Climate change imprinting on stable isotopic compositions of high-elevation meteoric water cloaks past surface elevations of major orogens

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ABSTRACT
Stable isotope paleoaltimetry has been widely used to estimate Cenozoic surface elevation of major orogens. The influence of global climate change on stable isotope paleoaltimetry is uncertain, with proposals that warming could cause either overestimates or underestimates of past surface elevations. In this study we increase atmospheric $p$CO$_2$ by two and four times in an isotope-tracking atmospheric general circulation model to investigate the effect of global warming on oxygen isotopic compositions of precipitation ($\delta^{18}$O) over the continents. As in other climate models, the response in the GENESIS version 3 model to global warming is an amplification of upper troposphere temperatures through enhanced infrared absorption and a reduction in the surface to upper-level temperature gradient. Due to the temperature dependence of isotopic fractionation, vapor $\delta^{18}$O ($\delta^{18}$O$_v$) follows suit, leading to a reduction in the surface to upper troposphere $\delta^{18}$O$_v$ gradient. In regions of subsidence, including the major orogens and deserts, downward mixing of $^{18}$O-enriched vapor from the troposphere to the near surface further reduces the lapse rate of $\delta^{18}$O. As a consequence of these effects, the isotopic composition of precipitation in high-elevation regions, including the Tibetan Plateau, Rocky Mountains, European Alps, and Andean Plateau, increases by 3‰–6‰ relative to that at low elevations. Neglect of this climate effect on high-elevation $\delta^{18}$O has likely led to underestimates of the surface elevation of Cenozoic orogens.

INTRODUCTION
The isotopic compositions ($\delta^{18}$O, $\delta$D) of precipitation and surface water decrease with elevation (Dansgaard, 1964). This altitude effect is mainly attributed to Rayleigh distillation, the progressive depletion of heavy isotopes ($^{18}$O and D) from vapor and precipitation, as an air mass moves over an orographic barrier and precipitates rain. However, in regions of strong convection or subsidence, air-mass mixing can cause the altitudinal decrease in $\delta^{18}$O and $\delta$D to deviate from values expected from Rayleigh distillation (Lee et al., 2007). On average, the oxygen isotopic composition of precipitation decreases with elevation at a rate of 2.8‰ km$^{-1}$ (Poage and Chamberlain, 2001).

The altitude-isotope relationship has been exploited to estimate past surface elevations by employing the isotopic composition of near-surface authigenic minerals as a proxy for ancient meteoric waters. Using empirical isotopic lapse rates, changes in the isotopic composition of these minerals in chronosequences are interpreted to estimate the timing and magnitude of past elevation change. This technique, known as stable isotope paleoaltimetry, has been applied to reconstruct Cenozoic paleoel- evation histories of the Andean Plateau, Sierra Nevada of California, Basin and Range, Rocky Mountains, Cascade Mountains, European Alps, Southern Alps of New Zealand, Tibetan Plateau, and Himalayas (Mulch and Chamberlain, 2007). Implicit in this technique is accurate knowledge of the local isotopic lapse rate at the time that the proxy was deposited. In lieu of this information, modern isotopic lapse rates are often employed. Several studies have demonstrated that climate change associated with surface uplift can influence past isotopic lapse rates, complicating or compromising paleoaltimetry estimates (Ehlers and Poulsen, 2009; Galewsky, 2009; Poulsen et al., 2010).

The influence of global climate change on stable isotope paleoaltimetry has received less attention, even though the major orogens have been tectonically active through the Cenozoic, an interval of long-term cooling. Using a model of Rayleigh distillation, Rowley and Garzione (2007) estimated that due to the reduction in equilibrium isotopic fractionation with temperature, a lifting warm air parcel will undergo less isotopic fractionation than a cold one, yielding a smaller isotopic lapse rate. In contrast, using a simple upslope model of orographic precipitation, Molnar (2010) argued that an increase in saturation vapor pressure and specific humidity in a warmer climate will lead to higher orographic rainfall rates, an increase in isotopic fractionation through rainout, and larger isotopic lapse rates in orogenic settings. Neither of these models accounts for changes in environmental conditions or large-scale dynamics in a warmer climate. These opposing views lead to the unsatisfactory conclusion that paleoaltimetry estimates of Ceno- zoic surface uplift could be overestimates or underestimates due to the influence of global climate change on isotopic lapse rates.

