al., 2003) but the drip water study suggests otherwise. Drip water Mg/Ca ratios are in fact higher in the wet winter months than summer, and tracing with O isotopes does not suggest that this is due to a seasonal lag. Rather, we interpret from seasonal variations in pH and alkalinity data that cave PCO_2 is modulating seasonal $CaCO_3$ saturation and hence inducing more PCP in the winter; the PCO_2 variations also have the consequence that speleothem deposition in Golgotha Cave predominantly occurs during the winter/spring months. In more recent work, we have also established that PCO_2 (via solution pH) is the strongest influence on sulfate incorporation and, hence, we propose that sulfate profiles can be used to identify PCO_2 controls. The PCO_2 variations may also have a specific interpretation in terms of seasonality (cf., the Austrian Obir cave where low PCO_2 reflects strong incoming air circulation at low winter temperatures; Spötl et al., 2005).

However, at Golgotha Cave we also observe that the highest Mg/Ca ratios were reached during 2006 (Fig. 2), which was the driest year on record. This implies that the effect of residence time on this process is also important on interannual timescales (cf., McDonald et al., 2004) and can possibly be distinguished from the seasonal PCO_2 effect. We are currently working on identifying the specific processes in relation to Mg sources that lead to these residence-time effects, in order to gain more confidence in the expected range of values that can be attributed to it under present-day conditions.

Note

Moondyne Cave stable isotope data is available for download from www.ncdc.noaa.gov/paleo/speleothem.html

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Temperature and precipitation records from stalagmites grown under disequilibrium conditions: A first approach

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A variety of climate archives are studied to reconstruct past variations in Earth's climate. Recently, stalagmites have come into focus, due to their long, continuous growth periods and improved dating techniques. These archives provide high-resolution stable carbon ($\delta^{13}C$) and oxygen ($\delta^{18}O$) isotope profiles, which record information about climate-related parameters at the time of growth. While the $\delta^{18}O$ of stalagmites grown under conditions of isotopic equilibrium depend on the $\delta^{18}O$ value of the drip water and the cave temperature, the interpretation of stable oxygen isotopes from stalagmites grown under disequilibrium conditions is more difficult, due to the additional influence of the drip interval (i.e., the time between two subsequent drops feeding the stalagmite) on the isotope signal. Stalagmites that demonstrably grew under disequilibrium conditions, as indicated by a positive correlation between $\delta^{13}C$ and $\delta^{18}O$ along individual growth layers (Hendy tests), have traditionally been rejected from intensive research. However, a quantitative description of disequilibrium fractionation effects might enable the reconstruction of both temperature and drip interval from isotope profiles of these stalagmites.

Here, we present a numerical model (Combined Stalagmite Model; CSM) that calculates variations in temperature and precipitation from the isotope profiles from along the growth axis and individual growth layers, as well as the age-depth relation of stalagmites grown under conditions of isotopic disequilibrium.

Model parameters

The CSM is based on the inversion and combination of previously developed models. These are growth models (Dreybrodt, 1999; Kaufmann and Dreybrodt, 2004; Mühlinghaus et al., 2007) and isotope models that calculate the isotopic enrichment of carbon and oxygen, both along the growth axis and individual growth layers, assuming an irreversible Rayleigh fractionation process (i.e., the irreversible removal of CO_2 through degassing and $CaCO_3$ through precipitation, from the solution layer on top of the stalagmite) (Mühlinghaus et al., 2007; submitted). The models include the most important parameters describing the cave system and the overlying soil, such as temperature, water supply, the isotopic composition of the drip water, the partial CO_2 pressure of the soil and the cave atmosphere, and the mixing coefficient, which describes mixing between the impinging drop and the existing solution layer.

The idea of the CSM is based on the consideration that the proxies (i.e., growth rate, $\delta^{13}C$ and $\delta^{18}O$ profiles), which are common stalagmite data sets, show different dependencies on the model parameters. Due to their high temporal resolution, the most important data sets are the carbon and oxygen profile along the growth axis. While $\delta^{13}C$ reveals a strong dependence on drip interval but only a weak one on temperature, $\delta^{18}O$ is influenced by both parameters (Mühlinghaus et al., submitted). Thus ,a drip interval signal can be extracted from the carbon isotope profile, which is in turn used to correct the oxygen isotope profile for the influence of the drip interval, in order to obtain the temperature information.

