polar ice caps are especially promising types of archives which were formed from snowfalls over very long periods of time (up to several hundred thousand years). Snow scavenges a variety of solid and liquid constituents from the atmosphere, which are subsequently stored in the ice in chronological order and can later be retrieved and analysed by use of sophisticated techniques.

The present issue of Spatium is devoted to the topics of solar forcing, the Earth's climate and to some aspects of how information is retrieved from ice cores. However, a complete overview on all aspects of climate change would by far exceed the scope of this small booklet. The interested reader is referred to the following sources:

- PAGES (Past Global Changes) Programme, jointly sponsored by the United States and the Swiss National Science Foundation (http://www.pages-igbp.org.)

- R. von Steiger, Das neue Bild der Sonne (1998), Spatium Nr. 2.

- Hoyt, D. V. and K. H. Schatten (1997): The Role of the Sun in Climate Change. New York, Oxford University Press.

The Sun: Our Daytime Star

On the one hand, our Sun is simply an ordinary star, one of more than 100 billion in our galaxy. On the other hand, it is a very special star for us because it is by far the closest (8 light minutes compared to 4 light years). In comparison to the planet Earth, several of the Sun's properties are quite impressive. Its diameter of 1,390,000 km is more than 100 times the Earth's diameter, its mass equals more than 300,000 times the Earth's mass and its surface temperature equals 5,800 K. The conditions in the Sun's core (the inner 25% of its radius) are extreme compared to the conditions on Earth. The temperature is 16 million Kelvin and the pressure is 250 billion atmospheres. These are the conditions required to maintain the present energy production, which makes the Sun shine.

The Sun is by far the largest object in the solar system. It contains more than 99.8% of the total mass of the Solar System, and Jupiter contains most of the rest. At present, the Sun consists of about 92.1% hydrogen and 7.8% helium by number of atoms; other heavier elements such as metals only make up for 0.1%. This composition changes slowly over time as the Sun converts hydrogen to helium in a giant nuclear power plant in its core. Every second, about 700 million tons of hydrogen are converted to about 696 million tons of helium. This means that 4.3 million tons of mass are converted into energy every second, generating a power of $3.86 \cdot 10^{26}$ Watt. This power travels from the core towards the surface of the Sun in the form of radiation (radiative zone). On its way it is continuously absorbed and re-emitted at increasingly lower temperatures. Having reached about $^{2}/_{3}$ of the solar radius the gas is too cool and hence too opaque for radiation to pass, so convection sets in. In the adjacent convection zone, energy is transported by hot material rising to the surface and cool material sinking to the bottom, forming huge convection currents.

Overall, it is a long way. It takes the radiation several million years to work its way out from the core to the solar surface (photosphere). From the surface, the power is radiated into space. If this total power reached the Earth it would take only 10 seconds to evaporate all the water stored in the oceans and the ice caps on Earth! In reality, only about 1 part per billion reaches the Earth. All the same, the amount of solar energy that arrives on the surface of the Earth every hour is greater than the total amount of energy that the world's population consumes in a whole year. The radiation emitted is primarily visible light. This is no coincidence: during the hundreds of millions of years of the evolution the spectral sensitivity of our eyes has been perfectly matched to that part of the sunlight's spectrum which contains most of the energy.

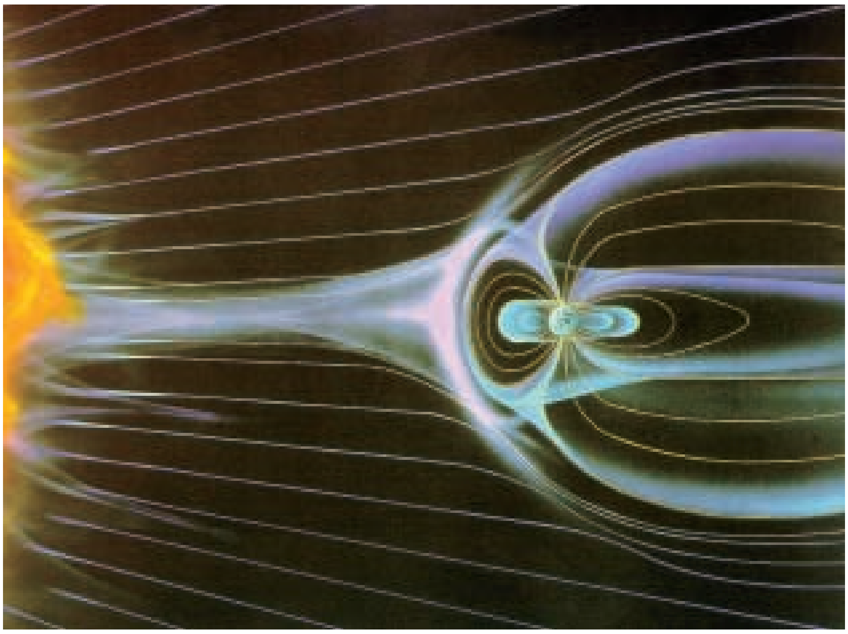

Figure 2
In this cartoon the Sun's atmosphere continually expands from the left into interplanetary space. The flow of ionised gas, called solar wind, carries frozen-in magnetic fields from the Sun into space. When sweeping by the Earth, it deforms the geomagnetic field. Explosive eruptions lead to sudden "space storms" which can seriously affect the Earth. The solar wind fills a space larger than 100 times the distance from Sun to Earth. The magnetic field deflects the charged cosmic ray particles. Therefore, the cosmic ray flux is reduced considerably within the solar system during periods of high solar activity. (Credit: ESA).

The radiating surface of the Sun, called photosphere, is a very thin layer of only a few hundred kilometres with a temperature of about 5,800 K. In a more or less regular rhythm of 11 years, the golden face of the Sun is disgraced by dark spots: the famous sunspots **(Figure 1)**. Sunspots are caused by dense magnetic flux tubes that cross the solar surface and hinder the convective heat transport to the surface. Therefore, sunspots are "cool" regions, with temperatures of only 4,000 K. They look dark in comparison with the surrounding areas. Sunspots can grow very large, up to 100,000 km in diameter.

The outermost region of the solar atmosphere, the corona, extends into space for millions of kilometres. However, the beautiful crown of the Sun is visible to the naked eye of the observer only during an eclipse.

The Sun's magnetic field is very strong compared to the geomagnetic field and also very complicated. The magnetosphere extends well beyond the outermost planet Pluto and plays an important role in shielding the Earth's surface from high-energy cosmic rays, which, otherwise, would endanger life on Earth **(Figure 2)**.

Apart from heat and light, the Sun also emits a low-density stream of charged particles (mostly electrons and protons) called solar wind, which spreads throughout the solar system with a speed of several hundred kilometres per second. The solar wind and the much higher energy particles ejected by solar flares can have dramatic effects on the Earth ranging from power line surges to the beautiful aurora phenomenon.

The Sun has a life cycle like a living creature. It was born out of cosmic dust about 4.5 billion years ago. Since then it has used up about half of the hydrogen in its core. It will continue to burn hydrogen for another 5 billion years or so (although its luminosity will approximately double in that time, see **Figure 3**). Eventually, it will run out of hydrogen fuel in the core and its life cycle will come to an end. This will set off a number of dramatic changes: The Sun will turn into a red giant by increasing its diameter beyond the Earth's orbit, swallowing all the inner planets and then creating a planetary nebula by throwing out part of its gaseous shells. This will be the termination of all life on Earth. Finally, it will collapse to a white dwarf and its light will extinguish.

