ing an absolute "ice-core calendar", to permit direct comparison with contemporaneous isotopic and meteorological data, still persists: Although the data measured in the ice core provide unmistakable evidence for the passage of time, where does a particular month (or season or year) actually begin and end? Thus, in spite of the unusually high resolution, the Fiescherhorn ice-core chronology may not be able to support evaluation of isotope-climate relations with the same level of confidence or at temporal scales equivalent to that possible using data from sampling of monthly composite precipitation.

Indeed, this limitation can be demonstrated by comparing the stacked Fiescherhorn $\delta^{18}O$ record with the monthly composite precipitation $\delta^{18}O$ record from Grimsel, a high-elevation station (1950 m) less than 25 km distant (lower panel, Fig. 1). Even extensive adjustment to achieve a best-fit with this monthly time-series yields only weak correlation, in spite of the visual impression imparted by the strong annual cycling in both records and the similar longterm trends. Subsequent comparison with the North Atlantic Oscillation index (not shown), which generally correlates significantly with composite monthly European isotope records, also reveals weak correspondence. The most likely explanation to account for the apparent deficiency in the ability of this glacier to archive paleoprecipitation is revealed clearly by the plot shown in Figure 2, which shows that no correspondence exists between the net annual accumulation at Fiescherhorn and the amount of annual precipitation at Grimsel. This probably reflects at least in part the influence of drifting and other postdepositional processes that remove or redistribute snow, reminding us that alpine glaciers (and certainly to some extent polar ice sheets) are dynamic, open systems for precipitation, and that due caution is required in attempting to decipher their isotopic records.

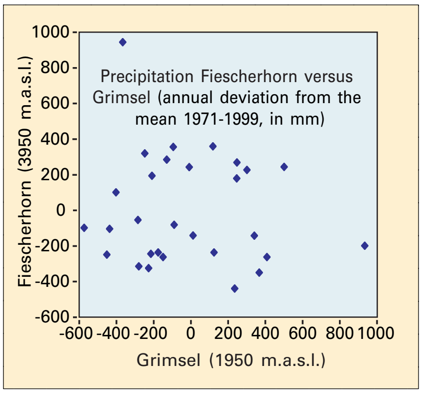

Fig. 2: Comparison of net annual accumulation at Fiescherhorn and precipitation amount at Grimsel. The lack of correspondence, consistent with the weak isotopic correlation evident in Fig. 1, underscores the need for critical evaluation of alpine ice core records.

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Holocene Variability in the Indian Ocean Monsoon: A Stalagmite-Based, High-Resolution Oxygen Isotope Record from Southern Oman

Dominik Fleitmann[1], **Stephen J. Burns**[2], **Manfred Mudelsee**[3], **Ulrich Neff**[4], **Jan Kramers**[1], **Augusto Mangini**[4] **and Albert Matter**[1]

[1] Institute of Geological Sciences, University of Bern, Switzerland; fleitman@geo.unibe.ch, kramers@geo.unibe.ch, albert.matter@geo.unibe.ch
[2] Department of Geosciences, Morrill Science Center, University of Massachusetts, USA; sburns@geo.umass.edu
[3] Institute of Meteorology, University of Leipzig, Germany; mudelsee@rz.uni-leipzig.de
[4] Environmental Physics, Heidelberger Academy of Sciences, Germany; Augusto.Mangini@iup.uni-heidelberg.de

The Indian Ocean monsoon is one of the major weather systems on Earth, affecting the economies, agriculture and fisheries of one of the most densely populated areas of the world. To date, analyses of how and why the monsoon varies through time have mainly been restricted to studies of meteorological records, which extend back perhaps 150 yr, or to investigations of lacustrine and marine sediments, which have a low time-resolution (typically greater than 100 years) and large age uncertainties. However, one sensitive monitor of monsoon variation having considerably finer temporal resolution is the oxygen isotope composition of stalagmites, such as those from Qunf Cave (17°10′ N, 54°18′ E; 650 m.a.s.l.) in