Model description

To determine the characteristics of temperature and precipitation using the CSM, some simplification of the model parameters need to be made. Firstly, all parameters (except temperature and drip interval) are assumed to stay constant over the whole growth period of the stalagmite. This is a major simplification for parameters such as the isotopic composition of the drip water, which indeed shows temporal variations due to its correlation to temperature, for instance. For other parameters, like the mixing coefficient, this approximation may only disguise small temporal variations, which can be neglected in this first approach.

This simplification enables the CSM to run with only two input variables: The mean $\delta^{13}C$ value of the drip water and the temperature at any point of time during the growth period of the stalagmite (e.g., the recent cave temperature). This yields a temperature and drip interval record of high temporal resolution. For the other parameters, such as the CO_2 partial pres-

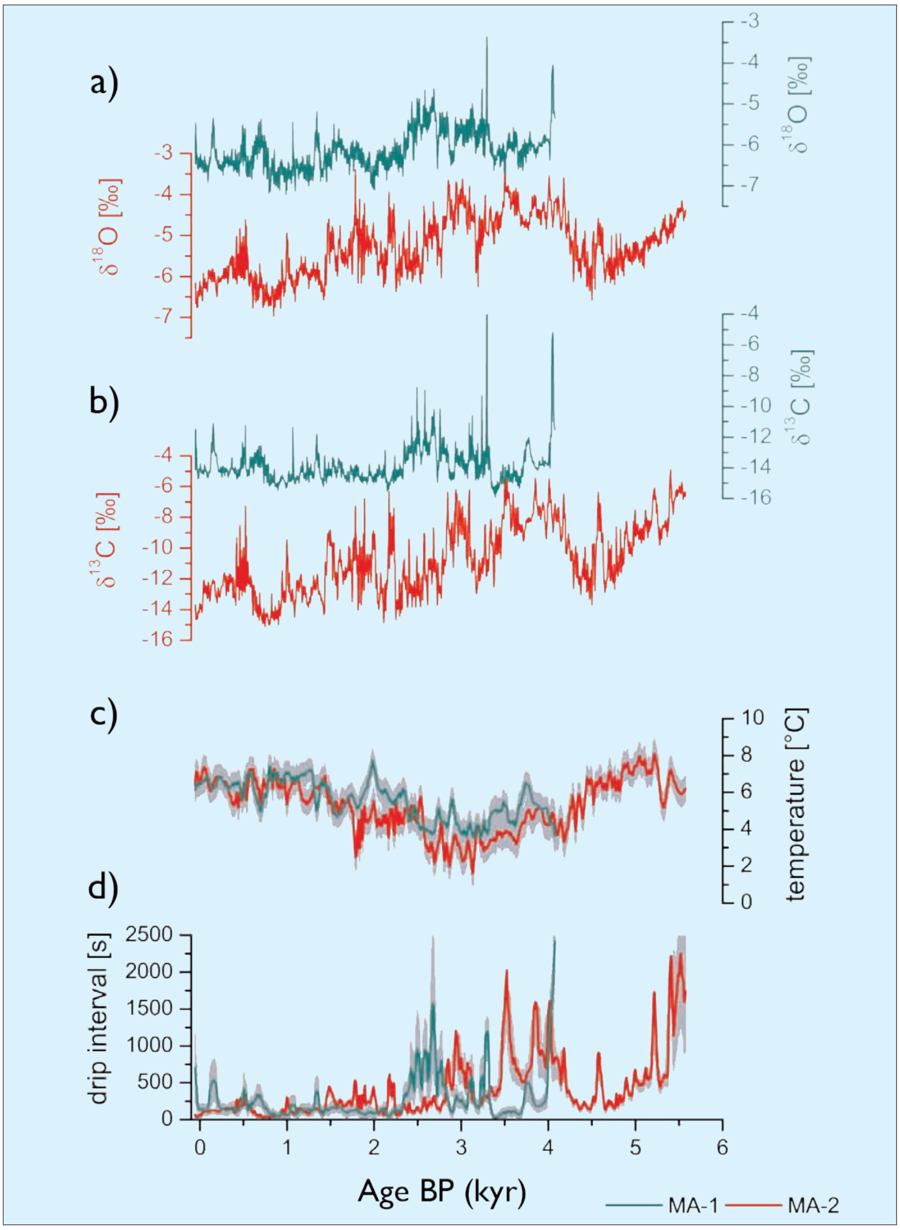

*Figure 1: (**a**) Oxygen and (**b**) Carbon profiles of stalagmites MA-1 (cyan) and MA-2 (red) from southern Chile. (**c**) Temperature and (**d**) drip interval (in seconds), reconstructed from the stalagmites, were calculated by the Combined Stalagmite Model and are smoothed by a 20-point running mean. Errors have been determined using a Monte Carlo simulation (at least 6000 iterations) and are indicated by the gray shaded area.*

sure of the soil and cave atmosphere, the mixing coefficient and the isotopic oxygen composition of the drip water mean values are determined. These represent the most likely values of the corresponding parameters during the growth period of the stalagmite. For these parameters no temporal variations can be obtained with the current model version.

Application and results

The model was applied to two stalagmites from southern Chile that were precisely dated using the Th/U method (MA-1 and MA-2, Schimpf, 2005; Kilian et al., 2006). These stalagmites grew under disequilibrium conditions in a small cave next to each other during the last 4.5 kyr BP. However, the δ^{13}C and δ^{18}O profiles along the growth axis showed a different influence of isotope fractionation under disequilibrium (Fig. 1a, b).

