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Geochimica et Cosmochimica Acta 105 (2013) 342–359
Geochimica et Cosmochimica Acta
www.elsevier.com/locate/gca

Isotopic and hydrologic responses of small, closed lakes to climate variability: Hydroclimate reconstructions from lake sediment oxygen isotope records and mass balance models

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Received 5 October 2011; accepted in revised form 15 November 2012; available online 2 December 2012

Abstract

Hydroclimate sensitivity simulations were conducted with a lake-catchment hydrologic and isotope mass balance model adapted to two small, closed lakes (Castor and Scanlon) located in the Pacific Northwest. Model simulations were designed to investigate the combined influences of persistent disequilibrium, reddening, and equifinality on lake water and sediment (i.e., biogenic and endogenic carbonate mineral) oxygen isotope ($\delta^{18}O$) values and to provide a basis for quantitative, probabilistic climate reconstructions using lake sediment $\delta^{18}O$ records. Simulation results indicate that within closed-basin lakes changes in long-term (i.e., multi-decadal) precipitation amounts produce inconsistent responses in lake water and sediment $\delta^{18}O$ values that are strongly influenced by lake basin outseepage and morphometry. Simulations of variable initial conditions in which randomly generated monthly climate data (i.e., precipitation, temperature, and relative humidity) were used to force the model during the equilibration period (which precedes the application of instrumental climate data) demonstrate that Castor Lake and Scanlon Lake have a somewhat limited isotopic 'memory' of ~10 years. Additional tests conducted using a Monte Carlo ensemble (in which random climate data were used to force the model) combined with $\delta^{18}O$ analyses of water samples collected from 2003 to 2011 AD, indicate that within small, closed lakes in the Pacific Northwest November–February precipitation is the strongest seasonal, climatic control on sediment oxygen-isotope values. Further, a Monte Carlo based reconstruction of 20 year average November–February precipitation amounts strongly correlates ($R^2 = 0.66$) to instrumental values from the 20th century (with all observed values falling within modeled 95% prediction limits), indicating that probabilistic, quantitative paleoclimate interpretations of lake sediment $\delta^{18}O$ records are attainable.

1. INTRODUCTION

The oxygen ($\delta^{18}O$) and hydrogen (δD) isotopic composition of lake water is influenced by multiple factors including lake morphology, catchment size and hydrologic characteristics, groundwater throughflow rates, and climate variations (Gonfiantini, 1986; Almendinger, 1990; Smith et al., 1997; Leng and Marshall, 2004; Steinman et al., 2010a). Despite the multitude of controls on lake hydrology, isotopic processes within lakes are well understood due to a large number of modeling and observational studies (e.g., Gat, 1970; Hostetler and Benson, 1994; Donovan et al., 2002) in which the effects of climate, catchment and groundwater controls have been described and reproduced through model experiments. This abundance of research has formed a basis for qualitative and semi-quantitative paleoclimate interpretations of lake sediment (i.e., biogenic or endogenic carbonate) $\delta^{18}O$ and δD records (Sachs et al., 2009; Bird et al., 2011; Nelson et al., 2011) as well as model based quantitative reconstructions of paleoprecipitation and humidity (Ricketts and Johnson, 1996; Cross et al., 2001; Anderson et al., 2007; Jones et al., 2007). To date however quantitative paleoclimate reconstructions have not been produced in which modern sediment core isotope

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0016-7037/$ - see front matter
http://dx.doi.org/10.1016/j.gca.2012.11.027

records were interpreted using lake models to reproduce instrumental (i.e., measured) hydroclimatic variability for the purposes of model validation/verification (i.e., similar to exercises conducted in tree-ring based paleoclimate reconstructions). Obstacles to such efforts have included the complexity inherent in the combined influence of mean state (i.e., multidecadal to century scale) and stochastic (i.e., random, monthly to inter-annual) climate variations on lake hydrologic and isotopic evolution (Benson and Paillet, 2002; Leng et al., 2005; Steinman et al., 2010b) and the difficulty in accounting for these controls in lake models. Other problems have included a lack of instrumental climate data (Jones et al., 2005), insufficient observation or measurement of lake hydrologic and isotopic processes (e.g., outseepage rates), and the confounding effects of catchment alteration on modern lake hydrology. Overcoming these obstacles could potentially allow lake sediment isotope records to be quantitatively interpreted to produce statistically validated paleoclimate reconstructions.

