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Introduction

Water isotope systematics: Improving our palaeoclimate interpretations

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The stable isotopes of oxygen and hydrogen, measured in a variety of archives, are widely used proxies in Quaternary Science. Understanding the processes that control $\delta^{18}O$ change have long been a focus of research (e.g. Shackleton and Opdyke, 1973; Talbot, 1990; Leng, 2006). Both the dynamics of water isotope cycling and the appropriate interpretation of geological water-isotope proxy time series remain subjects of active research and debate. It is clear that achieving a complete understanding of the isotope systematics for any given archive type, and ideally each individual archive, is vital if these palaeo-data are to be used to their full potential, including comparison with climate model experiments of the past. Combining information from modern monitoring and process studies, climate models, and proxy data is crucial for improving our statistical constraints on reconstructions of past climate variability.

As climate models increasingly incorporate stable water isotope physics, this common language should aid quantitative comparisons between proxy data and climate model output. Water-isotope palaeoclimate data provide crucial metrics for validating GCMs, whereas GCMs provide a tool for exploring the climate variability dominating signals in the proxy data. Several of the studies in this set of papers highlight how collaborations between palaeoclimate experimentalists and modelers may serve to expand the usefulness of palaeoclimate data for climate prediction in future work.

This collection of papers follows the session on *Water Isotope Systematics* held at the 2013 AGU Fall Meeting in San Francisco. Papers in that session, the breadth of which are represented here, discussed such issues as; understanding sub-GNIP scale (Global Network for Isotopes in Precipitation, (IAEA/WMO, 2006)) variability in isotopes in precipitation from different regions, detailed examination of the transfer of isotope signals from precipitation to geological archives, and the implications of advances in understanding in these areas for the interpretation of palaeo records and proxy data – climate model comparison.

Here, we briefly review these areas of research, and discuss challenges for the water isotope community in improving our ability to partition climate vs. auxiliary signals in palaeoclimate data.

1. Isotopes in precipitation and surface water

Understanding water isotopes in proxies and models begins with their measurement in atmospheric vapor and water, ongoing now for over five decades, through established monitoring networks, individual research projects, and remote sensing, at temporal scales ranging from seconds to monthly composites (Darling et al., 2006). From the proxy perspective, however, with the exception of ice cores, the water isotopes incorporated within archives are rarely derived directly from precipitation. Rather, terrestrial isotope archives, such as lake sediments, speleothems and trees, incorporate surface and near-surface waters that may or may not have the same relationships to climate as atmospheric vapor and precipitation. This complication is addressed by Gibson et al., Jones et al., Anderson et al., 2016 and Murkowska et al. 2016. However, for all archives, the understanding of local-to-regional climate controls on precipitation isotope compositions, needed to evaluate isotope proxy records, typically comes from either a few, distant, long-term network stations, or from short-term local measurements if financial and logistical constraints allow (e.g., Bailey et al., 2015; Berkelhammer et al., 2011; Ersek et al., 2012; Klein et al., 2015; Liu et al., 2014). Thus, in terms of monitoring water isotopes in space and time, there is presently notable interest in the proxy community focused on (1) developing strategic precipitation and surface water monitoring approaches to observe isotope systematics between climate, local-to-regional precipitation, and individual proxy archive locations and (2) how to apply monitoring measurements and to appropriately develop proxy calibrations with space-for-time or time-

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for-space relationships, with appreciation for relative strengths and limitations.

Three studies in this special issue address monitoring of precipitation and surface water and assess implications for paleoclimatic interpretations. Sánchez-Murillo et al. (2016) investigate the commonly applied tropical “amount” effect on precipitation isotope ratios identified from GNIP measurement over multiannual time scales, known to substantially weaken at shorter time scales. They present isotope measurements of daily Costa Rican precipitation for 2013 from three strategic locations to more precisely identify regional climate controls on rainfall δ^{18}O. Similarly, Klein et al. (2016) interpret the McCall glacier ice core record from Northern Alaska based on 254 event-based precipitation samples obtained nearby over an 18-year period. Utilizing the temporal climate-isotope relationships identified from a fixed location, they apply a local δ^{18}O-T coefficient to the ~65 year long ice core record, with consideration for vapor source and circulation changes. Finally, (Anderson et al. 2016) present a new long-term monitoring network in North America of isotopes in Rocky Mountain snowpack with ~20 years of integrated snowpack measurements at 57 locations. The temporal and spatial measurements provide the first opportunity for comparisons between mid-latitude snowpack isotope composition and climate variability. New insights are utilized to re-evaluate previously presented Holocene isotope records with snowpack dominated water sources.

