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Stable isotope paleoaltimetry is widely used to infer past elevations of orogens due to the robust systematic inverse relationships between elevation and oxygen ($\delta^{18}O$) and hydrogen (δD) isotopic composition of meteoric waters recorded in geologic archives, such as paleosol carbonates or hydrous silicates. This $\delta^{18}O$-elevation relationship (or isotopic lapse rate) is commonly attributed to the preferential rainout of heavy water isotopologues from air masses ascending over topography. However, numerous non-linear climatic processes, such as surface recycling, vapor mixing, variability in moisture source, and precipitation dynamics, can also influence the isotopic lapse rate and thus complicate stable isotope paleoaltimetry estimates. This highlights the need for a better quantitative understanding of topographic and regional climatic effects on the isotopic composition of ancient waters. Through topographic sensitivity experiments, Boateng et al. (2023) suggested plausible changes in isotopic lapse rates across the Alps in response to different diachronous surface uplift scenarios and validated that the expected isotopic signal difference due to elevation changes is significant enough to be reflected in geologic archives.

Recent paleoelevation reconstructions across the Alps estimate the mean elevation of >4000 m in the Central Alps during the Middle Miocene (Krsnik et al., 2021). These high elevation estimates have been attributed to the complicated transition from pre- to mid-Miocene Central Alps with a diverse landscape and a complex topography, mainly driven by the rapid exhumation of deep-seated core complexes, followed by a rearrangement of the drainage system. However, the paleoelevation estimate is based on the assumptions that the isotopic lapse rate (1) is similar to the modern lapse rate (~2.0 ‰/km), which is lower than the global average, (2) did not change during the deposition of the paleoaltimetry proxies compared to the present day, and (3) remained constant across the entire Alps.

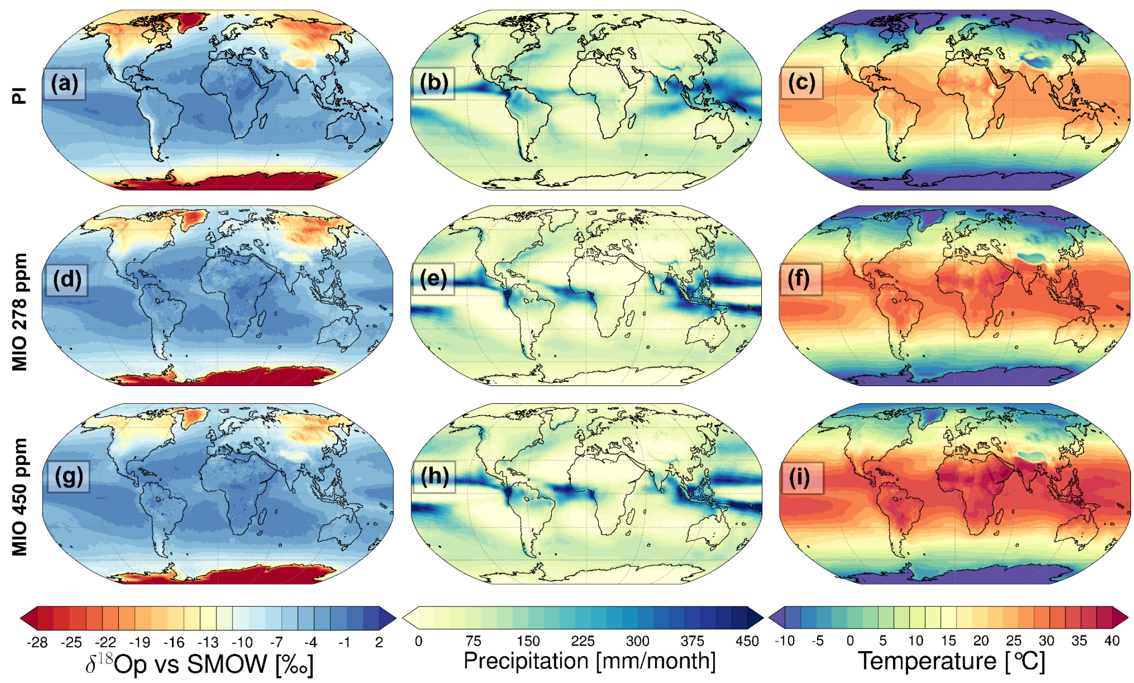

Fig. 1: Simulated annual climatologies of δ^{18}Op, precipitation, and near-surface temperature in response to the paleoenvironment condition is the Pre-Industrial (PI), Middle Miocene Climate Optimum (Mio 450 ppm) and Middle Miocene Climate Transition (Mio 278 ppm) [Boateng et al. in preparation]