Besides these large but very slow and steady changes over billions of years, the Sun also exhibits variability on much shorter time scales. After a period of large variability in its young age the Sun calmed down and became a relatively stable star, an important condition for the evolution of life on Earth. Nevertheless, the Sun is a variable star. Today, on time scales of millennia and shorter, fluctuations in the energy production in the core are extremely small (10^{-8}), and very small (10^{-6}) in the energy transport through the radiative zone (⅓ to ⅔ of the Sun's radius). In the convection zone, however, turbulence gives rise to fluctuations of up to percents on various time scales. Finally, the emission of radiation from the solar surface is given by the temperature of the photosphere, which is not homogeneous. Active magnetic regions (faculae) are warmer and sunspots are colder than the surrounding solar surface. On average, the faculae overcompensate the cooling effect of the sunspots leading to a slightly brighter Sun during periods of high activity. Periods of higher solar activities with many sunspots are followed by minima in an 11-year cycle. In addition, there are other variations with periodicities of approximately 90, 200 and possibly 2,000 years.

Sometimes, the Sun relaxes and becomes quiet for several decades or even a few centuries. The famous Maunder Minimum (1645–1715 AD) was such an event, a period during which hardly any sunspots were detected. It is interesting to note that the Maunder Minimum falls into a period characterised by generally lower temperatures and glacial advances known as the Little Ice Age.

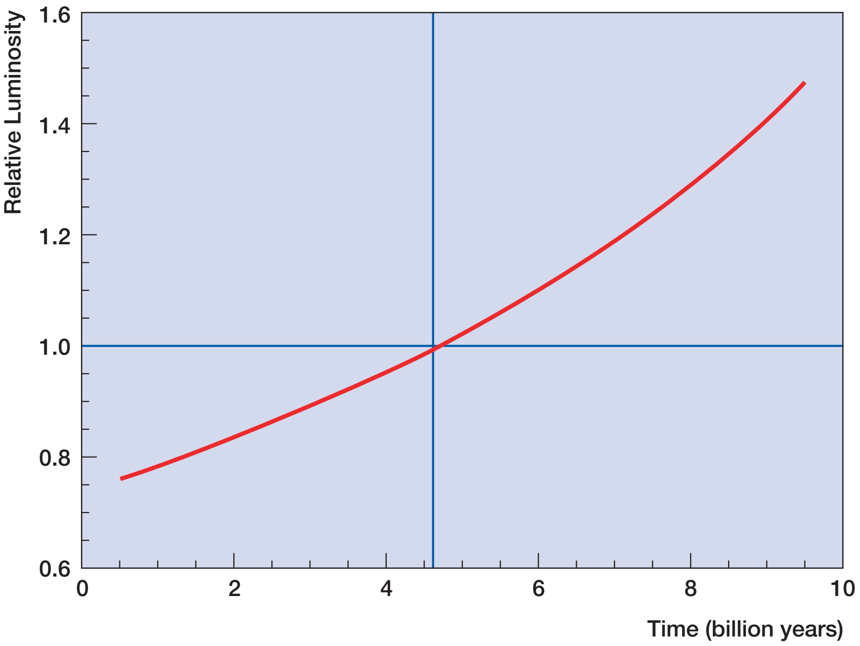

Figure 3
The standard solar model reveals that the solar luminosity (total solar energetic output) has continuously increased since the formation of the solar system 4.55 billion years ago and will continue to do so for another 5 billion years until most of the hydrogen in the core is burned to helium. This change is too slow to be relevant on time-scales of millennia. (Credit: W. Mende).

The Climate System: The Distributor and Equalizer of Energy on Earth

Following the laws of thermodynamics, the Earth's climate system seeks to redistribute the energy input from space equally: On top of the atmosphere, every square meter perpendicular to the axis Sun–Earth receives approx. 1,365 W of power from the Sun. This value is called the solar constant by tradition although we know that it is not constant over time. There are other sources of energy on Earth such as the tidal forces related to the Moon orbiting around the Earth or geothermal heat resulting from radioactive decay processes in the Earth's interior. However, their contribution is negligible in comparison to the solar input.

A very thin layer of only approximately $^{1}/_{1,000}$ of the Earth's diameter forms the stage on which the climate system acts. Basically, it consists of the atmosphere, the hydrosphere, the biosphere and the continents. For simple geometrical reasons the mean annual radiative input of the Sun is strongest in the equatorial regions, where the Sun is near the zenith and becomes lower at higher latitudes. This unequally distributed energy input leads to thermal gradients, which the climate system tries to level out by transporting energy from lower to higher latitudes. The energy is transported by wind, ocean circulation and water vapour. Instead of following a direct path to the poles, the transport follows a rather complex regime. This is due to several reasons: firstly, warm air masses are less dense and move upwards forming convection cells. Secondly the distribution of land and water and the physical topography affect the energy flow. Thirdly, the Coriolis force deflects air and water masses moving towards the poles to the right on the northern hemisphere and to the left on the southern hemisphere.

The first redistributor is the lower part of the *atmosphere,* the troposphere, where large wind systems are generated as a result of the different factors influencing the air masses moving north or south. The trade winds in the tropical zones, which played a key role at the time of the first *conquistadores* are probably the best known of these. The wind systems are the domain of meteorology dealing with cyclones and anticyclones, with air humidity and temperature eventually causing clouds and precipitation. The short term behaviour of all these quantities determines the daily weather. The long-term development of weather patterns defines the climate.

The second redistributor is the *hydrosphere,* which consists of the water in oceans, rivers and lakes, the ice in glaciers and polar ice caps, the vapour in the air, the droplets in clouds and the ground water. The thermal gradients induced by solar insolation cause the water to flow. Warm tropical waters flow pole-wards over the cooler deep-sea water. Evaporation increases the salinity of the water and thus its density. Cooling further increases the density of the water until it begins to sink to the bottom of the ocean from where it flows back, closing the loop. These processes generate the great streams on Earth such as the Gulf Stream in the northern Atlantic or the Humboldt Stream west of South America. The amount of water involved in the circulation system of the North Atlantic, which is an important part of the global oceanic conveyer belt, is equal to about 100 Amazon Rivers. Interruption of this conveyer belt would change the climate conditions in northern Europe dramatically. London would experience winters like Irkutsk in Siberia.

The third redistributor is the radiation, which is reflected, absorbed and emitted by the Earth's surface, by greenhouse gases and clouds in the atmosphere.

An astronaut travelling through the solar system will inevitably have his attention drawn to the blue planet, the Earth, which looks completely different from all the other planets. The main reason for this special appearance are the oceans and the clouds. The *biosphere* also plays an important role. In spite of the fact that it uses only a very small part of the solar energy input, the biosphere has e.g. produced all the oxygen present in the atmosphere. All the fossil fuel we are combusting within a few centuries is solar energy which was accumulated by the biosphere over millions of years. Presently, mankind lives primarily on solar energy delivered to Earth in the past.

Although, at first glance, the task of redistributing energy seems rather simple, this is not the case. In fact, the climate system is extremely complex. Everybody knows that forecasting the weather for more than a day is a challenging task. Even professional meteorologists who can rely on a dense global network of weather stations, satellites and most sophisticated computer models are unable to make reliable predictions for more than a few days. The reason for this is that the weather conditions are the result of a very large number of processes and their complex interaction on various time and length scales. Because the behaviour of the weather system is to some part chaotic even the most powerful computers will not be able to solve this problem in the future.

