Preface to Stable isotopes in hydrological studies in the tropics: ecohydrological perspectives in a changing climate

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Preface to stable isotopes in hydrological studies in the tropics: Ecohydrological perspectives in a changing climate

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1 | PREFACE

Tropical regions (comprised between the Tropics of Cancer and Capricorn, 23.5°N to 23.5°S) cover approximately 36% of the Earth's landmass. They are home to 40% of the world's population, which is projected to increase over 50% by 2030 (State of the Tropics, 2014). During the last decade diverse scientific disciplines, environmental institutions, governments, and stakeholders have increased awareness of the importance of current tropical climate variability and the associated ecohydrological and societal responses (González, Georgescu, Lemos, Hosannah, & Niyogi, 2017; Wright et al., 2018). On the basis of the premise that warming-related changes in regional and global circulation patterns will affect tropical precipitation (Chou & Neelin, 2004) and may lead to an intensification of extreme events (i.e., an increase in tropical cyclone intensities, unprecedented floods, and severe droughts; Meehl et al., 2000; Walsh et al., 2016), risk management and water resources management in the tropics represent a major challenge (Seneviratne et al., 2012).

The global distribution of rainfall depicts maximum values in the tropics, where the incoming solar radiation peaks and the largest concentration of atmospheric water vapour is observed at a deeper tropopause. However, as the tropical belt is mostly covered with oceans, precipitation is not easy to monitor. Tropical ecohydrological conditions are usually under the influence of complex land–ocean–atmosphere interactions (Esquivel-Hernández, Sánchez-Murillo, Birkel, Good, & Boll, 2017; Wilcox & Asbjornsen, 2018) that produce a dynamic cycling of mass and energy composed of water vapour mixing ratio distributions, cloud formation mechanisms, precipitation and convergence, ecohydrological connectivity and services, groundwater recharge processes in complex aquifers, runoff generation, rapid land use changes, and vegetation dynamics.

The use of stable isotopes of water ($^{18}O/O^{16}$, $^{17}O/O^{16}$ $^{2}H/^{1}H$), second order variables (*d*-excess, *lc*-excess, or ^{17}O-excess), and other geochemical tracers (naturally occurring, industrial gases, or artificial substances) has been successful from observations (Sánchez-Murillo, Brooks, Elliot, & Boll, 2015) to tracer-aided modelling (Tunaley, Tetzlaff, Birkel, & Soulsby, 2017). Despite the recent advances in understanding stable isotope dynamics in hydrological studies, ecological assessments, climate variability analysis, and reconstructing paleoclimate conditions, a consensus exists regarding the urgent need for long-term and better spatial coverage of monitoring efforts. Particularly in tropical mountainous regions, whereby orographic effects, local moisture recycling, canopy interception, and intense evapotranspiration combined with complex microclimates may play an important role in influencing the isotopic ratios. Recently, the development of relatively inexpensive instrumentation based on laser spectroscopy has enhanced our ability to achieve greater temporal and spatial resolution of isotopic data; however such implementation in the tropics has not been fully exploited yet (Vuille, 2018).

For example, a literature search of published studies from 2000–2018 (ISI Web of Science) combining the keywords "isotopes" and "Europe"/"North America"/"Tropics" demonstrates the large bias among studies conducted in North America and Europe versus those conducted across the tropics (Figure 1). This research gap is explained by the considerably lack of (a) national and international research funding for isotopic monitoring in the tropics, (b) analytical instrumentation and appropriate facilities, (c) research-oriented graduate programs, and (d) societal–political stability in multiple countries in combination with the inherent complexity and remoteness of the studies sites. However, in recent years, pantropical research initiatives such as "Stable isotopes in precipitation and paleoclimatic archives in tropical areas to improve regional hydrological and climatic impact models" coordinated by the Isotope Hydrology Section of the International Atomic Energy Agency (https://www.iaea.org/projects/crp/f31004) have significantly improved water stable isotope monitoring (both spatially and temporally) across tropical regions (both continental and maritime) as well as in regions depending on tropical water vapour budgets.

Therefore, this special issue (Special issue: Stable isotopes in hydrological studies in the tropics) is extremely timely. The special