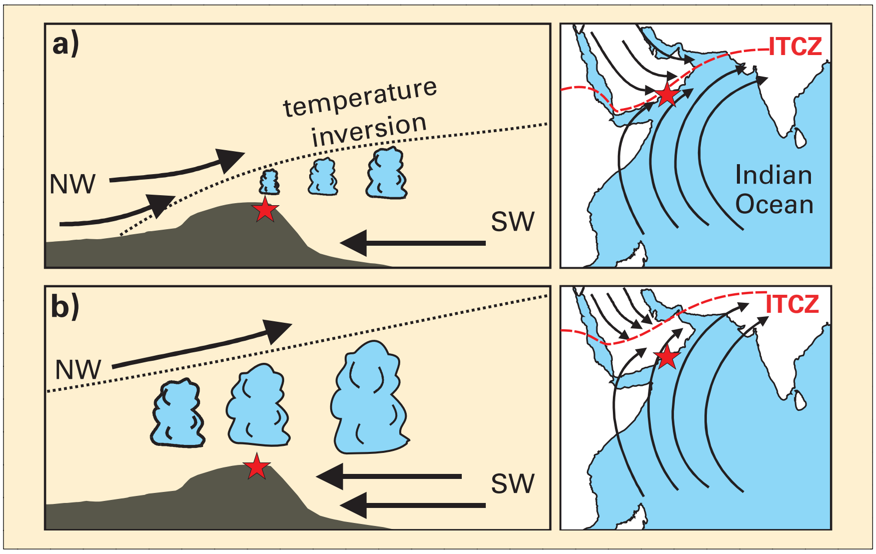

*Fig. 1: **a** Modern summer circulation pattern over Southern Oman. The red star shows the location of Qunf Cave. The black dashed line shows the position of the temperature inversion and the red dashed line the location of the ITCZ. **b** Schematic figure of summer circulation pattern at around 7 kyr BP.*

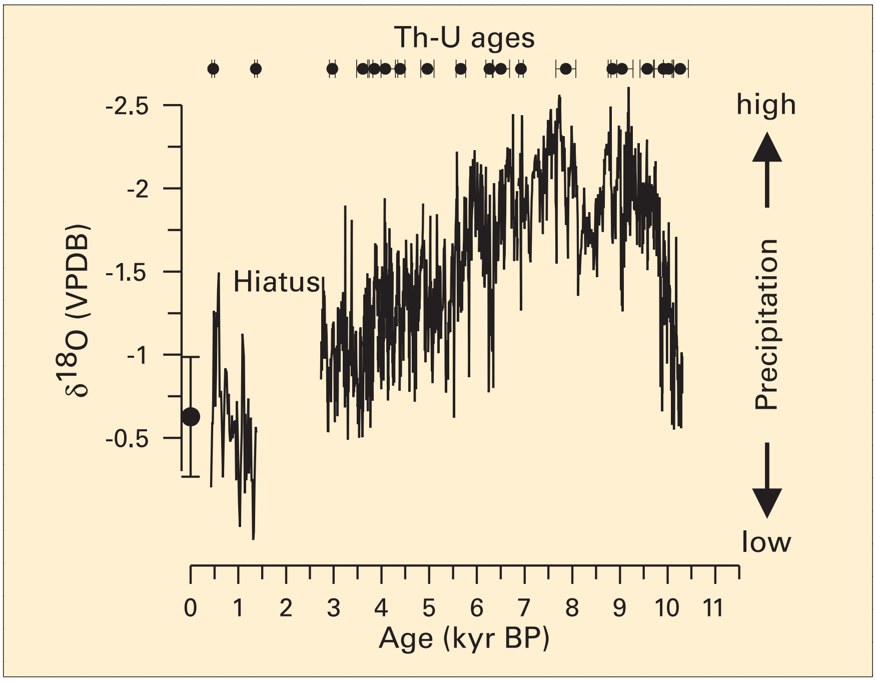

Fig. 2: Stalagmite Q5 oxygen isotope record from Southern Oman. Black dots above are U-Th-ages (Fleitmann et al., submitted). Black dot with vertical error bar shows the $\delta^{18}O$ range of modern stalagmites (101 stable isotope measurements, ~50 years).

southern Oman (Fig. 1a), which precipitate from drip water that accurately reflects the oxygen-isotope content of local monsoon rainfall (Fleitmann et al., 1999).

