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Response of meteoric $\delta^{18}O$ to surface uplift — Implications for Cenozoic Andean Plateau growth

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ABSTRACT

The timing and magnitude of surface uplift provide important constraints on geodynamic models of orogen formation. Oxygen isotope ($\delta^{18}O$) and mass-47 isotopolog (Δ_{47}) compositions from terrestrial carbonate sediments have been used with modern isotope and temperature lapse rates to infer past surface elevations of the Andes. However, these paleoaltimetry interpretations are contentious because variations in the oxygen isotope composition in meteoric water ($\delta^{18}O_p$) are caused by changes in elevation (orographic) and regional climate. Here, we use a limited-domain isotope-tracking general circulation model to simulate changes in $\delta^{18}O_p$ and isotopic lapse rates in response to Andean surface uplift, and to re-evaluate $\delta^{18}O$ and Δ_{47} changes in late Miocene carbonates previously associated with rapid Andean growth. Results indicate that Andean surface uplift leads to changes in low-level atmospheric circulation and an increase in precipitation along the eastern Andean flank which influences isotopic source and amount effects. Simulated changes in Andean $\delta^{18}O_p$ are not systematic with an increase in surface elevation, but are instead a function of orographic thresholds that abruptly change regional climate. A $\delta^{18}O_p$ decrease of >5‰ over the central Andes and an increase in isotopic lapse rates (up to 0.8‰ km^{-1}) coincide with Andean surface uplift from 75 to 100% of modern elevation. These changes in the isotopic signature could account for the entire 3–4‰ $\delta^{18}O$ depletion in late Miocene carbonate nodules, and suggest an Andean paleoelevation of ~3000 m (75% of modern elevations) before 10 Ma.

1. Introduction

The timing and rates at which current Andean Plateau (AP) elevations were attained are debated. A rapid and recent rise of ~2.5 ± 1 km between 10 and 6 Ma has been proposed based on $\delta^{18}O$ and mass-47 isotopolog (Δ_{47}) compositions ('clumped isotopes') of late Miocene terrestrial carbonates (e.g. Garzione et al., 2006, 2008; Ghosh et al., 2006b). This interpretation has been questioned by paleoclimate modeling studies that have highlighted the sensitivity of stable isotope paleoaltimetry interpretations to climate change (Ehlers and Poulsen, 2009; Insel et al. 2009; Poulsen et al., 2010). Furthermore, geological and recent biotaxa evidence suggests AP growth was slow and steady since at least the Eocene (~40 Ma), and implies elevations of ~2000 m prior to 20–10 Ma (e.g. Alpers and Brimhall, 1988; Barnes and Ehlers, 2009; Picard et al., 2008; Rech et al., 2006; Schlunegger et al., 2010; Sebrier et al., 1988). Thus, significant debate exists on the elevation history of the AP and the influence of climate change on paleoelevation reconstructions.

Oxygen isotope paleoaltimetry uses $\delta^{18}O$ preserved in geological archives (e.g. carbonates, silicates, volcanic glasses) as a proxy for ancient meteoric $\delta^{18}O$. The composition of $\delta^{18}O$ ($\delta^{18}O = ([(^{18}O/^{16}O)_{sample}/(^{18}O/^{16}O)_{standard}] - 1) * 1000$) in these archives is controlled by the temperature and the composition of meteoric water at the time of mineral formation, both of which are related to elevation (e.g. Chamberlain et al., 1999; Drummond et al., 1993; Siegenthaler and Oeschger, 1980). The elevation–$\delta^{18}O$ relationship reflects Rayleigh distillation of the heavy isotope (^{18}O) through condensation and precipitation as air masses are adiabatically cooled. Due to the correlation between $\delta^{18}O$ of meteoric water ($\delta^{18}O_p$) and elevation, mountain surface uplift can be reconstructed through stable isotope studies of authigenic (in-situ formed) minerals, assuming that past isotopic lapse rates ($\Gamma_{\delta^{18}O}$, the rate of changes in isotopic ratio with altitude) were analogous to modern rates. Based on these assumptions, a 3–4‰ $\delta^{18}O$ shift in late Miocene carbonate nodules from the AP has been interpreted to reflect ~2.5 km of surface uplift (Garzione et al., 2006; Ghosh et al., 2006b).