In the case of climate change, which we will discuss later on, the situation is less chaotic, but still very complex. This is illustrated by the fact that the best answer at present to the question of the response of the climate system to a doubling of the atmospheric CO_2 concentration is not a precise figure but a temperature range (2–5 °C). This as yet unsatisfactory answer can only be improved by a

Figure 4
The glacier near Grindelwald photographed in 1858 and 1974. (Credit: F. Martens, H.J. Zumbühl in Hydrologischer Atlas der Schweiz).

better understanding of the climate system. The clue to this lies in the past. Careful study of the climate changes in the past will allow us to identify the key processes and determine the response to changes in the forcing. Nature is generous enough to provide us with a variety of archives, which contain all the necessary information to reconstruct the history of the Earth's climate and the forcing. However, reading and deciphering this information is not always an easy task.

Climate Archives: The Diaries of Nature

For the last several centuries, reconstruction of the climate history is comparatively simple. Beside direct physical measurements, there is a wealth of information in written historical documents. Even paintings can be a useful source of climate information. Paintings and more recently, photographs of a glacier from the same site document very nicely how its size changes with time and how dramatic the present global warming is **(Figure 4)**. Another example is depicted in **Figure 5**, showing a market on the frozen River Thames in the winter 1813/1814. It is reported that such markets and other events took place on the Thames during winter quite regularly as from the 15th century, but never again after 1814.

For earlier times, ice itself serves as an archive. Glaciers in high mountains and ice sheets in the

Figure 5
Market on the River Thames in London in the year 1813/1814. Between 1400 and 1814 such markets were quite common. In the winter of 1683/1684 the ice reached a thickness of 26 cm and the river was completely frozen for 2 months.
Painting by Luke Clement. (Credit: Wetterbuch, Christian Verlag, 1982, ISBN 3-88472-080-5).

Figure 6
The extent of ice cover on Mt. Kilimanjaro (5,895 m) decreased by 81% between 1912 and 2000. In 1889, when Hans Meyer first climbed Kibo, the crater rim was nearly encircled by ice. Today only a small fraction of this ice remains. Clearly visible is the banding of the ice sheet associated with the annual cycles. In the background Mt. Meru. (Credit: Andri Schlaepfer).

polar zones store climate information for centuries to hundreds of millennia. They truthfully record the average climate conditions, levelling out the capricious moods of the weather. One example of such an archive is the glacier on Mt. Kilimanjaro **(Figure 6)**, which is of special interest since it stores climate information on the tropical zone. Unfortunately, this irreplaceable archive is melting away quickly due to the increasing mean temperature.

Precipitation in form of snow scavenges various constituents of the atmosphere and stores them chronologically, layer by layer. Increasing pressure from additional layers causes the snowflakes to compact and become ice. The consequence of this formation process is that the ice not only preserves all the atmospheric constituents such as aerosols and dust, it also contains air bubbles that enable scientists to determine the atmospheric composition and in particular the concentration of greenhouse gases in the past. This unique property makes ice the only archive that virtually stores all the climate forcing factors such as greenhouse gases, aerosols and volcanic dust and cosmogenic isotopes reflecting solar variability. Ice cores also contain information on the corresponding climate responses: temperature, precipitation rate, wind speed and atmospheric circulation. **(Figures 7** and **8)**.

Reading and deciphering the information nature stored in archives is, however, not a simple task. For example, the temperature signal is stored in the form of the oxygen isotope ratio $^{18}O/^{16}O$ in ice. The corresponding temperature can only be determined if this ratio can be measured with high precision and if the relationship between the $^{18}O/^{16}O$ ratio and the temperature is known. Solar variability, on the other hand, is recorded in the ice through solar wind induced modulation of the cosmic ray flux. Some high energetic cosmic ray particles travelling through our galaxy penetrate into the Earth's atmosphere where most of them collide with nitrogen or oxygen atoms. If these atoms are hit by fast travelling

Figure 7
View of a typical drill-site for shallow ice-cores up to 300 m length in Greenland. The building in the background is the former American radar station of Dye 3.

cosmic ray particles they can break up into smaller atoms, so called cosmogenic radioisotopes such as ^{10}Be. Opposite to stable isotopes, radioisotopes disappear by radioactive decay and are therefore very rare. Within a few half-lives they reach an equilibrium between production and decay. On Earth there is a total amount of only about 100 tons of ^{10}Be.

> ***Isotopes are atoms which are chemically identical but differ in mass due to a different number of neutrons in the nucleus.***

During periods of high solar activity there is a stronger solar wind. Magnetic fields carried by the solar wind deflect the cosmic ray particles more efficiently and hence reduce the production rate of cosmogenic isotopes in the atmosphere. These isotopes are removed from the atmosphere mainly by rain and snow and some of them are stored in ice caps and glaciers preserving information on the prevailing space weather conditions. Therefore, if we measure a reduced ^{10}Be concentration in an ice core we can conclude that less ^{10}Be was produced by cosmic rays. Such lower production rate indicates a stronger shielding of the cosmic rays induced by more intense solar wind, which, in itself, is the result of increased solar activity.

This relationship between the concentration of the Beryllium isotope ^{10}Be in a Greenland ice core and the sunspot number as a proxy of solar activity can be seen in **Figure 9**. More specifically, the analysis of the cosmogenic isotopes ^{10}Be and ^{36}Cl in ice and ^{14}C

Figure 8
Deep-drilling (2,000 to 3,000 metres) is performed underground and takes about 2 to 3 years (Summer seasons). The drill is lowered into the borehole, drills a core of about 2,5 m length and is then brought up to the surface again. The picture shows how the ice-core is taken out of the drill. The liquid is used to prevent the borehole from closing.

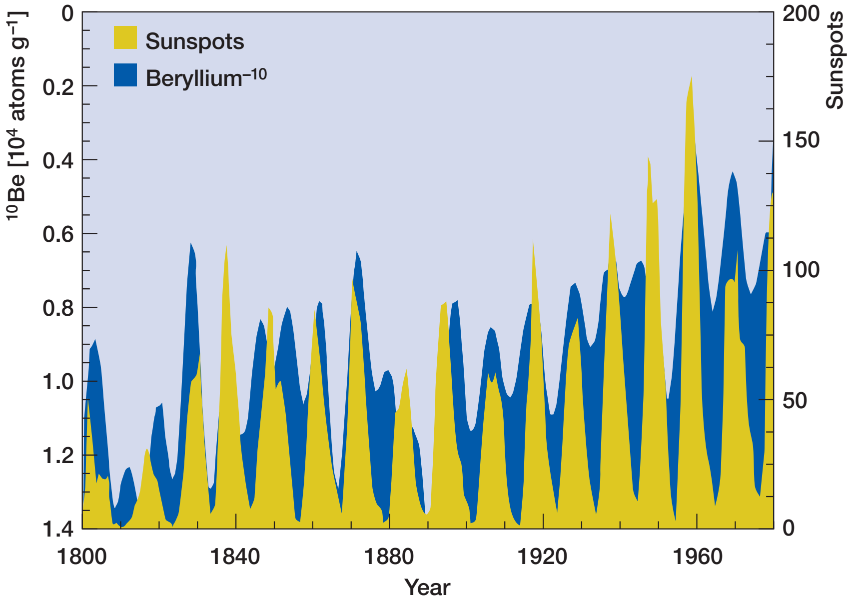

Figure 9
Comparison between the observed mean annual number of sunspots with the concentration of ^{10}Be atoms in the ice-core from Dye 3 (Figure 7). A large number of sunspots correspond to higher solar activity, more solar wind, fewer cosmic rays, lower production rates of ^{10}Be and therefore a lower ^{10}Be concentration. Both records show a clear 11-year Schwabe cycle and a long-term trend interrupted by short periods of reduced solar activity around 1815 and 1900.

in tree rings reveals not only that solar variability is partly cyclic with periodicities around 11, 90, 200 years and possibly longer ones, but also that the beginning of extended periods of low solar activity, so called grand minima, often coincide with rapid climate changes. This points to a relationship between solar activity and climate.