Presently, the area lies at the northern limit of the summer migration of the ITCZ and the associated Indian Ocean monsoon rainfall belt. Annual precipitation in this region is highly seasonal - more than 80% of total annual precipitation (400-500 mm yr^{-1}) falls during the summer monsoon months (July to September) when dense clouds and mists cover the region. The clouds are unable to rise higher than about 150 m because of a temperature inversion created by the convergence between hot dry northwesterly winds off the land and the low-level southwest monsoon winds off the ocean (Fig. 1a). As a result, monsoon precipitation occurs as fine drizzle, seldom exceeding more than 5 mm d^{-1}, unlike the heavy rains normally associated with strong convective monsoonal rainfall.

Stalagmite Q5 was deposited in two phases from 10.3 to 2.7 kyr BP and from 1.4 to 0.5 kyr BP (the data are presented on the ^{14}C absolute age scale where "present" is defined as AD 1950). The oxygen isotope profile (Fig. 2) has an average time-resolution of 5 yr. When stalagmites are deposited in isotopic equilibrium (i.e., no evaporation), calcite $\delta^{18}O$ values reflect either changes in the isotopic composition of precipitation or changes in mean annual air temperature within the cave. Previous work on stalagmites from northern and southern Oman have demonstrated that changes in calcite $\delta^{18}O$ over time primarily reflect changes in the amount of precipitation (Burns et al., 2001; Neff et al., 2001). More negative $\delta^{18}O$ values indicate greater monsoon precipitation, because $\delta^{18}O$ of monsoon-type precipitation is commonly correlated inversely to the amount of precipitation (the so-called "amount effect", see Dansgaard, 1964).

The $\delta^{18}O$-profile (Fig. 2) of stalagmite Q5 shows three distinct features. First, a rapid increase in monsoon precipitation between 10.3 and 9.8 kyr BP is indicated by a sharp decrease in $\delta^{18}O$ from -0.8‰ to ~-2‰. Second, an interval of generally high monsoon precipitation lasting from 9.8 to 5.5 kyr BP with $\delta^{18}O$ values averaging -2‰. Third, a long-term gradual decrease in monsoon precipitation starting at around 7 kyr BP is indicated by a slow shift in average $\delta^{18}O$ from -2.2‰ at 7 kyr BP to ~-0.9‰ (slightly more negative than $\delta^{18}O$ values of modern stalagmites) at 2.7 kyr BP. Furthermore, the early to mid-Holocene period of generally high monsoon precipitation was apparently interrupted by three distinct intervals of reduced precipitation, occurring at around 9.2-9.1, 8.5-8.1 and 6.3-6.2 kyr BP.

What circulation pattern controlled the amount of monsoon precipitation in southern Oman over the course of the Holocene? The Q5 $\delta^{18}O$ record is consistent with the scenario depicted in Figure 1b, showing postulated northward displacement of the ITCZ around 7 kyr BP. Such a shift of the ITCZ into the Arabian Peninsula, as inferred from lake sediments (McClure, 1976) and stalagmites (Burns et al., 2001; Neff et al., 2001), would lift the height of the temperature inversion, leading to stronger convective cloud development and higher monsoonal rainfall over southern Oman. Moreover, the fine structure in the Q5 $\delta^{18}O$ record suggests that characteristic variations also occur at much higher frequencies, affording the opportunity to gain insight into monsoon circulation dynamics and variability under a range of boundary conditions, and at time-scales relevant to humans.

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