

Lake sediments as climate archives

Lakes accumulate sediments continually, a process that has been ongoing since their formation, in many cases for several thousand years or even longer. The sediment consists of biological remains from the lake itself and its surroundings, as well as soil particles and other non-biological material originating from the lake catchment and also the atmosphere. Hence, the sediment sequence in each lake is a continuous environmental archive, which contains information about the history of the lake and its surroundings.

Getting sediments out of the lake

Lakes are a common landscape feature, particularly in formerly glaciated regions. They are geographically widely distributed, covering large climatic gradients from warmer low-land to colder high-mountain sites. As a consequence, a high density of archives in different climatic settings can be found and

analysed. Numerous coring techniques for retrieving lake sediment cores have been developed, taking into account the properties of the different sediment types, but as well as logistical constraints. Lakes that are covered by ice during winter are often cored from the ice surface, which provides a stable coring and working platform. However, coring from floats and boats is also possible.

Widely applied corers are so-called gravity corers, where essentially a core tube is lowered into the sediment to retrieve a sediment sequence. Sediment corers can be both rope and rod operated. An alternative to gravity corers are so-called freeze corers, which provide undisturbed cores from the unconsolidated water-sediment interface. These corers are first filled with dry ice and ethanol and then lowered into the sediment, where the sediment then freezes onto the outer surface of the corer.



Sediment records from mountain lakes located above tree line are valuable climate archives, as the effects of human disturbances are relatively low in alpine regions.

Accurate dating is crucial

In order to extract climate-related information from lake sediments, it is essential to establish a reliable chronology. Some lakes have annually laminated sediments, also called *varves*, where couplets of light and dark bands are formed each year similar to tree-rings, which allow good chronological control by simply counting dark and light layers. However, most often the sedimentary records are homogenous and without any pronounced annual layers, requiring different dating techniques. Commonly applied methods are based on radio-isotopic dating, such as lead (Pb-210, half life 22.3 yrs) and carbon (C-14, half-life >5500 yrs). Due to the half-life of these isotopes, the lead method can be applied for sediments that are not older than 150 yrs, whereas the carbon method is applicable for sediments up to several tens of thousand years old. The disadvantages of these methods are the relatively high dating uncertainties, which are considerably higher than in varved sediment sequences. Complementary dating methods are included where possible to confirm a developed chronology, for example, marker horizons from well-known events such as ashes from volcano eruptions or the caesium record (Cs-137) from the reactor-incident in Chernobyl.

Climate proxies in lake sediments: non-biological climate indicators...

A wide variety of climate-related information can be extracted and investigated from lake sediments. Here, I distinguish between climate reconstructions that are based on non-biological and biological remains, in this context often referred to as climate “proxy”-indicators (that is, they serve as an approximation or replacement for the missing instrumental data). Some physical and geochemical properties of lake

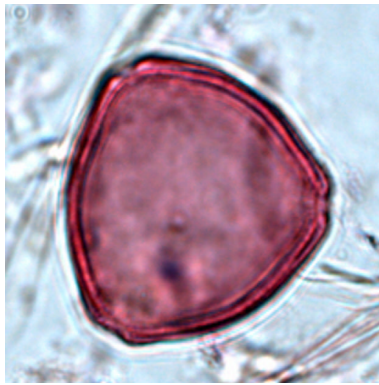
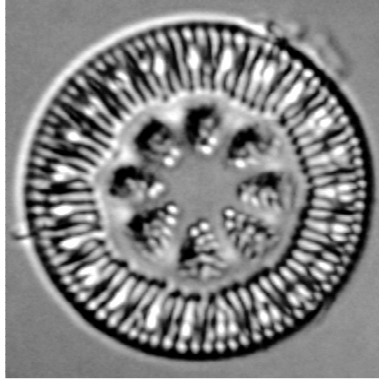
sediments can be related to climatic variables. For example, the thickness of annual layers (varves) contains valuable information about past productivity or erosional input. Attractive looking correlations have been developed between varve thickness and atmospheric circulation patterns, such as the Northern Atlantic Oscillation (NAO). In certain circumstances, textural analysis (mineralogical composition, grain size, form of minerals) can reveal key information on the origin and potential trajectories of deposited material. For example, Saharan dust may be found in lake sediments far away from the Sahara, giving some indirect information about prevailing past atmospheric circulation patterns.