Combining the information from ice with additional information from other archives such as lake and sea sediments, loess deposits, peat bogs, tree rings, corals, speleothems and others provides a much more complete picture of how the climate system behaved in the past and which were the driving forces.

Accelerator Mass Spectrometry: Unravelling the Secrets of Cosmogenic Isotopes in Ice Cores

Since the late seventies, there has been great progress in the analytical techniques used to read the information stored in archives. An increasing number of additional parameters can be measured and the analytical sensitivity has improved significantly. This is especially true in the case of cosmogenic isotopes, which can now be measured by so-called Accelerator Mass Spectrometers (AMS). The Swiss Federal Institute of Technology of Zurich (ETHZ) was among the first laboratories in Europe to operate such an instrument.

Mass spectrometers are complex technical systems designed to separate and measure atoms with different masses. In a conventional mass spectrometer the material is ionised and then accelerated by a high voltage. The accelerated ions are formed to a beam by electrical and/or magnetic lenses. A magnet separates the ions into different beams depending on their masses. In the case of cosmogenic isotopes (^{14}C, ^{10}Be, ^{36}Cl) we are faced with extremely small numbers of atoms, which even further decrease with time due to radioactive decay. For example, the ^{14}C/^{12}C ratio in our body is about $12 \cdot 10^{-13}$, in the body of the ice man it is about $6 \cdot 10^{-13}$ and in the body of a Neanderthal man it is as low as 10^{-15}. Measuring such small ratios exceeds the capability of conventional mass spectrometers due to background problems caused by isobars (^{14}N in the case of ^{14}C) and molecules (e.g. ^{13}CH). A great step forward was the development of the Accelerator Mass Spectrometer (see **Figure 10**), which works along the same principle as a conventional mass spectrometer, but accelerates the ions to approximately 1,000 times higher energies. At these energies the molecules are destroyed and every single ion reaching the detector can be identified and counted individually. The power of this analytical technique is best illustrated by a simple comparison. The task of determining the ^{10}Be concentration in 1 kg of ice is comparable to measuring the ink concentration in 1 litre of water from lake Constance after putting a small drop (3 microliters) of ink into the lake and allowing it to mix completely!

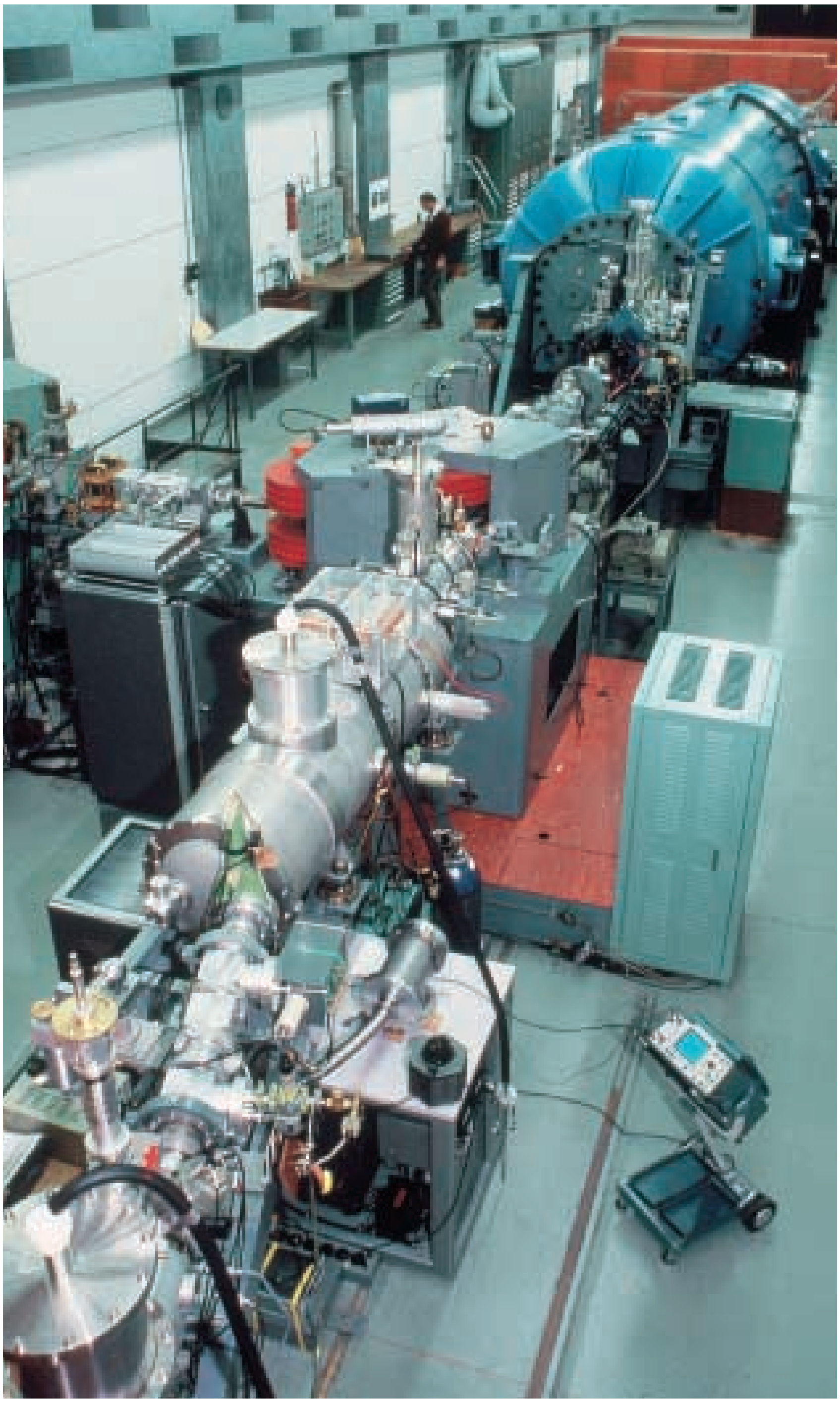

Figure 10

View of the accelerator mass spectrometer of ETH/PSI, which is used to measure the ^{10}Be concentration in ice. The central part of this instrument is the tandem accelerator (blue tank in upper right corner), which accelerates the Beryllium ions to very high energies (20 MeV). This is necessary to analyse ice samples of 1 kg containing as few as 10 million ^{10}Be atoms.

Climate Change: The Story of Perpetual Change

Newspapers and scientific journals tell us the story of the present climate change, the global warming. Ice cores and other archives tell us the story of the climate in the past. It is a story of perpetual change:

20,000 years ago: The world looked completely different. Sea levels were lower by some 100 m. Large parts of Switzerland were covered by ice. Glaciers carved the landscape and transported huge rocks over hundreds of kilometres found today as erratic blocks.

5,000 years ago: A young man tried to cross the mountains from Italy to Austria. He died at an altitude of about 3,200 m and was buried under snow and ice for more than 5000 years. In the year 1991, his tomb of ice was opened due to global warming and his body was discovered by hikers.

2,000 years ago: The Romans expanded their empire and conquered part of England. Thanks to favourable climatic conditions they were even able to produce wine on the British isle.

1000–1300: The Vikings took advantage of the favourable climate conditions to explore the sea in the north and west. On a big island in the north, Erik the Red

settled down with a group of people and lived well on agriculture and keeping cattle. They called this island Greenland.
Gothic churches were constructed all over Europe. Culture flourished on a global scale.

1400–1850: The weather became worse. Sea ice severed the connection to Greenland. The cattle died. Greenland turned from a green to an icy island.
In Switzerland, the glaciers advanced considerably. They covered areas where there had been forest **(Figure 4)**. Since then, they are generally retreating.