In this contribution we investigate the influence of global climate change, and specifically Cenozoic cooling, on oxygen isotopic compositions of precipitation ($\delta^{18}$O) using an isotope-tracking global climate model. We compare results from preindustrial and warm climate scenarios and demonstrate that, due to enhanced upper troposphere warming, isotopic lapse rates in orogenic settings are reduced in a warmer climate.

MODEL DESCRIPTION AND EXPERIMENTS
Three modern-day experiments were completed with atmospheric $p$CO$_2$ levels of 1x (280 ppmv), 2x (560 ppmv), and 4x (1120 ppmv) preindustrial levels. The simulations were completed using the GENESIS version 3.0 earth system model, which consists of an atmospheric general circulation model (AGCM) coupled to multilayer models of vegetation, soil and land ice, and snow (Thompson and Pollard, 1997). Sea-surface temperatures and sea ice are computed using a 50 m slab oceanic layer with diffusive heat fluxes and a dynamic sea-ice model. A land-surface transfer model accounts for the physical effects of vegetation, soil, and soil water. Because the representation of topographic gradients is important for simulating rainfall $\delta^{18}$O in these regions, a spectral resolution of T63 (~1.9°) was implemented in the AGCM and land-surface model. The AGCM has 18 vertical levels.

In our version of GENESIS, water isotopic transport and fractionation processes have been added to the atmospheric physics (Mathieu et al., 2002). The $^{18}$O/$^{16}$O and D/H ratios are predicted in atmospheric vapor, liquid, and ice, and also in soil water reservoirs. Fractionation is modeled as a result of condensation and evaporation in the free atmosphere and from surface waters. Atmospheric ratios are transported using the same Lagrangian transport as for bulk vapor and clouds. The simulation of meteoric and seawater $\delta^{18}$O and $\delta$D in GENESIS has been shown to compare well with modern global observations (Mathieu et al., 2002; Zhou et al., 2008; Poulsen et al., 2010) and paleoextrapolation models of rainfall $\delta^{18}$O (Poulsen et al., 2007). In agreement with observations, GENESIS simulates an altitude effect and low
\( ^{18}\text{O} \) (v is vapor) over high-elevation surfaces (Fig. DR1 in the GSA Data Repository).

Simulations differ only in the prescription of atmospheric \( p\text{CO}_2 \). All other boundary conditions, including geography, atmospheric trace gases (\( \text{CH}_4, \text{N}_2\text{O}, \text{chlorofluorocarbons} \)), orbital parameters, and land-surface characteristics, were set to A.D. 1991–1995 values. Each simulation was integrated more than 40 model years. The results shown here represent averages over the final 10 model years.

**CLIMATE MODEL RESULTS**

In GENESIS, the 4× increase in \( p\text{CO}_2 \) leads to global mean annual warming of 6.5 °C. The primary oxygen isotopic response, \( \Delta^{18}\text{O} \), to global warming is an increase in \( ^{18}\text{O} \), due to reduced isotopic fractionation during surface evaporation at higher temperature (Fig. 1). Because of polar amplification of greenhouse warming, high- and mid-latitude regions undergo \( ^{18}\text{O} \) increases of several per mil (‰), while zonal average increases at low latitudes are generally <2‰ (Fig. 1B; Poulsen et al., 2007; Zhou et al., 2008).

Regional \( \Delta^{18}\text{O} \) varies substantially from the zonal average. In particular, high-elevation regions including the Rocky Mountains, the Andean Mountains, the European Alps, and the Tibetan Plateau have \( ^{18}\text{O} \) increases of >3‰ and as much as 8‰ (Fig. 1C). The \( ^{18}\text{O} \) increases at high elevations are systematically greater than those at low elevations with the consequence that the \( ^{18}\text{O} \) gradient across orographic settings decreases by ~2‰–6‰.

