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INVITED COMMENTARY

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# Current state and future challenges in stable isotope applications of the tropical hydrologic cycle (*Invited Commentary*)

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## 1 | CURRENT APPLICATIONS

Both basic research and applications of stable isotope hydrology in the tropics have come a long way since the seminal work by early pioneers such as Dansgaard (1964), Gat (1996), and Araguas-Araguas, Froehlich, and Rozanski (2000). Stable isotopes are now routinely used in tropical meteorology, contributing to diagnosing a number of synoptic-scale atmospheric processes, including cyclone water and energy budgets (Lawrence & Gedzelman, 1996), boundary-layer processes (see review in Galewsky et al., 2016), the role of stratiform versus convective processes in tropical precipitation (Aggarwal et al., 2016; Zwart, Munksgaard, Protat, Kurita, & Bird, 2018), intraseasonal (Kurita et al., 2011) and intra-storm variability (Cobb, Conroy, Hitta, & Bosma, 2018; Conroy, Noone, Cobb, Moerman, & Konecky, 2016), the role of raindrop re-evaporation in convective systems (Lee & Fung, 2008; Risi, Bony, & Vimeux, 2008) and its contribution to lower tropospheric humidity (Worden, Noone, & Bowman, 2007), or detection of changes in moisture source contribution (e.g., Gimeno et al., 2012; Levin, Zipser, & Cerling, 2009). The advanced use of information on the isotopic composition of water vapour may hold potential for improving operational meteorology and weather forecasting (e.g., Yoshimura, 2015). Galewsky et al. (2016) give an excellent review on current stable isotopic applications in studies of atmospheric circulation and the hydrologic cycle.

Stable isotopic mixing models are commonly applied to determine the contribution of plant transpiration versus soil and open water evaporation to the isotopic composition of the lower troposphere (e.g., Moreira et al., 1997). Such isotopic studies of biometeorological processes are important to understand changes in transpiration associated with deforestation and land use change and can pinpoint the relevance of plant transpiration to the overall atmospheric water budget in tropical catchments and at a global scale (e.g., Good, Noone, & Bowen, 2015; Jasechko et al., 2013; Wang, Good, Caylor, & Cernusak, 2012).

In surface and groundwater hydrology, d-excess is often analysed as an indicator of the degree of local recycling and evaporation in surface water (lakes, rivers), subsequently also affecting groundwater. Indeed, stable water isotopologues have long been used to analyse the run-off contribution of individual storms through hydrograph separation (see reviews by Buttle & McDonnell, 2004 and Klaus & McDonnell, 2013). On longer timescales, isotopic mixing and mass balance models also are often used to estimate water recharge to aquifers but also contributions of groundwater to river base flow (Vianna Batista et al., 2018) or the relevance of glacier melt to river run-off (Mark & McKenzie, 2007). These results can have important implications for groundwater use, informing and guiding regulations on the optimal management of water resources (e.g., Madrigal-Solís, Fonseca-Sánchez, Núñez-Solís, & Vadillo, 2018).

Maybe the most significant contribution of stable isotope hydrology has been in advancing our understanding of climate variability on longer timescales, ranging from interannual to millennia and beyond. The realization that the stable isotopic composition of precipitation is sensitive to variations in atmospheric circulation through transport, mixing, and phase changes has led to significant progress in our understanding of tropical modes of coupled ocean–atmosphere variability, such as El Nino - Southern Oscilation (ENSO) (Tan, 2014; Vuille & Werner, 2005; see also Kurita, Ichiyanagi, Matsumoto, & Yamanaka, 2018), the Indian Ocean Dipole (Konecky, Russell, Vuille, & Rehfeld, 2014), or the global monsoon (Araguas-Araguas, Froehlich, & Rozanski, 1998; Gao, Dai, Yao, & Risi, 2018; Tian, Masson-Delmotte, Stievenard, Yao, & Jouzel, 2001; Vuille et al., 2012; Vuille, Werner, Bradley, & Keimig, 2005) and its onset and demise (Yu et al., 2016). A large number of tropical archives contain long records of past variations in the isotopic composition of meteoric waters, facilitating the reconstruction of such modes from tropical ice cores (Thompson & Davis, 2005), speleothems in monsoon regions (Cheng, Sinha, Wang, Cruz, & Edwards, 2012; Cruz Jr. et al., 2005; Fleitmann et al., 2003; Lachniet, 2009; Wang et al., 2001), calcite or biomarkers in lake sediments (Bird et al., 2011; Leng & Marshall, 2004; Zhang et al., 2011), tree ring cellulose (Brienen, Helle, Pons, Guyot, & Gloor, 2012; McCarroll & Loader, 2004; Miller et al., 2006), or coral records from across the tropical ocean (Cobb, Charles, Cheng, & Edwards, 2003; Tudhope et al., 2001).

