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

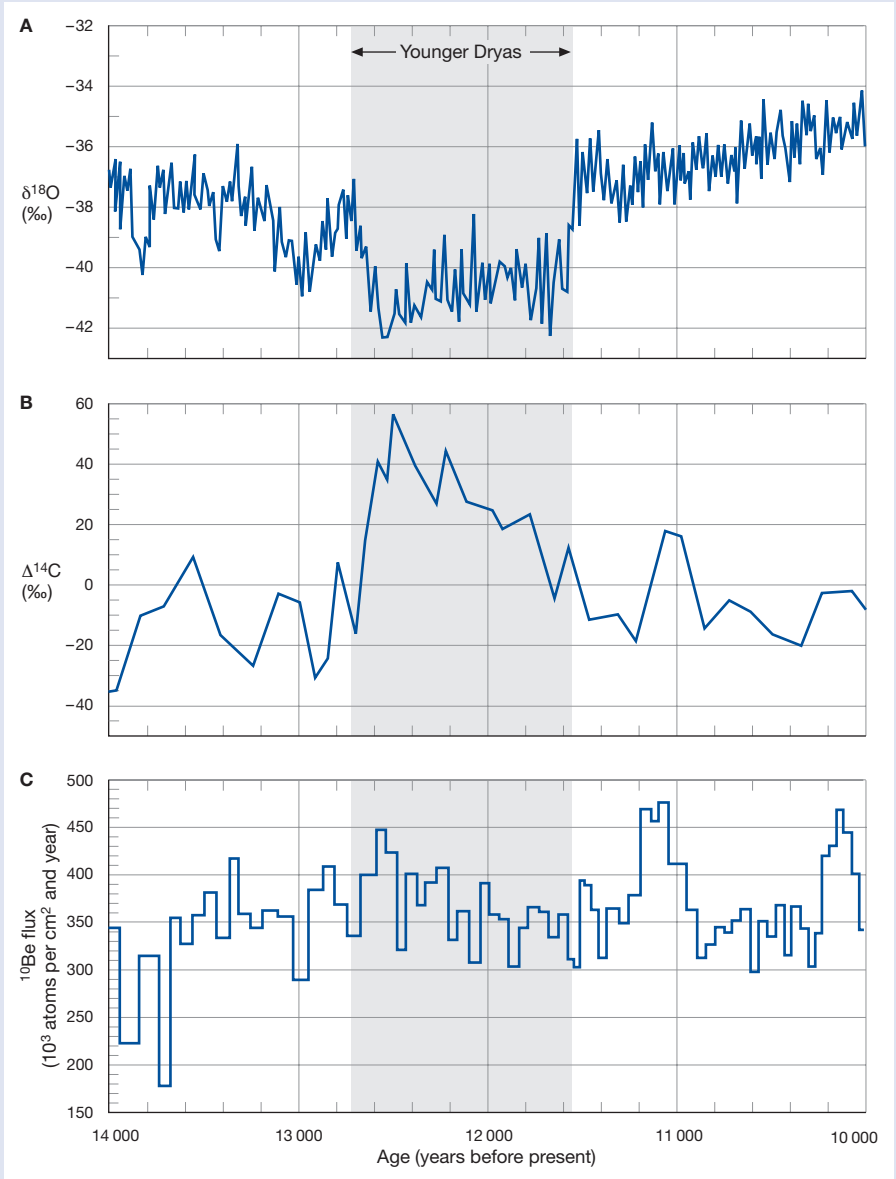

Fig. 1: Temperature, atmospheric ^{14}C concentration and ^{10}Be flux during the Younger Dryas.
A) $\delta^{18}O$ as a measure of the temperature in Greenland (see also lead article).
B) Reconstruction of the atmospheric ^{14}C concentration expressed as $\Delta^{14}C$ based on the sediment investigations 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.