However, factors other than elevation change influence the modern climatology of $\delta^{18}O_p$ along the Andes, such as precipitation (amount effect), water vapor source, wind patterns, ENSO, and remote climate pattern (e.g. Sepulchre et al., 2009; Sturm et al., 2007b; Vuille et al., 2003). General atmospheric circulation models indicate that Andean surface uplift causes substantial changes in

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South American regional climate (e.g. Ehlers and Poulsen, 2009; Garreaud et al., 2010; Insel et al., 2009; Poulsen et al., 2010). In particular, an abrupt increase in Andean precipitation and convection is associated with Andean threshold elevations of 50–70% of modern heights (Insel et al., 2009; Poulsen et al., 2010). These changes in regional paleoclimate can influence isotopic fractionation and source effects that cause dramatic changes in the paleo-$\delta^{18}O$ composition (Ehlers and Poulsen, 2009). Thus, late Miocene changes in central Andean $\delta^{18}O$ could be related to the intensification of precipitation associated with relatively minor surface uplift (Poulsen et al., 2010).

The clumped isotope carbonate thermometer has been used as an independent approach to paleoelevation reconstructions. This technique relies on the temperature dependence of the abundance of bonds between rare, heavy isotopes (i.e. $^{13}C^{18}O^{16}O$) in the carbonate mineral lattice, expressed as Δ_{47} (the ratio of mass 47 to mass 44 isotopologs in a sample from that ratio expected for a stochastic distribution of isotopes in that sample) (Ghosh et al., 2006a; Ghosh et al., 2006b). The ordering, or 'clumping', of heavy isotopes into bonds with each other is favored at low temperatures and the growth temperature of a carbonate mineral can be defined by the analysis of the isotopic constituents of the carbonate alone. The Δ_{47} derived temperatures have been used to reconstruct Andean paleoelevations assuming modern temperature lapse rates with elevation (Ghosh et al., 2006b). However, it has been shown that an increase in Andean plateau elevations not only results in adiabatic cooling directly linked to elevation gain, but also in non-adiabatic cooling associated with regional climate change (Ehlers and Poulsen, 2009). That could lead to a change in temperature lapse rates over time and influence paleoaltimetry estimations based on temperature changes.

Previous studies have implemented either high-resolution non-isotope tracking regional models (e.g. Ehlers and Poulsen, 2009; Insel et al., 2009) or global climate models with isotope tracking capabilities (e.g. Jeffery et al., 2011; Poulsen et al., 2010). In this study we extend this previous work by using a high-resolution limited-domain general circulation model with isotope diagnostics (REMOiso). In comparison to global spectral climate models, the limited-domain model provides a better representation of Andean topography at a horizontal resolution that approaches the spatial scales represented by proxy data. Results highlight the behavior of $\delta^{18}O_p$ and temperature under past topographic and climate conditions and refine orographic threshold elevations for significant changes in $\delta^{18}O_p$. Specifically, we (1) estimate changes in $\delta^{18}O_p$ due to Andean surface uplift and provide predictions of precipitation patterns and $\delta^{18}O_p$ for specific Andean heights; (2) quantify the changes in isotopic lapse rates in response to Andean surface uplift; and (3) evaluate the geological/isotopic evidence for surface uplift with specific focus on Δ_{47} estimates. The integration of model results and observations suggests that regional climate change in response to surface uplift caused changes in the stable isotope record.

2. Method

To quantify the influence of Andean surface uplift on $\delta^{18}O_p$ and oxygen isotopic lapse rates, we use a numerical three-dimensional limited-domain general circulation model with isotope-tracking capabilities (REMOiso) (Sturm et al., 2005; Sturm et al., 2007a). Isotope fractionation and transport processes are embedded at all stages of the hydrological cycle by defining isotopic counterparts to all water-related variables. Therefore, the species H_2O^{18} and HDO are treated independently from the predominant H_2O^{16}, but undergo the same processes including equilibrium and kinetic fractionations (Sturm et al., 2005). Stable water isotopologs are treated as passive tracers in soil moisture and snow layer and all vapor fluxes from the surface are considered non-fractionating. All experiments are forced using modern boundary conditions, including stable water isotopes, from the ECHAM-4 global climate model with specified SSTs derived from monthly satellite data (i.e. HadSST; Hoffmann et al., 1998).