In addition, the amount of organic matter in the sediment can be used as a proxy of past primary production in the lake and its catchment. Low-land lakes within forested or agricultural areas show often a considerably higher proportion of organic material than low-productive alpine lakes without any vegetation in the lake catchment. Recently, near infrared spectroscopy (NIRS) has as well been applied to characterise not only the amount, but also the composition or quality of the organic matter in lake sediments, leading to reliable climate-estimates. Many other physical and geochemical approaches are possible too, just to mention the use of stable isotope analysis, which can provide estimates of past climate, as well as in some cases the amount and origin of precipitation from lake sediments.

...and biological climate indicators

Identifiable remains of past vegetation in a lake catchment are usually deposited in the form of pollen and plant macrofossils (e.g., pieces of leaves and stems). The analysis of pollen spectra in lake sediments allows an indirect reconstruction of vegetation

patterns, which is in fact related to a well-defined climatic envelope. However, as many pollen are wind-dispersed, some records can be affected by long-distance transported pollen, leading to an unrepresentative picture of the vegetation within a particular lake catchment.



Examples of biological remains in lake sediments that contain information about past climatic conditions. From the top to the bottom: a diatom (algae), a pollen grain (vegetation remain) and a head capsule of a chironomid larvae (non-biting midge).

Another powerful tool related to past vegetation is the analysis of the stomata density in leaves. Through the stomata a plant regulates, for example, uptake of CO_2 , and the density of stomata of certain plant species (e.g., birch) have been successfully calibrated to ambient CO_2 -concentrations.

In addition to the preservation of a record of past vegetation in the catchment surrounding the lake, lake sediments also contain numerous other climate proxy indicators that are derived from the lake itself. For example, primary producers such as diatoms (single-celled algae) are found in sediments, and due to their siliceous structure they are preserved for a long time. Furthermore, the composition of algal pigments can be analysed and allows an assessment of past ultraviolet (UV) radiation intensity and cloudiness. Many zoological indicators are also preserved in the sediment and are identified as useful climate indicators, such as larvae remains (head capsules) of chironomids (non-biting midges), beetles, and crustacean such as cladocera or ostracodes.

Turning the biological indicators into quantitative temperature estimates

Most reconstruction approaches are based on a calibration using a so called space-for-time-replacement approach. Surface sediments (e.g., 0-1 cm) of many lakes (ideally >100) are sampled, with these lakes covering broad climatic gradients. For each lake, the biological proxy indicators that are present in the surface sediments are identified and related to ambient water temperature, which is closely related to the prevailing air temperature. Using multiple regression and calibration techniques, a quantitative temperature optima and tolerance can be determined for each species at present-day conditions. In a next step, this calibration function (or transfer function) is applied on a sediment sequence from a specific

lake, covering a time-period of up to several millennia. In this way, the present-day distribution patterns are used to quantitatively reconstruct past temperature based on the subfossil remains. The underlying assumptions for this approach are: (1) a diverse and climate-sensitive species assemblage is well preserved in the sediment, (2) the ecological requirements for these species have not change considerably during the time-period of interest, and (3) climate and climate-related variables do in fact exert a strong and significant influence on the biological community through time.

Limitations and problems

These organism-based transfer functions are usually predicting temperature with accuracy of $\sim 1^{\circ}\text{C}$, which may lead to the problematic situation that the prediction errors of a transfer function actually may exceed the magnitude of climate change. Another limitation is a so-called no-modern-analogue situation. This situation occurs when the subfossil assemblage composition in part of the sediment record, oftentimes in sediments from several thousand years ago, has no modern analogue or equivalent along the present-day climate gradient. This may hamper the

application of a developed transfer function.

Variables other than climate can also interact with the biological community and exert a strong influence. For example, chironomids are highly dependent on the oxygen levels in a lake, and diatoms are controlled as well by the acidity and nutrient availability. These factors are not linearly related to climate and may distort calibration approaches.

Besides direct influences of temperature on biological assemblages, numerous indirect effects may play an important role. Climate controls not only the air and lake water temperature, but also other processes such as ice-cover duration, snow availability in the catchment, ground-water flow or atmospheric nutrient deposition. All these processes, often mediated through the lake catchment, are important, which may contribute to a reduction in the predictive ability of biological climate indicators in lake sediments.

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