the other hand, years of negative NAO are characterized by colder and drier winters. It appears that these lakes are located at a sensitive climatic boundary, where just a few degrees warming during the winter (+NAO) results in a considerably shortened period of snow cover, even to the point where no persistent snow cover forms (Vehviläinen & Lohvansuu, 1991; Vehviläinen & Huttunen, 1997). As a consequence, the peak discharge in spring is severely reduced, catchment erosion is significantly lower and less allochthonous mineral matter is transported and deposited on the lake bottom. One period of weakened spring discharge and erosion has been identified from Finnish varved sediments to have occurred between AD 980-1250 (Saarinen et al., 2001, Tiljander et al., in press). This period coincides with the Medieval Climate Anomaly. Its climate implications are under intensive investigation.

However, due to local system dynamics, it is evident that the relationships between external forcing factors and the annual accumulation of mineral/organic matter are neither linear nor stable over time. Post-isolation catchment stabilization, vegetation succession, human disturbance and extreme events like forest fires exert a considerable influence on catchment erosion and the nature of the varved records. At the end of the day, the properties of clastic-organic varves in Fennoscandia reflect the annual flux of mineral matter to the sedimentary basins via a multitude of interacting factors. The main aim of future work is to use a variety of analytical methods, such as high-resolution digital image analysis (e.g. Tiljander et al., 2002, Ojala & Francus, 2002, Saarinen & Pettersson, 2002), mineral magnetism (Snowball et al., 1999), pollen, and charcoal analysis to discriminate

between the major factors that drive the sedimentation.

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¹⁴C as an Indicator of Solar Variability

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Introduction

The quasi-constant concentration of ¹⁴C on the Earth is maintained by a balance between its radioactive decay and its production from atmospheric nitrogen. This production is possible due to the high-energy protons from cosmic radiation. Atoms of ¹⁴C enter the biogeochemical cycle, where carbon circulates between the atmosphere, terrestrial biosphere and the oceans. Since the characteristic exchange rates between reservoirs and times of circulation within individual reservoirs are significant with respect to the half-life of ¹⁴C, radiocarbon concentration on the Earth is not uniform, being the highest in the atmosphere and distinctly lower in the deep oceans.

Charged particles emitted from the Sun produce a magnetic field in interplanetary space. This field inhibits penetration of low-energy cosmic-ray protons into the center of the solar system. As a rule, an increase in solar activity corre-

Figure 1: Comparison of radiocarbon production rate (Q/Q_0) and records of solar activity in recent centuries.

sponds to a decrease in the flux of galactic cosmic rays impinging on the Earth. The intensity of cosmic radiation in the atmosphere is also modulated by the Earth's magnetic field. To first-order approximation, the globally averaged ¹⁴C production rate is inversely proportional to the square root of the geomagnetic dipole moment (Lal, 1988).

Reconstruction of Atmospheric ¹⁴C Levels in the Past

Past variations in atmospheric ¹⁴C concentration have been reconstructed as a "by-product" of radiocarbon calibration. During the Holocene period, this calibration is based on ¹⁴C ages of bi-decadal or decadal tree-ring samples, dated absolutely by means of dendro-

Figure 2: Estimate of Sun-induced fluctuations in ^{14}C production rate over the last 10,000 years. Right-hand side: Frequency distribution of bidecadal production rate averages. The sunspot number scale is based on the correlation in recent centuries.

chronology (Stuiver et al., 1998). These data document $\pm 20\%$ fluctuations in atmospheric $\Delta^{14}\text{C}$, usually 100-300 years long, superimposed on an almost monotonic downward trend from ca. 120‰ at the beginning of the Holocene to ca. 0‰ at the end of the 19th century.

Over the last few centuries, ^{14}C concentration has also been measured in single-year tree-ring samples (e.g. Stuiver and Braziunas, 1993). These data reveal quasi-periodic $\Delta^{14}\text{C}$ fluctuations with an amplitude as low as 2.5‰.

The Relationship Between ^{14}C Production and Solar Activity in Recent Centuries

As noted above, there is a more direct relationship between solar activity and the rate of ^{14}C production than ^{14}C concentration. Fluctuations in ^{14}C concentration can be caused by changes in ^{14}C production; this may also reflect solar and/or geomagnetic variability, as well as changes in the global carbon cycle. In general, no single one of these causes can be isolated from the others unless additional information is available. Such information is provided by records of ^{10}Be in the ice caps of Greenland and Antarctica. Like radiocarbon, ^{10}Be is produced in the atmosphere by cosmic rays, however it falls out almost immediately, hence its concentration in sediments reflects mostly local cosmogenic production rates. Fine correlation between 100- to 300-year-long features of the ^{14}C and ^{10}Be records of the last and earlier millennia indicate that these features are related to Sun-induced changes in production rate

(e.g. Bard et al., 1997). On the other hand, model considerations using archeomagnetic data lead to the conclusion that the long-term decrease in $\Delta^{14}\text{C}$ results from secular changes in the geomagnetic field (Stuiver et al., 1991).

In historical records, solar activity is quantitatively represented by the number of sunspots (Wolf number). Although correlation between sunspot number and past ^{14}C changes has been discussed in numerous papers, only a few have directly compared sunspot number with ^{14}C production rate (e.g. Stuiver and Quay, 1980). This correlation is presented here (Fig. 1). ^{14}C production rates are calculated from annual values of ^{14}C concentrations (Stuiver and Braziunas, 1993) with the PANDORA model of the global carbon cycle (used, for example, by Goslar et al., 2001).