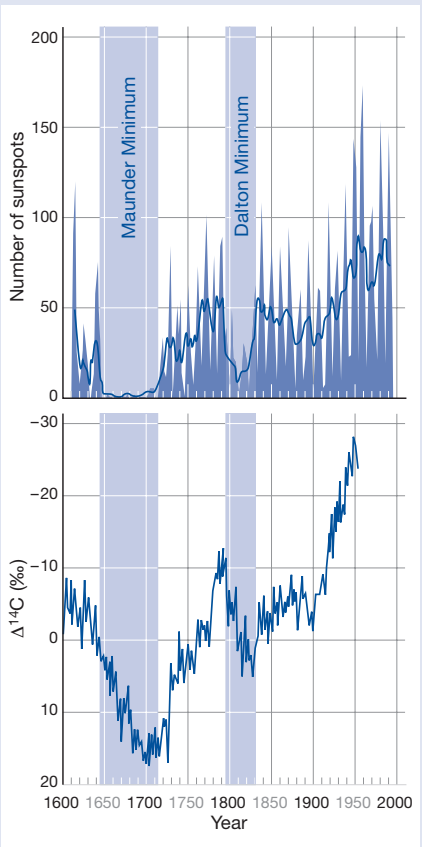

Fig. 2: Comparison of the number of sunspot groups with the changes in atmospheric ^{14}C concentration. In phases of reduced solar activity, such as during the Maunder and Dalton Minima, the atmospheric ^{14}C concentration increased ($\Delta^{14}C$ is shown inverted).

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.

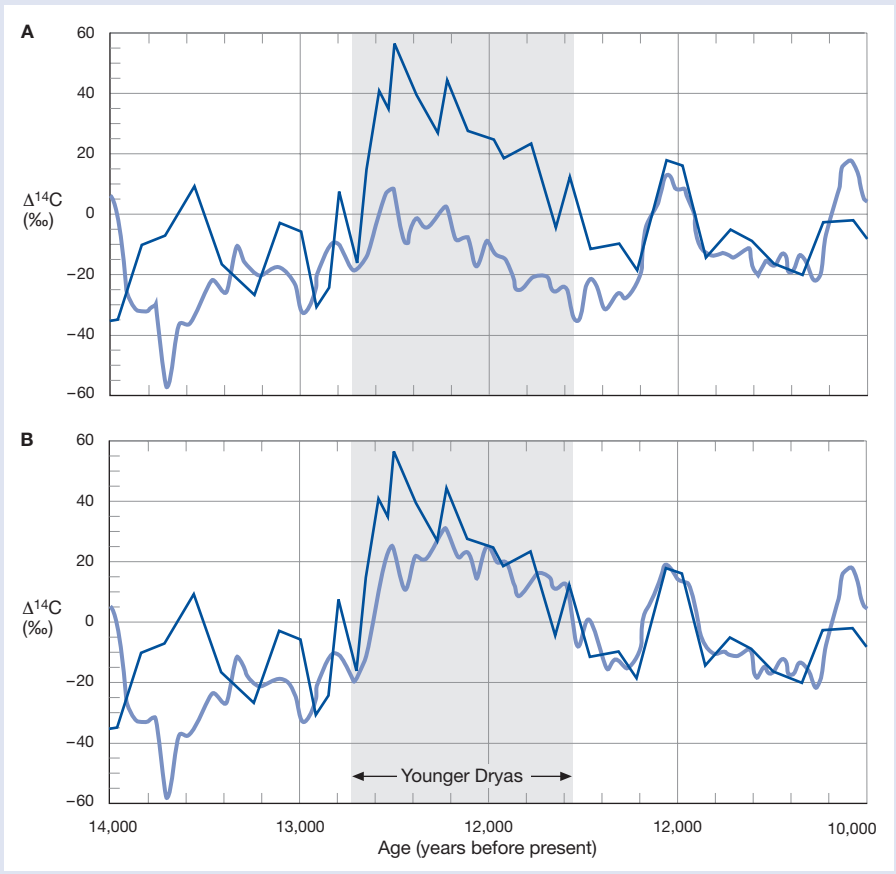

Fig. 3: Model of the atmospheric ^{14}C concentration (light-blue curves):
A) taking only into account radionuclide production,
B) taking into account both radionuclide production and ocean circulation.
For comparison the actual reconstructed ^{14}C concentration is again represented (dark-blue curve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