Today: Mankind is concerned about the ongoing rapid global warming.

These are just a few examples to illustrate that the climate system never reached stable conditions for long periods of time. In other words: the climate has always been variable. What are the causes of this variability? We can distinguish between external and internal factors with respect to the planet Earth.

Potential External Factors: Forcing the Climate

Since the Sun is the dominant source of energy on Earth it is also the main candidate for introducing variability in the climate system. First, we will consider sources of variability of the Sun itself. Then we will discuss how the Earth's orbit around the Sun is perturbed by the gravitational forces of the other planets and how this affects insolation.

Climate Change and Solar Forcing: The Solar Connection

On time scales of solar evolution, reliable models show that, compared to today, solar luminosity was lower by approximately 30% shortly after the formation of the solar system and has increased slowly but steadily over the past 4.5 billion years **(Figure 3)**. As mentioned earlier, there may be fluctuations in the transport of heat from the core of the Sun towards its surface, in particular in the convection zone where, like in boiling water, hot gas bubbles rise quickly to higher levels while cooler gas sinks down to be reheated. This turbulent boiling creates a characteristic pattern of granulation on the surface. Fluctuations in the heat transport cause changes in the solar luminosity.

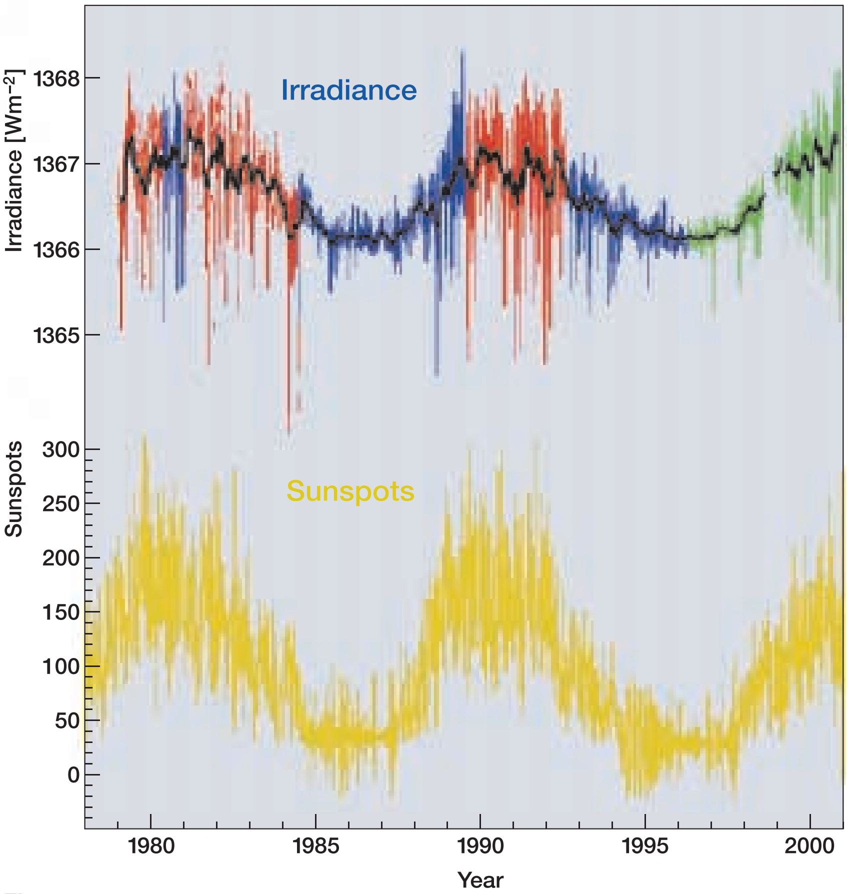

Figure 11
Comparison of the solar irradiance with the sunspot numbers for the last two Schwabe cycles. The irradiance record is a compilation of data from different satellites. During periods of high solar activity there are more sunspots, darkening a small part of the solar disk (visible in the negative excursions of the irradiance). However, the brightness of the Sun is increased at the same time, overcompensating the darkening effect of the sunspots. (Irradiance data: credit: C. Fröhlich, PMOD).

On very short time scales, information on the inconstancy of solar forcing comes from different sources:

Since 1978, direct measurements of the total solar irradiance are made by satellites equipped with radiometers. They show a relatively small amplitude of total solar irradiance of about 0.1% within one 11-y cycle **(Figure 11)**. Unfortunately, at present, these measurements cannot tell us how much the solar constant changes over decades to centuries. However, from the climate point of view, centuries and millennia are the more important time scales.

Luminosity: Total power emitted by the Sun.

Irradiance: Total power arriving at the top of the atmosphere in the distance of 1 astronomical unit (average distance between Sun and Earth)

Since, for obvious reasons, nobody wants to wait for decades to millennia to learn more about the long-term behaviour of the Sun, a complementary project was initiated to simultaneously study a large number of sun-like stars (stars with properties very similar to the Sun). A monitoring program of this kind began 3 decades ago. The results obtained to date from sun-like stars indicate a potential for much larger solar variations than those observed by satellites over the short time period of 20 years.

Theoretical considerations suggest that, as a general rule, slow changes in solar variability tend to have larger amplitudes than fast changes. Variability on time scales up to 20,000 years seems possible. Moreover, the climate system generally reacts more sensitively to slow changes than to fast changes. Building up an ice sheet, for example, takes a long time.

The so-called Little Ice Age (approx. 1400–1850) is characterised by generally lower solar activity compared to today. During this time there were several periods with very low activity. During the Maunder Minimum (1645–1715) hardly any sunspots were observed in spite of the continuous efforts of several researchers directing their newly invented telescopes towards the Sun. Since approx. 1700, the solar activity has steadily increased and was only interrupted by some weak minima around 1815 and 1890 **(Figure 9)**. From **Figure 11** we know that an increase in solar activity results in an increase in solar irradiance. If this relationship, which was only established for the last two decades, also holds true for longer periods of time, we have a tool in hand to estimate solar irradiance in the past. Using sunspot numbers or ^{10}Be data from ice cores we can reconstruct the history of solar activity, which in turn reflects the solar irradiance. This postulated relationship can be tested by comparing the solar forcing signal (^{10}Be) with the climate response (temperature). In fact, **Figure 12** shows that high ^{10}Be concentrations (low solar activity) in an ice core from Dye 3, Greenland, **(Figure 7)** coincide with cold temperatures (reduced irradiance). It has been estimated that the solar constant was reduced during the Maunder Minimum by about 2.5‰ compared to today. This could account for most of the observed cooling. ^{14}C data from tree rings and ^{10}Be data from ice cores show that during the past 10,000 years a number of such minima in solar activity occurred. Many of them can be related to climate deteriorations, which suggests a solar connection. A good example is the market on River Thames mentioned earlier, which took place in the winter 1813/1814, precisely at the onset of such a solar minimum **(Figure 12)**.

When it comes to the question of the mechanisms responsible for the observed climate changes, no final answers are yet available. Beside the most important changes in the total irradiance, which induce a variety of feedback and amplification processes there are other mechanisms which may also play an important role. For example, the relative change of ultraviolet radiation during a solar cycle is much larger than the change of total radiation. Since the ultraviolet component of the spectrum is responsible for the production of ozone in the stratosphere, considerable effects on the stratospheric chemistry and dynamics can be expected.

