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Stable isotope paleoaltimetry of high relief terrain: An atmospheric dynamics and landscape evolution perspective

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Stable isotope ratios in rain and snow from mountainous regions show a strong correlation with altitude. To the extent that these isotopic ratios are preserved in the geological record, they may provide a powerful constraint on the surface uplift history of mountain belts. Existing interpretive frameworks for paleoaltimetry are based on linear regressions of modern precipitation isotope transects or on a Rayleigh distillation model of air parcel ascent along a moist adiabatic temperature lapse rate. Neither of these frameworks accounts for the fully nonlinear dynamics of airflow over high-relief terrain, which predicts substantial deviations from the moist-adiabatic ascent model under common atmospheric conditions. The Weather Research and Forecast model (WRF), a numerical weather prediction model, has been modified to include a simplified isotope physics parameterization and has been used to explore the links between topography, atmospheric state, and precipitation isotopes. The controlling nondimensional parameter for atmospheric flow over terrain is Nh/U, where N is the Brunt-Vaisala frequency, a measure of atmospheric stability, h is the orogen- scale relief, and U is the horizontal wind speed. When $Nh/U<1$, winds can flow directly over topography and WRF precipitation isotopes match those predicted by the moist-adiabatic Rayleigh model. When $Nh/U>1$, the winds are blocked by the topography and are deflected around it. In these cases, the maximum elevation of condensation is much lower than the range crest, and precipitation isotopes are consequently substantially less depleted than predicted by the moist adiabatic Rayleigh model. Furthermore, the along-strike length of an orogen and the presence of valleys are shown to exert a strong influence on precipitation isotopes in blocked flow regimes because of the dynamical link between terrain length and atmospheric flow blocking. Terrain- blocked atmospheric conditions are common, especially in regions of high relief, but their impact on the geological record, especially on records used for paleoaltimetry studies is unknown. The model results show that these records are strongly influenced by climate and landscape evolution, and that interpretations in terms of changes in surface elevation alone may be unwarranted.