The maximum ^{14}C production rate in the last millennium occurred between AD 1645 and 1715, during the period when sunspots were almost lacking (Maunder Minimum).

Figure 3: Shapes of Maunder-type (red), Spörer-type (blue) and Wolf-type (black) maxima in ^{14}C production rate during the Holocene.

Similar maxima, between AD 1290-1390, 1400-1600, and 1800-1860 are known as Wolf, Spörer and Dalton, respectively. Since the nineteenth century, atmospheric radiocarbon concentration has been seriously affected by fossil fuel combustion and nuclear tests. The first effect can be taken into account in the calculations, based on the known history of fossil fuel consumption. The second effect precludes model calculations of ^{14}C production after 1950.

Production of cosmogenic isotopes depends on both the Earth's and the Sun's magnetic field. It can be expressed as:

$$Q = C * A_{\text{geo}} * A_{\text{sol}}$$

where C denotes the production rate by cosmic rays not attenuated by solar and geomagnetic fields, and A_{geo} and A_{sol} are the respective attenuation factors. The latter geomagnetic factor has been modeled using a reconstruction of the Earth's magnetic field, as in previous studies (e.g. Goslar, 2001).

There is a striking correlation between mean sunspot number in consecutive sunspot cycles (S) and average values of ^{14}C production (Q). Although annual values of ^{14}C production also correlate significantly with annual sunspot number, the single-year Q-S regression coefficient is distinctly lower than that for cycle averages. One reason for this is that annual values of Q are different in different minima of solar activity, despite very similar minimum sunspot numbers (i.e. close to 0). This means that solar activity expressed by the sunspot number is not unequivocally related to ^{14}C production. Indeed, it has been known for some time that sunspots are not directly tied to the magnetic properties of the solar wind. A more direct measure of solar magnetic field properties is provided by Aa indices, which reflect the magnitude of short-term magnetic activity measured in two antipodal laboratories. Both sunspot number and Aa index reveal an 11-year cycle but, unlike sunspots, the minimum Aa differs for

different cycles and the minimum values appear correlative to the cycle-averages of sunspot numbers (Fig. 1). Nevertheless, since reconstruction of $\Delta^{14}\text{C}$ in the Holocene relies on bidecadal data, in using it as a proxy of solar activity, the relationship between Q and S cycle-averages still seems applicable.

Characteristic Features of ^{14}C Production in the Holocene

The $\Delta^{14}\text{C}$ record in the Holocene allows the ^{14}C production rate to be calculated provided the parameters of the global carbon cycle are known. In previous studies (e.g. Stuiver and Braziunas, 1988), it has usually been assumed that those parameters were constant and the same as today. The record of past ^{14}C production rates calculated according to this assumption shows 100- to 300-year-long fluctuations superimposed on a long-term trend. Assuming that this trend re-

flects the changes in geomagnetic field, Sun-induced changes of the ^{14}C production were calculated (Fig. 2).

The distribution of Q/Qo values has no right-hand tail (i.e. almost no value exceeds 130%). This is consistent with equation 1, which requires that the attenuation not be larger than 1 (as it was, for example, during the Maunder Minimum). This consistency provides additional support for the interpretation of the obtained record in terms of past solar activity.

Stuiver and Braziunas (1988) noted distinct similarities between fluctuations in ^{14}C production, and distinguished nine Maunder-type and eight Spörer-type maxima. Calculations using up-to-date ^{14}C calibration data (Stuiver et al., 1998) suggest that some maxima, previously qualified as Maunder, are distinctly shorter (Fig. 3). Since this group includes the Wolf maxi-

mum (AD 1290-1390), we propose referring to these shorter events as Wolf-type.

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Reconstruction of Low- and High-Frequency Summer Temperature Changes From a Tree-Ring Archive of Fennoscandian Forest-Limit Scots Pine

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Material and its Ecogeographical Setting

Tree-ring samples of Scots pine (*Pinus sylvestris* L.) were collected from living trees, dead standing logs, old buildings, and subfossil wood from peat-bogs and small lakes (Eronen et al., 2002).

The selected dataset containing 1081 tree-ring series. The latter archive is the major source of samples.

The area is situated between 68° and 70° N, 20° and 30° E, in the northern Fennoscandia (Fig. 1). Homogeneity of tree-ring data over the geographical distribution was demonstrated (Lindholm, 1996). Highly consistent tree-ring chronologies may be built from diverse sites as well as from various age-classes of pine trees (Lindholm et al., 2000; Lindholm et al., submitted).

Figure 1: Sampling sites in northernmost Fennoscandia, with national coordinates. Present pine-limit is marked with a broken line.

Chronology Temporal Ranges

At present, the northern Finnish supra-long pine chronology spans from 5520 BC to AD 2001 (Eronen et al., 2002). As dendrochronological cross-dating yields annual

resolution to tree-ring data, inter-annual-to-decadal scale variability is resolved by most methods of building chronologies. Variation at the multi-centennial time-scale has recently been successfully extracted from the northern data using specified techniques in signal extraction (Helama et al., 2002). Annual accuracy of dendrochronological dating is a prerequisite for several paleoclimate examinations, including quantitative multi-disciplinary comparisons, multi-proxy reconstructions and climate forcing studies (e.g. Ogurtsov et al., 2002). The further extension of this chronology may become possible given that there is a gap between the time of arrival of pine, as indicated by pollen analysis, and the beginning of the earliest tree ring series (Eronen et al., 2002). On the other hand, possibly conditions for