The regional changes in surface \( ^{18}\text{O} \) are directly linked to warming in the troposphere. In the 4× experiment, higher temperatures raise the atmospheric saturation vapor pressure according to the Clausius-Clapeyron relation. The increase in saturation vapor pressure enhances surface evaporation and moistening of the atmospheric boundary layer, resulting in higher specific humidity. At low latitudes, where the low-level troposphere is near saturation, convection transports vapor upward, increasing absolute humidity aloft. Moistening enhances troposphere warming through infrared absorption and reduces the surface to upper level temperature gradient (Fig. 2A). The troposphere response to greenhouse gas loading in GENESIS is a robust feature in climate models and has been observed in satellite measurements (Soden et al., 2005).

Due to the temperature (\( T \)) dependence of isotopic fractionation, \( \Delta^{18}\text{O} \) largely mimics \( \Delta T \). However, because \( \Delta^{18}\text{O} \) at any level is a

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1GSA Data Repository item 2011186, supplementary material, Figure DR1 (simulated annual amounted-weighted precipitation \( ^{18}\text{O} \) for the modern climate) and Figure DR2 (annual amounted-weighted \( ^{18}\text{O} \) predicted using prescribed sea-surface temperatures and a slab-ocean model), is available online at www.geosociety.org/pubs/ft2011.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.
function of the integrated fractionation as the air parcel is lifted from the surface through the troposphere, the maximum tropospheric $\Delta^{18}O_{p}$ is offset to higher altitudes relative to the maximum $\Delta T$. The net effect of warming then is to increase tropospheric $\delta^{18}O$ and to decrease the near-surface to upper level $\delta^{18}O$ gradient throughout low and middle latitudes (Fig. 2B). In polar regions, surface warming is sufficiently large that increases in surface $\delta^{18}O$ are similar to those in the troposphere, so that the near-surface to upper level $\delta^{18}O$ gradient is not substantially reduced.

The large increase in $\delta^{18}O$ over high-elevation surfaces results from the nonuniform increase in $\delta^{18}O_{v}$ through the troposphere. Precipitation forms once an air parcel reaches saturation at the lifting condensation level (LCL). The LCL occurs at higher altitudes over high-elevation surfaces than it does over low-elevation surfaces (note the LCL in Fig. 3). As a consequence, precipitation over high-elevation surfaces condenses from vapor from higher altitudes that is more enriched in $\delta^{18}O$ due to warming than precipitation that forms over low-elevation surfaces (Fig. 3).

Subsidence of middle and upper troposphere vapor over the orogens further increases high elevation $\delta^{18}O$ in a warmer world. Subsidence in orographic settings may result through gravity waves, which generate downward motion over a mountain and on its leeward side, in the westward limb of a stationary wave trough, or through large-scale sinking in monsoon regions (Broccoli and Manabe, 1997). Subsidence mixes middle tropospheric vapor, enriched in $\delta^{18}O$ relative to near-surface vapor, downward over the orogen. This effect can be seen in the downward deflection of $\delta^{18}O_{v}$ over the highest elevations (Figs. 3A and 3B) and on the leeward side of the mountains (Figs. 3B and 3C). Rainfall condensed from this vapor is also enriched in $\delta^{18}O$. The incursion of $\delta^{18}O$-enriched vapor into the lower troposphere is not limited to orographic regions, but generally occurs in regions of strong subsidence. Saharan low-level $\delta^{18}O$, for example, is 8‰–10‰ higher in the 4x experiment, leading to a $\Delta^{18}O_{p}$ increase by >6‰ and up to 9‰.

For clarity, we focused here on the isotopic response to a 4x increase in CO$_2$. In the 2x experiment, the global average temperature increase is 2.8°C. The isotopic response in the 2x case is similar but of smaller magnitude than the 4x case (Fig. 1C).