Lake surface water $\delta^{18}O$ values in seasonal climates are primarily controlled by the balance between the inflow of fresh meteoric water (e.g., via the subsurface and catchment runoff) during the cooler seasons (when evapotranspiration rates are low and catchment water balance is positive), water losses through evaporation during the warmer seasons, and outflow through non-fractionating pathways (i.e., overflow and outseepage through the lake bed). The isotopic composition of inflowing water is an additional control that is influenced by various factors including temperature at the time of precipitation (e.g., in the mid-latitudes summer rainfall $\delta^{18}O$ values are high and winter values are low) and the origin and rainout history of the air mass (Dansgaard, 1964; Rozanski et al., 1992, 1993). Hydrologically closed lakes lose the majority of water through evaporation and are more isotopically enriched relative to open lakes, which lose the majority of water through non-fractionating outflows. The limiting cases are a closed lake that loses all water through evaporation, and therefore is at the limit of isotopic enrichment (Gat, 1984), and an open lake that loses no (or very little) water through evaporation, and maintains an isotopic composition similar (or identical) to that of meteoric water (von Grafenstein et al., 1996; Hammarlund et al., 2002; Anderson et al., 2005).

In seasonal climates, closed lakes are in a state of persistent intra- to inter-annual (i.e., transient) hydrologic and isotopic disequilibrium (Gibson et al., 2002; Shapley et al., 2008; Jones and Imbers, 2010) resulting from disparity in seasonal water inflow and losses through evaporation. This shorter-term disequilibrium, however, exists within a longer-term equilibrium state in which short timescale (e.g., seasonally derived) isotopic variations produce average $\delta^{18}O$ values over many years that are primarily a function of mean state climate conditions (Steinman et al., 2010b). Given that smaller lakes typically have shorter residence times, seasonality can exert a strong influence on small lake water isotopic evolution, leading to large intra-annual variance in surface water $\delta^{18}O$ values. Because of these circumstances, small lakes respond more quickly to decadal to sub-decadal climate variability, and therefore have the potential to produce sediment paleoclimate archives that contain information on a wide range of timescales.

Although small lakes exhibit greater seasonal sensitivity, they have several characteristics that make them relatively easier to model and therefore understand in the context of paleo-interpretations of lake sediment isotope records. Small lakes, for example, generally have simple catchments that span a narrow elevation range and that contain relatively few soil and vegetation types, factors that are difficult to account for when determining hydrologic characteristics such as soil available water capacity. Additionally, small lakes are typically overlain by advected air masses that contain minimal moisture derived from lake surface evaporation, an important distinction given that measuring the fraction of advected air over a large lake is difficult and adds complexity to calculations of the isotopic composition of evaporation (Benson and White, 1994). Accounting for the fundamental differences between large and small lakes is important in model design and potentially precludes the use of large lake models on smaller lakes, and vice versa, in paleoclimate applications.

The relative hydrologic and isotopic simplicity of small lakes notwithstanding, there are several inherent aspects of all lake systems that can potentially complicate paleoclimate interpretations of sediment geochemical variations: namely, the persistent state of disequilibrium (in both lake hydrology and isotopic processes), reddening (i.e., red noise in water and sediment geochemical values), and equifinality. Persistent disequilibrium occurs to a greater degree in small lakes and can lead to extensive water geochemical variance over seasonal to inter-annual timescales. This may cause difficulties when interpreting, for example, isotope records from lakes in which the timing of carbonate mineral formation changes substantially from year to year or when mixing (e.g., through bioturbation) changes the temporal resolution of sediment. Reddening is a condition in which lake responses to climatic perturbation depend on the hydrologic and isotopic state of the lake at the time of the climatic change. Reddening has been investigated through modeling studies (Benson et al., 2002; Steinman et al., 2010a) and is a generally well understood complicating factor for the interpretation of lake sediment geochemical records, especially in the case of large lakes with long residence times. Equifinality results in part from reddening and persistent disequilibrium and is defined as a state in which many possible climate (and resulting lake hydrologic and isotopic) scenarios can produce a specific lake water or sediment geochemical (i.e., $\delta^{18}O$ or salinity) value. Equifinality occurs to a greater extent in lakes that have a similar sensitivity to two or more hydroclimatic variables. One example would be a lake system in a monsoonal setting in which the majority of precipitation falls during the warmer season, a scenario that could lead to a high level of both temperature and precipitation sensitivity (Henderson and Shuman, 2009) and could lead to an inability to distinguish in the sediment record between past wetter or cooler (and hotter or drier) conditions. All three of these characteristics (disequilibrium, reddening, and equifinality) can produce "noise" in lake sediment geochemical records that, depend-