Although observational and paleoclimatic studies have significantly advanced our understanding of the past and present tropical hydrologic cycle, the advent of isotope-enabled climate models has revolutionized the field. Such models have proven key to advancing our understanding of the dynamics and forcing mechanisms that drive isotope variations across spatial and temporal scales, and opened up new possibilities for detailed analyses of processes affecting the isotopic composition of precipitation (Colose, LeGrande, & Vuille, 2016; Hoffmann, Werner, & Heimann, 1998; Jouzel, Hoffmann, Koster, & Masson, 2000; Risi, Bony, Vimeux, & Jouzel, 2010; Schmidt, LeGrande, & Hoffmann, 2007; Vuille, Bradley, Werner, Healy, & Keimig, 2003). Although less common, some modelling groups have also incorporated stable isotopic tracers into regional isotope-enabled climate and hydrologic models (Belachew et al., 2016; Durán-Quesada et al., 2018; Stadnyk, Delavau, Kouwen, & Edwards, 2013; Sturm, Hoffmann, & Langmann, 2007; Yoshimura, Kanamitsu, & Dettinger, 2010), allowing for more detailed atmospheric studies over regions of complex terrain or focusing on specific isotopic processes related to streamflow and run-off generation or spatially distributed isotopic lake water balance. Because stable water isotopologues are tracers of the hydrologic cycle, they are on the other hand also ideally suited to test the realism of climate model parameterizations when simulating the tropical hydrologic cycle (Schmidt, Hoffmann, Shindell, & Hu, 2005) and can yield important modelling constraints for atmospheric water vapour transport, mixing, and phase change.

Although the interpretation of paleoclimate records has benefitted tremendously from the physical underpinning of isotope-enabled climate models, problems with scale-mismatch and archive-specific interpretations remain. Climate models can provide the direct isotopic composition of water vapour and precipitation, yet the mechanistic processes affecting the isotopic composition during the formation of the proxy itself are not simulated. Therefore, so-called proxy system-models (isotopic forward models) are increasingly being developed to simulate the actual proxy system, which senses and then archives the isotopic composition (Baker & Bradley, 2010; Dee et al., 2015; Evans, Tolwinski-Ward, Thompson, & Anchukaitis, 2013; Hurley, Vuille, & Hardy, 2016). This fairly new avenue holds considerable promise and is a critical link, required to accurately compare and constrain the isotopic composition simulated in climate models with the actual measured values in natural archives.

## 2 | FUTURE CHALLENGES

Although the progress in tropical isotope hydrology over the past 50 years is impressive, there are also significant challenges that remain. For example, little work has so far been dedicated towards understanding of isotopic proxies of the hydrologic cycle other than the most commonly analysed isotope ratios $\delta^{18}O$ and $\delta D$. More recent work focusing on the derivates d-excess and the similar second-order variable $^{17}O$-excess, derived from the combination of $\delta^{17}O$ and $\delta^{18}O$ of water, are still in their infancy and their climatic relevance and relationship with the tropical hydrologic cycle are still uncertain and hard to come to grips with (Luz & Barkan, 2010). Model results suggest that convective processes, relative humidity, and raindrop re-evaporation serve as dominant first-order controls on d-excess and $^{17}O$-excess in tropical precipitation (Risi, Landais, Winkler, & Vimeux, 2013), but the processes are still poorly understood and require further study. Nonetheless, the combined use of these two proxies may prove to be very useful in future studies to better constrain the isotopic processes associated with tropical convection (Landais et al., 2010).

Perhaps the biggest issue facing the community today is the lack of a spatially dense and temporally continuous observational isotopic database. Unfortunately, the current measurement network is inadequate to address 21st century isotopic research challenges, and the scarcity of the available observational data across the tropics is a real hindrance for many studies and applications. Although the International Atomic Energy Agency - Global Network of Isotopes in Precipitation (IAEA-GNIP) network has proven invaluable for many applications, it suffers from large gaps both in space and time. Many additional data gathering efforts have been launched across the tropics on a regional scale, with the goal of collecting and monitoring the isotopic composition of tropical precipitation. However, most of these activities were restricted to time-limited campaigns or opportunistic sampling strategies tagged on to other data collection programs. Hence, most of these efforts are not well coordinated; the data are often collected using varying standards and techniques and are often times not publicly accessible. Maintaining a dense network over long periods of time across the tropics in a coordinated fashion is, however, essential for understanding the influence of tropical climate variability on the isotopic composition at decadal- to multidecadal timescales and for improving proxy calibration and model validation. Furthermore, such a network is vital for detecting and analysing the potential anthropogenic fingerprint in the isotopic composition of water vapour and precipitation as the tropical hydrologic cycle adjusts to the atmospheric warming and the increase in the amount of atmospheric water vapour. Indeed, stable water isotopologues are extremely powerful tools that serve a large scientific community including tropical hydrologists, atmospheric scientists, glaciologists, climate modellers, ecologists, geochemists, and paleoclimatologists. We therefore can ill afford to let another decade go by without having an adequate observational in situ network in place.

Satellite observations from space have for the past 2 decades provided an additional avenue to provide denser sampling over the tropics (e.g., Lee et al., 2012; Worden et al., 2012), but the data from these satellite missions are limited to the isotopic composition of atmospheric water vapour and do not provide a substitute for a dense in situ network of actual surface measurements of precipitation. In addition, the limited lifetime of satellite sensors requires continuous deployment of follow-up missions and careful calibration efforts to maintain long and continuous data sets from space.

Spatial interpolation techniques (Bowen & Revenaugh, 2003) and isotope reanalyses (Steig, Anderson, & Hakim, 2017; Yoshimura, Kanamitsu, Noone, & Oki, 2008) can also provide spatio-temporally complete data sets that are useful for some applications. Isotope reanalyses have the added advantage of providing additional, four-dimensional, spatially complete, and physically consistent meteorological data. Yet isotope data from reanalyses are model-dependent and although very useful, they are no substitute for in situ measurements. In fact, maintaining such isotope reanalysis efforts into the future implicitly requires dense and high-quality observational data.

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