# 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].

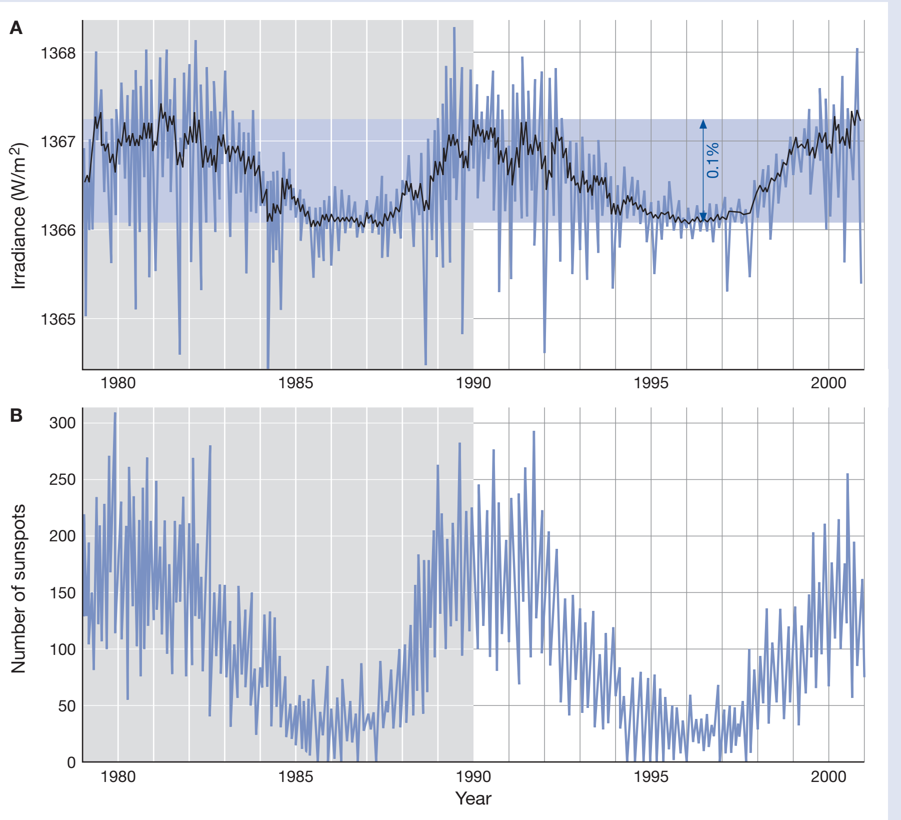


**Fig. 1: Irradiance measured by satellites since 1978 (A) [1] compared to sunspot counts (B) in the same period [4].**

## 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

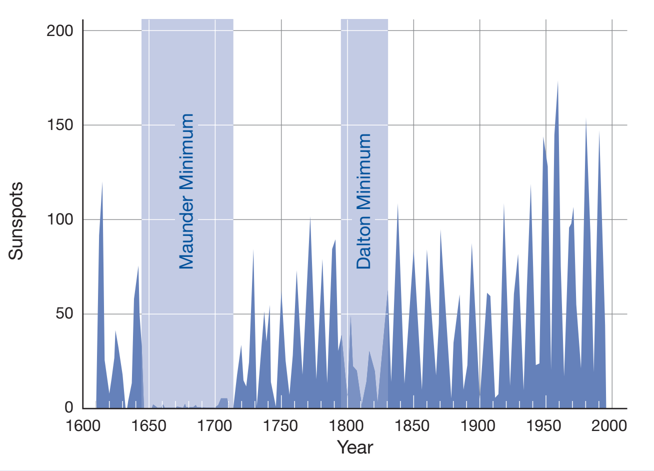


**Fig. 2: The sunspot count since 1610 [4], given as an annual average. The more active the sun, the more sunspots appear on its surface. Along with the clear 11-year cycle an increasing activity since the beginning of the 18th century can be observed.**