Here, we use a high-resolution isotope-tracking ECHAM5-wiso General Circulation Model to simulate the Middle Miocene climate and $\delta^{18}O_p$ responses to different surface uplift scenarios of the Alps (Fig. 1). More specifically, we performed topographic sensitivity experiments by varying the height of the Western/Central Alps and Eastern Alps under two atmospheric CO_2 concentration scenarios for Middle Miocene paleoenvironmental conditions. The simulated $\delta^{18}O_p$ values are consistent with the proxy reconstructions across the low- and high-elevation sites in the Alps (Fig. 2). The topographic scenarios indicated $\delta^{18}Op$ values differences of up to -10 ‰ between the low- and high-elevation sites, primarily due to changes in orographic precipitation and local near-surface temperature. Even though the differences across the low-elevation sites showed minor changes compared to the present-day climate, the high-elevation sites indicated significant changes mainly due to differences in moisture transport and moisture redistribution. These changes resulted in different isotopic lapse rates across the different transects around the Alps, contradicting the assumption of a regionally similar isotopic lapse rate.

Using the simulated Middle Miocene isotopic lapse rates with the reconstructed $\Delta\delta^{18}Op$ signal between the low-elevation Northern Alpine Foreland Basin and high-elevation Simplon fault gouge reveals an overestimation of paleoelevation estimates by 2 km when compared to the constant isotopic lapse rate of -2.0 ‰/km across the Alps (Fig. 2). These uncertainty estimates are an improvement of the previous paleoelevation reconstruction across the Alps and support the integration of paleoaltimetry and paleoclimate modeling to reconstruct past surface elevations accurately.

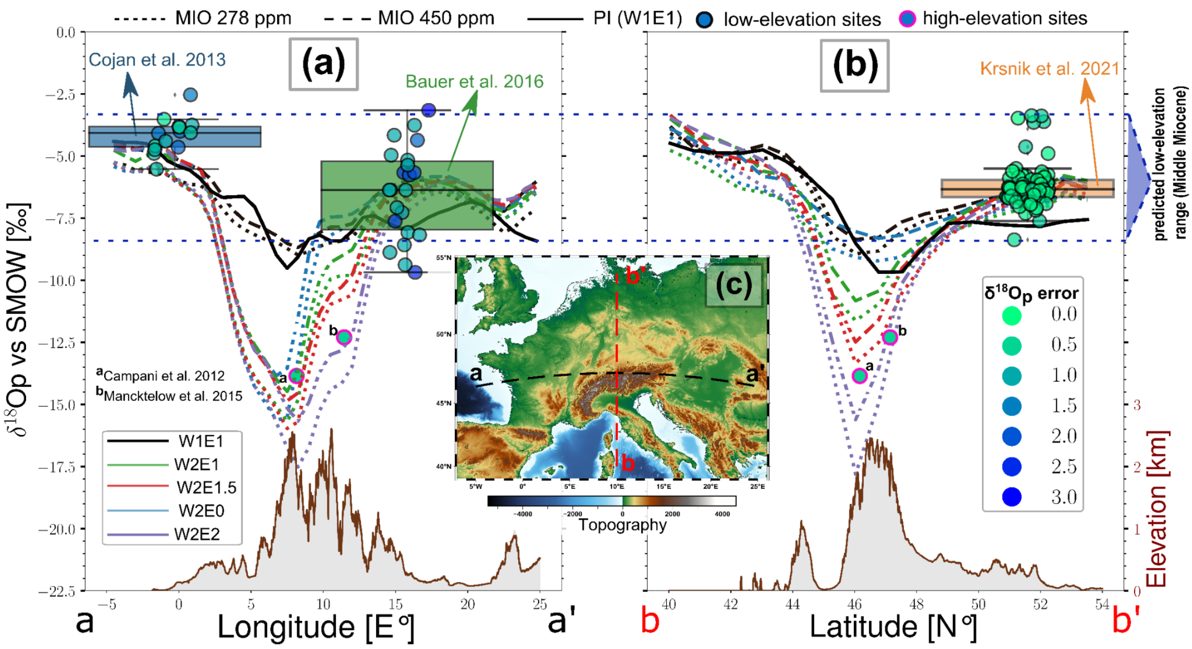

Fig. 2: Spatial profiles of simulated Middle Miocene $\delta^{18}Op$ values in response to the different topographic configurations and its comparison to the low- and high-elevation proxy reconstructions [Boateng et al. in preparation]

References

Boateng, D., Mutz, S. G., Ballian, A., Meijers, M. J. M., Methner, K., Botsyun, S., Mulch, A., and Ehlers, T. A.: The effects of diachronous surface uplift of the European Alps on regional climate and the oxygen isotopic composition of precipitation, Earth System Dynamics Discussions [accepted], 1–45, https://doi.org/10.5194/esd-2022-48, 2022.

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