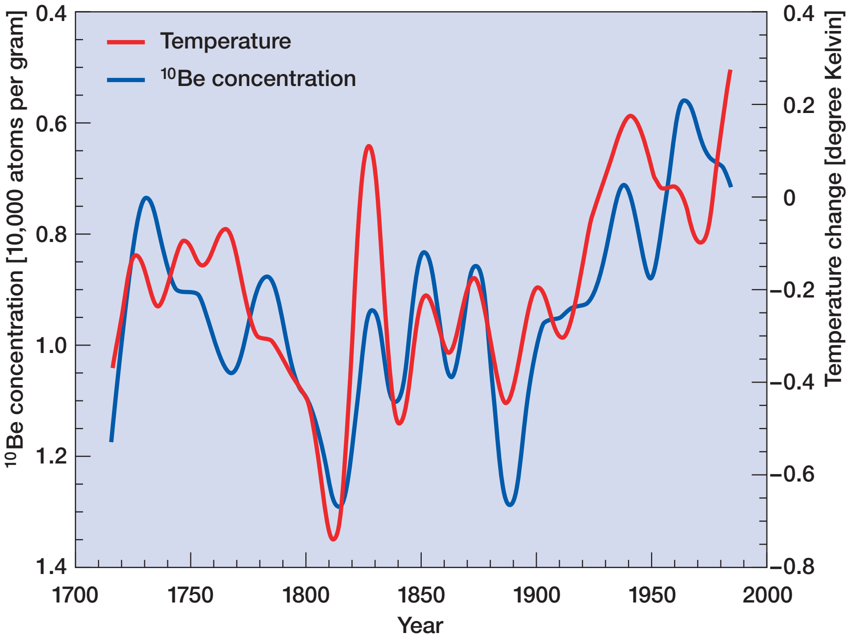

Figure 12
Comparison of the ^{10}Be concentration measured in an ice core from Dye 3 (Figure 7) reflecting the solar activity with a reconstruction of the northern hemispheric temperature. Both records were filtered to only show changes on time scales longer than 20 years. Note the solar minima (high ^{10}Be concentrations) around 1815 and 1890 which coincide with cold periods (Figure 5) and the rapid temperature increase during the first half of the 20th century.

Model results point to changes in tropospheric winds and storm tracks resulting from realistic variations in stratospheric ozone and solar ultraviolet radiation.

Finally, several authors have postulated indirect ways of how the Sun can affect the climate. For example, the interaction of cosmic ray particles with the atmosphere induces strong electrical currents, which may to some extent affect climatically important processes such as the condensation of water vapour and the formation of clouds. Although very speculative and controversial, these examples illustrate that we are far from understanding all the processes relevant for climate changes.

Climate Change and Variations in the Earth's Orbit: The Astronomical Connection

The Earth travels once a year around the Sun in an orbit, which, although elliptical in shape, is actually almost circular. At present, the deviation between the elliptical orbit and a perfect circle (the so-called eccentricity) is small, and the resulting maximum difference in the Sun-Earth distance between July 4th, when the Earth is farthest from the Sun (aphelion, 151.2 million kilometres) and January 4th, when it is closest (perihelion, 146.2 million kilometres) amounts to only 3%. However, averaged over a full year, the total radiation received by the Earth travelling along its present elliptic orbit differs only slightly from what it would receive if its orbit were circular (0.05 W m^{-2}). The effect of the small change in distance is too small to cause the seasons. But if one compares the total amount of solar radiation received by one hemisphere during summer and winter, it becomes obvious that this small discrepancy does exert a remarkable influence on the severity of the seasons. At present, the Northern Hemisphere is experiencing slightly cooler summers and warmer winters, while in the Southern Hemisphere, seasonality is, in contrast, somewhat amplified.

The seasons are the result of the tilt of the Earth's axis (the obliquity) relative to its plane of travel around the Sun (23°). Summer prevails on the hemisphere facing towards the Sun, whereas on the hemisphere facing away from the Sun, the days are generally shorter and colder. If the tilt were zero there would be no seasons. A larger tilt angle, on the other hand, would cause more extreme seasonality, with warmer summers and colder winters.

But the situation described above is not stable. The eccentricity, obliquity and the date of the perihelion all change slowly with time. These secular changes in the Earth's orbit are caused by the gravitational forces of the other bodies in the solar system. The relative positions of Jupiter and Saturn, especially, affect the eccentricity and the obliquity of the Earth's orbit. The effects on the orbital parameters are quasi-periodic because they consist of several components.

Eccentricity: This parameter changes with periodicities of 100,000 and 400,000 years. This effect influences the smallest and largest Sun–Earth distances. The greater the eccentricity, the larger the hemispheric asymmetry. In **Figure 13** the eccentricity is plotted for the past 400,000 and the coming 100,000 years. It was at its maximum 200,000 years ago, and is now declining towards a 400,000-year minimum, which will be reached in about 30,000 years. The eccentricity is the only orbital effect, which affects the annual global average of incident solar radiation. This global effect, however, is very small (a maximum of 0.6 Wm^{-2} in the daily mean or 2.4 Wm^{-2} for the solar constant), and cannot therefore be responsible for the observed 100,000-year periodicity in many paleoclimate records.

Obliquity: Gravitational forces cause the obliquity of the Earth's orbit to oscillate between 22° and 25°, with a periodicity of 41,000 years. The larger the obliquity, the greater the seasonal temperature variation at high latitudes.

Precession: The Earth's axis does not point in a fixed direction. Like a spinning top, which starts to gyrate around the vertical axis if you give it a nudge, the Earth's axis spins around, describing a large circle in the sky. The 'Polar Star' to which the axis now points will therefore be quite distant from the pole in a few thousand years. The cause of this precession, as it is called, is the equatorial bulge of the Earth. This bulge is formed by the Earth's rotation, which changes its shape from a perfect sphere to a slightly flattened one. The gravitational attraction of the Moon, the Sun and the planets on the bulge acts as the "nudge" which causes the Earth to precess like a spinning top.

As a consequence of the precession of the Earth, the perihelion and aphelion do not always occur at the same date each year, but instead move slowly through the seasons with a periodicity of about 23,000 years. This means that 11,500 years from now the perihelion will occur on July 4th, and seasonal temperature variations in the Northern Hemisphere will be larger than at present (colder winters, warmer summers), because the Earth will then be closest to the Sun during the Northern Hemisphere summer.

$\delta^{18}O$

relative deviation of the $\frac{^{18}O}{^{16}O}$ ratio of a sample from the $\frac{^{18}O}{^{16}O}$ ratio measured in present ocean water.

The last two orbital effects do not affect the total amount of the solar radiation received by the Earth, they only affect its geographical distribution. The variation of the obliquity spreads the radiation symmetrically polewards, while the precession controls its asymmetric distribution over the hemispheres.

The $\delta^{18}O$ data measured in deep sea sediments show a very distinct 100,000 year cycle of glacial and interglacial periods in phase with the eccentricity **(Figure 13)**. This seems to be in conflict with the weakness of the direct forcing. However, the importance of the eccentricity lies not in the change in the amount of the total radiation, but in its coupling with the precession. As matter of fact, the larger the eccentricity of the Earth's orbit, the greater the amplitude of the precessional variation. That means that the precessional amplitudes of the insolation at any given location on the Earth depend very much on the instantaneous degree of eccentricity. Hence, the eccentricity period is reflected in the amplitudes of the precessional effects (amplitude modulation of the precession by the eccentricity).