Simulations were performed for South America using a continental-scale domain with a horizontal grid spacing of 0.5° (~55 km) and 31 vertical levels. Three experiments were completed with Andean elevations representing 100%, 75%, and 50% of the modern Andes height. In other regions of South America, the topography was maintained at modern elevations. All other parameters remain the same between experiments. All three experiments were integrated over the ten-year period from 1989 to 1998. Because of the high computational cost, it was not practical to run REMOiso continuously over this time span. Instead, 15-month integrations, starting from the previous year's October and running through December of the simulation year, were completed. Each simulation year was initialized from the same initial conditions from a 21-month (January to September) simulation forced with boundary conditions for year 1993. Year 1993 was chosen for the spin-up, because it most closely resembled the 30-yr precipitation mean over the study area.

We present simulated annual amount-weighted mean $\delta^{18}O_p$ and isotopic lapse rates based on 10-year averages. Isotopic lapse rates are calculated every 0.5° latitude by linear regression of $\delta^{18}O_p$ for all grid points between peak and flank (~300 m) elevations. Absolute values of isotopic lapse rates are presented as a 4-point (~2° latitudinal) running zonal average. We note that by definition the lapse rate is defined as the rate of decrease of an atmospheric variable (e.g. temperature) with height. However, to be consistent with previous studies, we report isotopic lapse rates as the change in $\delta^{18}O_p$ with altitude. Thus, a $\delta^{18}O_p$ decrease of $-1‰\,km^{-1}$ elevation gain is reported as a lapse rate of $-1‰\,km^{-1}$, rather than $1‰\,km^{-1}$. However, as changes in isotopic lapse rates are described as changes in absolute magnitude, an increase in lapse rate is consistent with a more negative lapse rate (i.e. an increase from $-1.5‰\,km^{-1}$ to $-2‰\,km^{-1}$).

3. Results

3.1. Modern isotope climatology

REMOiso has been shown to realistically simulate modern large-scale climate and circulation patterns, and spatial variations in $\delta^{18}O_p$ in South America (Sturm et al., 2007a; Sturm et al., 2007b). In agreement with observations, simulated $\delta^{18}O_p$ is relatively high (-3 to $-6‰$) over the Amazon Basin due to evapotranspiration (Fig. 1b, 100% Andes). Once air masses reach the Andes, adiabatic cooling and condensation associated with rising air masses contribute to the isotopic depletion of vapor. Strong convergence, vertical ascent and rainout along the eastern Andean flank result in Rayleigh distillation which causes $\delta^{18}O_p$ to exponentially decrease with cumulative precipitation, and results in the lowest $\delta^{18}O_p$ ($<-12‰$) at high elevation sites along the Andes (Fig. 1b). Low $\delta^{18}O_p$ (-7 to $-10‰$) is also simulated in southern South America due to the latitudinal effect.

Simulated modern isotopic lapse rates ($\Gamma_{\delta18O}$) vary significantly along the Andes (Fig. 2a and e). Along the eastern flank, modern average $\Gamma_{\delta18O}$ range from $-2.09‰\,km^{-1}$ to $1.02‰\,km^{-1}$ between 10°N and 50°S (Fig. 2a). Along the western flank, simulated modern average $\Gamma_{\delta18O}$ vary between $-3.46‰$ and $0.22‰\,km^{-1}$ (Fig. 2e). Overall, the largest (most negative) lapse rates exist over the AP at ~20°S and in the southern Andes south of ~37°S. Lapse rates can be positive ($\delta^{18}O_p$ increases with altitude) where modern peak elevations in the model are below 2000 m (Fig. 2a, b, e). In the southern Andes, positive $\Gamma_{\delta18O}$ along the eastern flank are mainly related to an isotopic rain shadow effect, where the steady eastward decrease in $\delta^{18}O_p$ reflects the increasing distance from the principle water vapor source (South Pacific) (Stern and Blisniuk, 2002) and spillover of condensate to the leeward (eastern) side leads to further depletion