Each of these studies illustrates the potential for local to regional monitoring to inform interpretations of proxy records. For example, analyses of daily-scale Costa Rican precipitation and meteorological data provide a more dynamically-based understanding of variations that occur over the seasonal cycle. The dominant controls on precipitation and cave drip water, including vapor origin and transport, surface humidity, and lifted condensation levels have important implications for speleothem isotope time series in the region, which can be sampled at annual to sub-annual resolution (e.g., Lachniet et al., 2007). The event-scale precipitation data from northern Alaska (Toolik Lake), the first long-term measurements in the region, indicates a δ^{18}O-T coefficient of 0.36‰ per $^{\circ}$C, considerably lower than the range of spatial and temporal GNIP based estimates for this latitude (0.7–0.9‰ per $^{\circ}$C). Further analyses of the ice core suggests the significance of additional influences, including changes in source vapor related to sea-ice extent and decadal-scale North Pacific atmospheric circulation patterns. Lastly, the Rocky Mountain snowpack network also indicated a low spatial δ^{18}O-T relationship of 0.4‰ per $^{\circ}$C (similarly to northern Alaska), characterized by significant spatial heterogeneity. Temporal δ^{18}O-T relationships varied through time from 0.23 to 0.63‰ per $^{\circ}$C. Drier/warmer years had a tendency to have no statistically significant correlation at all that suggests the significance of post-depositional effects.

As demonstrated by these authors in particular, local-to-regional monitoring at a proxy location provides important evidence for location-specific physical processes, providing additional insight towards the ultimate paleoclimatic interpretation.

2. Modeling water isotopes and the climate

This special issue additionally highlights the utility of water isotope-enabled GCMs for the enhanced interpretation of proxy data. Using water isotope-enabled GCMs constitutes a point of common comparison with water isotope based climate archives and provides a basis for dynamical interpretations of the paleoclimatic data. In particular, modeling water isotopes in the atmosphere provides insights in the hydrological cycle including circulation changes, temperature, precipitation, condensation, evaporation and vapor source (Sturm et al., 2010; Dee et al., 2014).

Stable water isotope physics have been added to a number of GCMs to-date, including but not limited to: the National Center for Atmospheric Research Community Atmosphere Model (CAM2) (Lee et al., 2007), European Centre/Hamburg (ECHAM4) (Hoffmann et al., 1998), Goddard Institute for Space Studies (GISS) (Schmidt et al., 2007), Hadley Center Coupled Model 3 (HadCM3) (Tindall et al., 2009), iLOVECLIM (Roche, 2013), IsoGSM (Yoshimura et al., 2008), Laboratoire de Météorologie Dynamique Zoom 4 (LMDZ4) (Risi et al., 2010), Model for Interdisciplinary Research on Climate (MIROC) (Kurita et al., 2011), Global Environmental and Ecological Simulation of Interactive Systems 3 (GENESIS3) (Mathieu et al., 2002), Melbourne University General Circulation Model (MUGCM) (Noone and Simmonds, 2002), SPEEDY-IER (Simplified Parameterizations, Primitive Equation Dynamics with Isotope-Enabled Reconstructions) (Dee et al., 2014), and UVic ESCM (Brennan et al., 2012). Many of these isotope-enabled models have been compared by the Stable Water Isotope Intercomparison Group projects SWING and SWING2 (http://www.giss.nasa.gov/staff/gschmidt/SWING2.html; e.g. Conroy et al., 2013), and share the common capability of tracking changes in the hydrological cycle as they manifest in water isotope signals.

Explicitly embedding water isotope tracers within the physics of a GCM serves to check the reliability of proxy-environment relationships, and helps highlight potential uncertainties. In this issue, Holloway et al. illustrate the usefulness of the isotope-enabled Hadley Center Model (HadCM3) to examine the stationarity of the relationship between oxygen isotope ratios in seawater to sea surface salinity (δ^{18}Osw-SSS) on longer timescales. The isotope enabled modeling framework allows for the identification of uncertainties such as freshwater budget, circulation, and sea ice dynamics, and the impacts of such uncertainties on the stability of this widely-used δ^{18}Osw-SSS slope for paleoceanographic studies. Further, the authors identify that paleosalinity reconstructions may be more robust within specific regions, and identify these regions explicitly using the coupled isotope-enabled model. Their work importantly suggests that further constraint is needed when using the δ^{18}Osw-SSS gradient for reconstruction purposes.

Similarly, Holmes et al. (2016) illustrate the utility of isotope-enabled GCMs for enhanced interpretability of proxy archives. The authors employ HadCM3 to explore oxygen isotope variability in three lakes in western Ireland across the 8.2 ka (‘early Holocene cooling’) event. The study uses an ensemble of nine transient simulations centered on boundary conditions appropriate for 9ka with a freshwater melt push mimicking the draining of Lake Agassiz (Tindall and Valdes, 2011). Comparing the timing and magnitude of the isotopic excursions observed in the three Atlantic margin lakes to HadCM3 simulations of precipitation isotopes allows the authors to explore potential dynamical drivers of the observed cooling in Northern Europe. The study finds that all of the ensemble members show effective moisture (lower evaporation coupled with reduced precipitation) linked to a decrease in δ^{18}O of precipitation over the study area, and thus provide a climatic interpretation for the lake δ^{18}O records, as supported and confirmed by model experiments.

These studies illustrate the usefulness of isotope-enabled GCMs for providing additional dynamical constraints on paleoclimatic data interpretation. Water isotopes are a critical addition, facilitating direct comparison between model and archive by providing a common language linking the two.