For example in Berne, the difference in insolation between July 4th and January 4th has changed considerably with time. 80,000 years ago it was 425 $W\,m^{-2}$. Then it decreased by 85 Wm^{-2} to a minimum of 340 Wm^{-2} 65,000 years ago. After having attained a maximum of 410 Wm^{-2} about 60,000 years ago, it then decreased by 55 Wm^{-2} to reach another minimum of 355 Wm^{-2} 23,000 years ago, which coincides with the maximum of the last glaciation. This was followed by a rapid increase of 68 Wm^{-2} at the transition from the last Glacial to the Holocene, 11,000 years ago. Since then, the seasonal difference has been decreasing to its present value of about 365 Wm^{-2}. As already discussed, it will rise again to a new maximum within the next 11,500 years. However, for the next 50,000 years the seasonal difference will never again rise by more than 30 Wm^{-2} due to the declining eccentricity. Also, the two other orbital forcings reach a minimum in the next 30,000 years. This means that we must expect only small changes in the global climate due to orbital forcing during this time.

The uneven distribution of sea and land between the two hemispheres is important for the climatic response to changes in solar radiation. Therefore, a change in the hemispheric distribution of radiation can have a net effect on the global mean temperature. Processes, such as the melting and ablation of glaciers and the growth of plants, that are more sensitive to summer than to winter temperatures can accumulate the seasonal effects over thousands of years.

It was Milutin Milankovich who, 60 years ago, postulated that periodic variations in the Earth's orbital parameters affect the local insolation and could be the clue for some of the most prominent climate changes during the past million years.

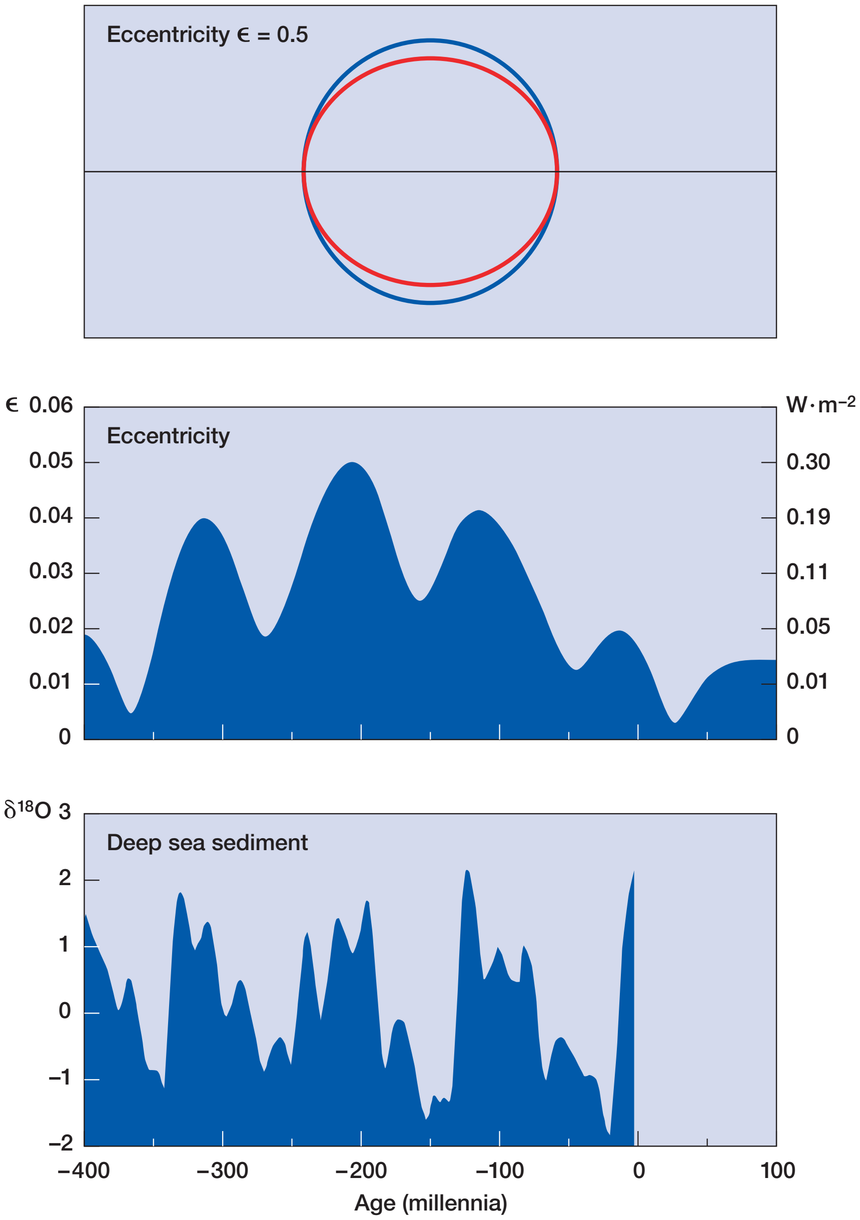

Figure 13
The analysis of the isotopic $^{16}O/^{18}O$ ratio in foraminifera (skeleton of plankton) stored in ocean sediments provides a means of reconstructing the sequence of glacial and interglacial periods (Bottom panel). Large values correspond to warm periods and vice versa. This sequence is dominated by a 100,000-year cycle but also shows shorter periodicities. It can be explained by the effects of the near-by planets on the orbit of the Earth (Milankovich theory). Small deviations from a circular orbit (eccentricity) (top panel) occur regularly with a dominant 100,000-year cycle. The middle panel shows the calculated changes of the eccentricity for the past 400,000 and the next 100,000 years. Note that the dramatic climate effects observed on Earth are due to very small deviations from the average annual forcing. (Lower panel: Credit: SPECMAP curve).

Climate Change and Internal Forcing: The Terrestrial Connection

A great variety of internal factors affect the Earth's climate system and its reaction to the solar input. It is beyond the scope of this short overview to mention all of them. Instead, a limited selection of some important parameters are presented below:

For many years, climatologists have observed a connection between large explosive *volcanic eruptions* and short-term climatic change. For example, one of the coldest years in the last two centuries was the year following the Tambora volcanic eruption in 1815. Explosive volcanic eruptions have been shown to have a short-term cooling effect on the atmosphere if they eject large quantities of sulphur dioxide and fine-grained dust into the stratosphere forming an opaque compound with water vapour. The coarse-grained dust returns to the Earth's surface within a few months and hence has little impact on the climate.

Continents slowly move over time. Their drift not only changes the direction of the large ocean currents but also the position of Antarctica. This large continent collects enormous amounts of water in form of ice, thereby changing the sea levels on a global scale. This in itself influences the amount of water transported by the winds. Higher humidity in the air masses tends to increase the cloud cover and the Earth albedo, thereby contributing to an increased scatter of sunlight back into space and hence causing a reduction of atmospheric temperature.

Greenhouse gases such as CO_2 allow the visible sunlight to enter the atmosphere and be absorbed by the land and sea surface, but they hinder the thermal (infrared) radiation that is emitted by the Earth's surface from escaping into space. Increasing density of greenhouse gases cause the climate to become warmer. The tropical rain forests bind huge amounts of carbon to build up their biomass. When it is burnt in the process of deforestation this carbon is released in form of CO_2, which contributes to the greenhouse effect **(Figure 14)**. As a result of industrialisation, a large part of the solar energy which had been accumulated as biomass over millions of years is now released within a few centuries by combustion of oil, coal and gas.