DISCUSSION AND IMPLICATIONS

Modeling Vapor and Precipitation Isotopic Compositions

The isotopic evolution of an air mass undergoing forced ascent is often treated as a Rayleigh distillation process in which the isotopic composition of the air mass progressively decreases through rainout. This treatment neglects large-scale circulation and mixing between the lifting parcel and its environment. Previous climate modeling and observational studies have shown that mixing during convection and subsidence affects the modern isotopic composition of vapor, causing it to deviate from values expected through Rayleigh distillation. In modern subtropical and monsoonal regions, the intrusion of low $\delta^{18}O$ from aloft depletes low-level air in the heavier isotope (Lee et al., 2007; Brown et al., 2008). Similarly, an isotopic rain shadow has been observed on the leeward side of mountain ranges due to adiabatic cooling and descent of low $\delta^{18}O$ air (Bloschl and Stern, 2005). Our results are consistent with these previous studies, and demonstrate that atmospheric subsidence of vapor enriched in $\delta^{18}O$ and D in a warmer climate increases high-elevation $\delta^{18}O$ and decreases the vertical $\delta^{18}O$ gradient.

Some limitations are implicit with the use of a relatively coarse resolution AGCM with a slab-ocean model. Spectral truncation of orography causes smoothing of finer topographic features. Thus, while large-scale isotopic patterns are robust, the model is too coarse to predict detailed patterns of $\delta^{18}O$ on a mountain range. In addition, the use of a slab-ocean model with zonal sea-surface temperatures may affect the strength and position of deep convection and subsidence. In the modern climate, deep convection occurs primarily over tropical regions of high sea-surface temperature, and is suppressed in tropical regions of oceanic upwelling (Graham and Barnett, 1987). To evaluate the influence of the slab-ocean model on the simulation of $\delta^{18}O_{p}$, we compare results from our 1x experiment with a simulation with prescribed modern sea-surface temperatures (Fig. DR2). The use of a slab-ocean model enhances large-scale subsidence over the continents, leading to slightly lower continental $\delta^{18}O_{p}$ over subtropical regions and mountains. Because the slab-ocean model was systematically implemented in all experiments, we consider GENESIS predictions of $\Delta^{18}O_{p}$ to be robust. Nonetheless, our results should be viewed as a guide to, but not an absolute prediction of, large-scale $\delta^{18}O_{p}$, and require confirmation by higher resolution climate models with dynamic ocean circulation.

Implications for Paleoaltimetry

Our results suggest that stable isotope records in high-elevation regions may be prone to climate overprinting that obscures changes in surface elevations. Is there evidence for this overprinting? Assuming that deep-sea carbonate $\delta^{18}O$ broadly tracks global climate, the Cenozoic was marked by a warming (~5°C) through the end Cretaceous and Paleocene, substantial cooling (~7°C) between the early-middle Eocene and early Oligocene, followed by smaller (~2°C) cooling events in the late Miocene and Pliocene–Pleistocene (Zachos et al., 2001). Over the same interval, atmospheric CO$_2$ fell from values generally >1000 ppmv to values <500 ppmv by the early Oligocene, and remained at relatively low levels through the Neogene (Pagani et al., 2005). Two sedimentary $\delta^{18}O$ records from western North America span this early Cenozoic interval of large climate change. Dettman and Lohmann (2000) reported an ~6‰ increase from the Campanian through the early Eocene in freshwater bivalve shell $\delta^{18}O$ from the U.S. Western Interior; this
was interpreted to record the isotopic composition of river water that drained the interior basins and adjacent mountains. Horton et al. (2004) reported a ~10‰ decrease in middle Eocene authigenic calcite, smectite, and chert δ18O from the Great Basin and Sierra Nevada of North America, and attributed as much as 4‰ of this signal to regional cooling. Although multiple interpretations of these records are possible, we suggest that they track early Cenozoic global warming and cooling trends, providing tentative confirmation of climate overprinting. On the basis and cooling trends, providing tentative confi rmations of these records are possible, we suggest Basin and Sierra Nevada of North America, Δδ18O is representative of regional lapse rates, paleoel-


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