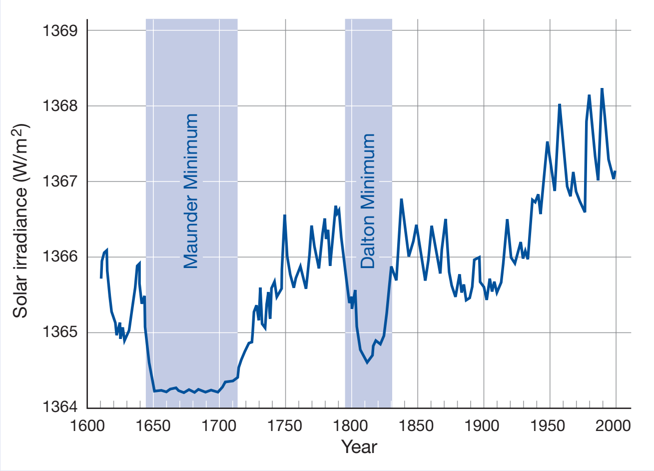


**Fig. 3: Irradiance reconstructed back to 1610. The reconstruction is based on sunspot drawings and observations of stars similar to the sun. Accordingly, irradiance has increased by 0.24% since the Maunder Minimum. Adapted from [2].**

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".**

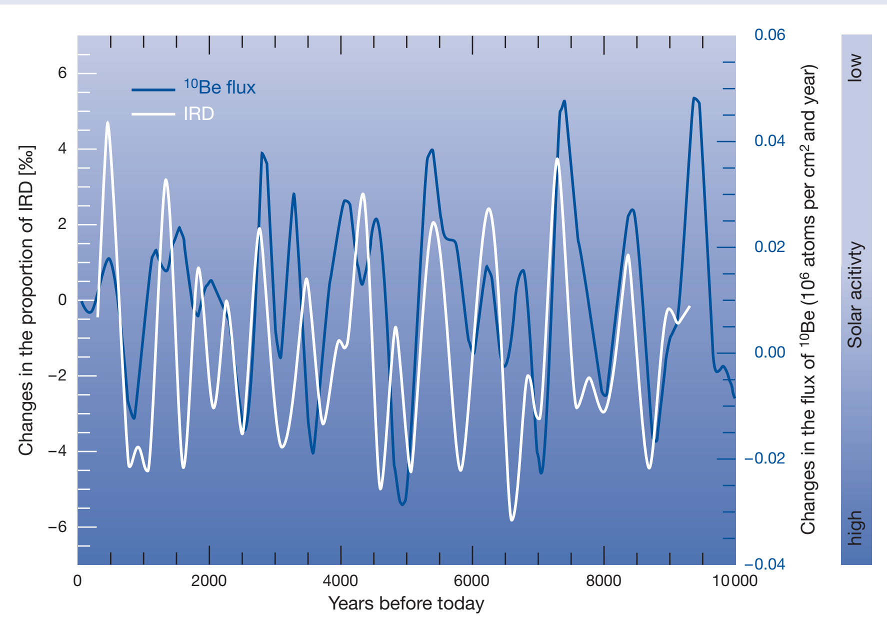


**Fig. 4: Changes in the $^{10}Be$ flux in the GRIP ice core (blue curve) and changes in the IRD proportion in the sediment (white curve). Simplified from [3].**


[1] Fröhlich C. (2000): Observations of irradiance variations. Space Science Reviews *94,* 15–24.

[2] Lean J., Beer J., Bradley R. (1995): Reconstruction of solar irradiance since 1610: implications for climate change. Geophysical Research Letters *22,* 3195–3198.

[3] Bond G., Kromer B., Beer J., Muscheler R., Evans M.N., Showers W., Hoffmann S., Lotti-Bond R., Hajdas I., Bonani G. (2001): Persistent Solar Influence on North Atlantic Climate During the Holocene. Science *294,* 2130–2136.

[4] Hoyt D.V., Schatten K.H. (1998): Group sunspot numbers: a new solar activity reconstruction. Solar Physics *179,* 189–219.