The drip intervals calculated from the two stalagmites show no correlation, most likely resulting from different degrees of kinetic fractionation, which may be explained by different drip sources (Fig. 1d). Hence, the amount of drip water feeding stalagmite MA-2 seems to have been limited, perhaps due to a smaller water reservoir. In the case of these stalagmites, drip intervals are directly related to precipitation, due to the sparse soil zone above the cave. Thus, large drip intervals indicate drier periods, while short drip intervals reflect wetter conditions. Although there is no significant correlation between the two reconstructed drip intervals, they follow a general trend of high water supply during the last 2.5 kyr BP, and lower water supply between 2.5 kyr and 6 kyr BP.

In contrast to the differences in the calculated drip intervals, the temperature records show a rather high correlation coefficient of $R^2 = 0.76$. This is remarkable since the correlation coefficient for the δ^{18}O profiles, which are used to extract temperature, is only $R^2 = 0.51$. This suggests that the CSM is able to extract reasonable temperature information from the given data sets. Although the two profiles reveal an offset of approx. 1°C between 1.6 kyr and 4 kyr BP (where MA-2 reconstructs lower values than MA-1), the trend and the main peaks of the two records show good agreement, particularly during the last 1.6 kyr, and between 2.5 kyr and 3.5 kyr (Fig. 1c).

The absolute temperature values, however, need to be handled with care. Stalagmite MA-1 shows a temperature variability of approx. 3-4°C and stalagmite MA-2 a variability of almost 4-5°C. These large variations may reflect regional effects on meteorology, however, one reason for this variability probably lies in the assumption of a fixed δ^{18}O value for the drip water. This value will change with temperature and variations in wind/rain trajectories. If, for instance, the δ^{18}O value of the drip water increased between 2 kyr and 4 kyr BP, the decreasing temperature trend would be attenuated and the variability damped. Thus, this temperature record might also include information about the δ^{18}O value of precipitation.

Summary

A combined stalagmite model was developed to extract drip interval and temperature variations at high temporal resolution from stalagmites grown under disequilibrium conditions. The obtained temperature signals are highly correlated over the whole growth period. The calculated drip intervals show no correlation, due to the different kinetic influence, and reflect a variable water supply. In addition, the results are insensitive to small variations of the input variables, which give confidence in the algorithm of the model and for further temperature reconstructions from stalagmites grown under such conditions.

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