> ***"…whereas all experiences are of the past, all decisions are about the future… it is the great task of human knowledge to bridge this gap and find those patterns in the past which can be projected into the future as realistic images…"***
>
> K. Boulding 1973

Epilogue

4.5 billion years ago, when the solar system was formed, Earth and possibly also Mars were the only planets with an appropriate distance to the Sun to become habitable. Since then, the Earth's climate has varied all the time. In spite of this dramatic variability at times, it always remained within the boundaries of habitability and never turned into a hot-house like Venus nor into a snowball like Mars. Most of this variability is related to the main source of energy, the Sun. Even in ancient times, people intuitively recognised the importance of the Sun and worshipped it. Stable and favourable climate conditions brought wealth and prosperity, unstable and unfavourable conditions such as droughts and floods caused famines, forced people to migrate to other places and sometimes even caused wars. Understanding the climate and forecasting changes was always an important issue so that people who were able to make reliable predictions were highly respected. Today our knowledge of how the climate system works is much advanced compared to those times. Our observation systems and computing capabilities allow us to collect huge amounts of data and to model the complex processes in the climate system. However, we are still far from understanding it in detail. The most promising strategy to improve our understanding is to study past and present climate changes in parallel. Obviously, studying past changes is more difficult.

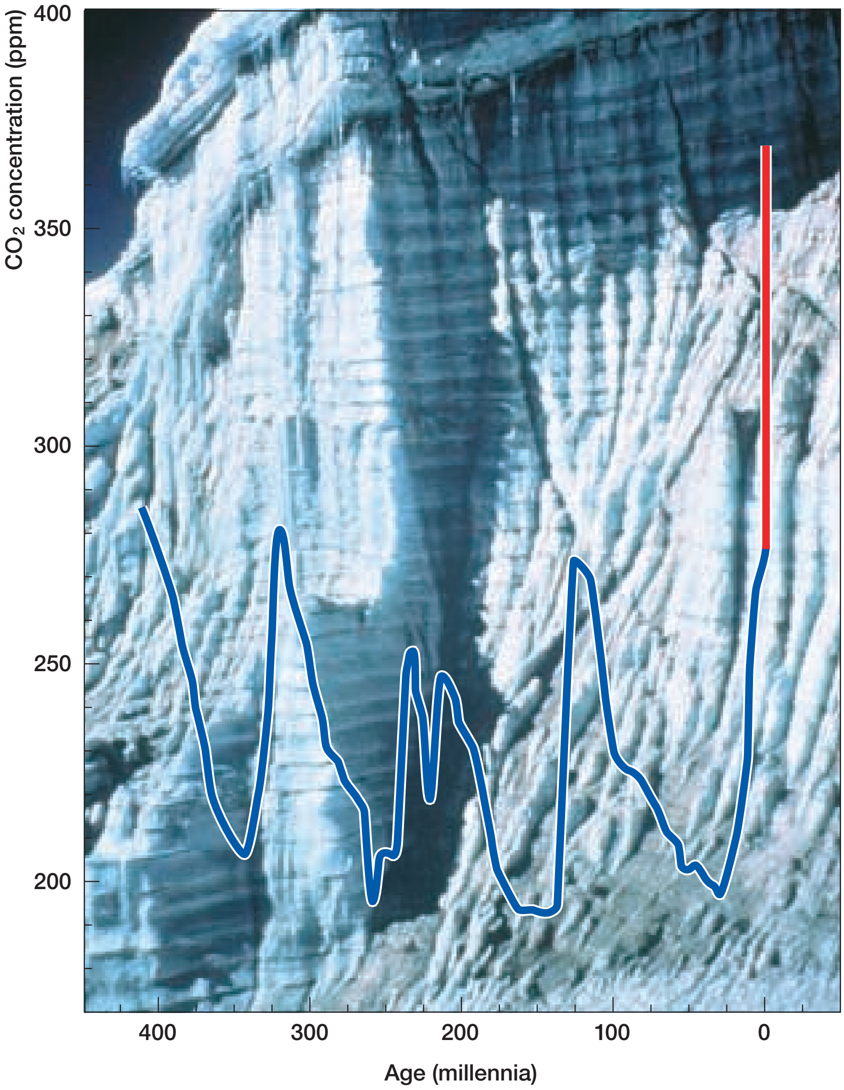

Figure 14
Global CO$_2$ concentration in parts per million (ppm) measured in air bubbles occluded in the Vostok ice core from Antarctica (blue line, credit: Nature 399: 429–436). The red line shows the man made increase in CO$_2$ since 1750 based on an ice core (Siple station, Antarctica, 1750–1953, credit: Nature 315, 45–47) and direct atmospheric measurements from Mauna Loa, Hawaii, 1959 to present, credit: http://cdiac.esd.ornl.gov). As a result of the global warming the glacier in the background (Quelccaya, Andes) no longer exists. (Photo: L. Thompson, Science 203: 1240–43).

Fortunately, nature built its own archives and kept track of most changes. We just have to find these archives, read and interpret the stored information and put together the individual pieces to have a complete picture of the temporal and spatial changes in the past. Without looking back into the deep past it will be impossible to estimate the anthropogenic and solar contribution to the present climate change and make reliable predictions about the future.

Looking back into the past is particularly important in the context of the controversial debate about the role man plays in the present global warming.

It is only about a century ago that mankind began to significantly interact with nature and perform a global experiment by increasing the atmospheric greenhouse gas concentrations to levels never experienced in the past half million years **(Figure 14).** In view of our still very limited understanding of how nature works and our responsibility for future generations we should think twice before performing such blind and uncontrolled experiments. Many species have been extinguished before. Up to today, Homo Sapiens is the first with the potential to cause his own extinction.

Acknowledgments

This article was written in close contact with several colleagues. The numerous scientific discussions with W. Mende who contributed many ideas were particularly useful and enjoyable. The conversations with H.J. Schlaepfer who handled all the editorial aspects with great experience and patience were very stimulating. The comments of R. Muscheler and M. Vonmoos and the careful linguistic corrections by C. Wedema improved the manuscript considerably.

SPATIUM

The author

Jürg Beer grew up in Gerlafingen in the Swiss midlands. He finished school with a "type A Matura" including Latin and Greek in Solothurn. In spite of this classical education, Jürg Beer was always interested in natural sciences, mainly in experimental and theoretical physics. In 1968 he registered at the University of Berne to study physics, mathematics and astronomy. He joined the group of Prof. Oeschger where he became familiar with low level counting techniques used to study environmental processes and reconstruct climate changes in the past. The development of a new and extremely sensitive analytical technique in 1977, the Accelerator Mass Spectrometry (AMS), opened up a large variety of new applications. Cosmogenic nuclides could now be measured virtually everywhere in the environment. This was the beginning of a very fruitful collaboration with the group of Prof. Woelfli at the nuclear physics department of the ETH in Zürich. Supported by the Swiss National Science Foundation, ETH and PSI and following the design of M. Suter and G. Bonani, the Tandem accelerator of the ETH developed into one of the world's leading AMS facilities. Jürg Beer took advantage of this unique opportunity and started to explore potential applications of cosmogenic radionuclides (mainly ^{10}Be and ^{36}Cl) in various natural archives such as polar ice cores and Chinese loess deposits.

In 1987, Prof. Imboden set up the department of environmental physics located at the Swiss Federal Institute of Environmental Science and Technology (EAWAG) in Dübendorf. Jürg Beer became the leader of the group "Radioactive Tracers" and extended his research activities. Since then, his group concentrates mainly on the analysis of the GRIP ice core from central Greenland and works on the reconstruction of the geomagnetic field, the solar activity and its influence on climate change. From 1994 to 1995 he spent a year at the High Altitude Observatory of the National Centre of Atmospheric Research (NCAR) in Boulder, USA to expand his knowledge of solar physics.

Jürg Beer is convinced that the key to understanding present and future climate changes lies in the past. He often sees himself in the role of a detective seeking for natural archives to collect all available traces of the mechanisms responsible for environmental changes. These traces are often partly erased and written in hieroglyphs, which can only be deciphered by the joint efforts of scientists from different fields.

Jürg Beer lives with his family near Zürich. His interest in nature is not restricted to his professional work. During his free time he enjoys hiking, biking and watching the beauties of nature.