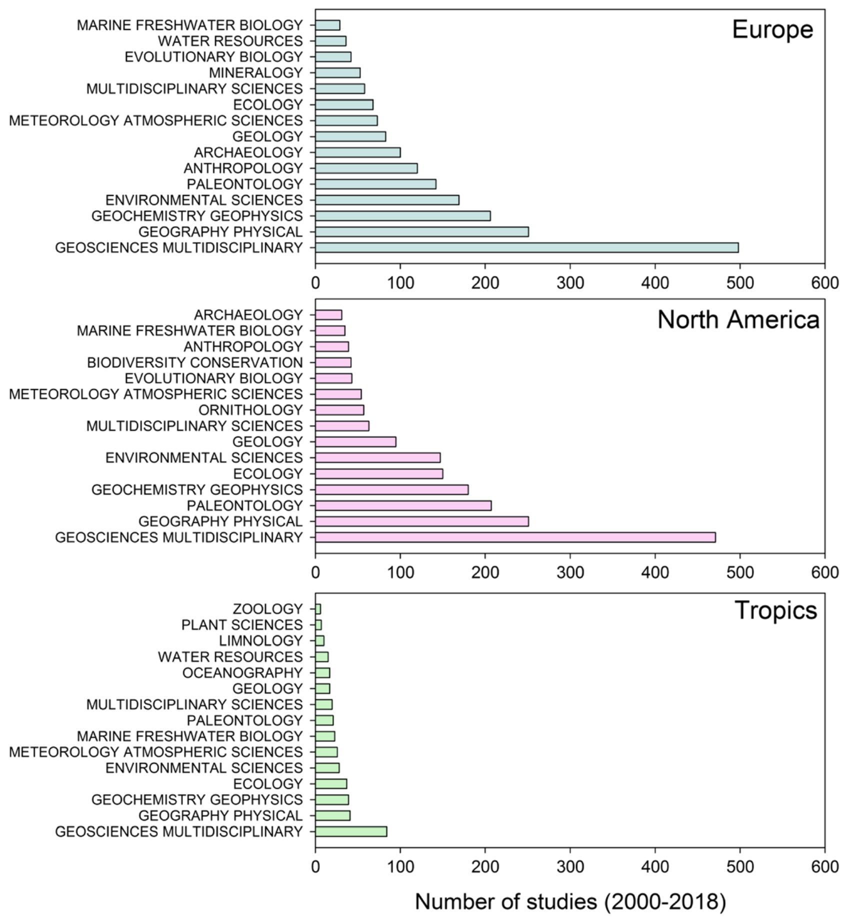

FIGURE 1 Literature search of published studies (ISI Web of Science) combining the keywords "isotopes" and "Europe"/"North America"/"Tropics" from 2000 to 2018

issue aims to improve the current understanding of (a) precipitation generation and key drivers controlling isotopic variations, (b) groundwater recharge processes in complex multilayer aquifers, (c) El Niño–Southern Oscillation (ENSO) influence on the tropical water cycle, and (d) surface and groundwater interactions (including nutrient transport) in agricultural–forestry landscapes, protected coastal and marine areas (e.g., mangroves) and high-elevation ecosystems (e.g., Páramo). The SI covers a wide spectrum of continental and maritime biomes across the tropics, including Australia, Brazil, Borneo, China, Colombia, Costa Rica, Galápagos Island, India, and Singapore.

2 | ATMOSPHERE–OCEAN PROCESSES

Understanding key drivers controlling stable isotope variations at different spatial (1 to 10^4 km: local to regional) and temporal (minutes to interannual: thunderstorms to ENSO) scales remains a challenge in the tropics. The continuous real time isotopic composition during rain events in Singapore (He et al., 2018) revealed that, besides the abrupt intraevent isotopic variations, convective activity prior to the events was strongly correlated with the observed isotope composition with a maximum correlation occurring with the accumulative convective episodes over the 2 to 3 days preceding the precipitation events. Typically, positive (enriched) and negative (depleted) excursions in the isotopic composition of tropical rainfall have been linked to the presence to the classical "amount effect" (Dansgaard, 1964). These types of statistical correlations are often not physically based, and interpretations at shorter timescales (i.e., days to minutes) are inadequate. Zwart et al. (2018) demonstrated that daily stable isotope variations in northern Australia reflect different rain and cloud types (described using high-resolution radar data), which are associated with the large-scale circulation regimes, rather than solely rainfall amounts. Schmitt, Riveros-Iregui, and Hu (2018) provided an analysis of stable isotope compositions on San Cristóbal of the Galápagos Islands, whereby a combination of factors such as precipitation amount, fog formation, subcloud kinetic fractionation, and the source of water vapour explained the observed seasonal and event-based variations.

Interannual to interdecadal variability in the tropics is known to be mainly driven by the sea surface temperature (SST) distribution, with ENSO leading the forcing (Gu, Adler, Huffman, & Curtis, 2007). Dai and Wigley (2000) provided a global overview of the effect of ENSO on global precipitation in terms of induced changes in the ascending motions and subsidence. Their study highlights the shifting of the intertropical convergence zone and the South Pacific convergence zone, which establish a major change in the spatial distribution of rainfall anomalies. Across the tropics, the impact of ENSO is largely associated with changes in rainfall anomalies (Stephens et al., 2018) and the consequent development of drought and wetter than normal conditions depending on the region and the phase of ENSO; with an identified opposite effect of ENSO on rainfall over land and ocean (Neelin, Chou, & Su, 2003). In the maritime continent, ENSO has been found to leverage air–sea interactions and generate a remotely driven wind forcing, which can lead to a local feedback mechanism between the winds and the SST anomalies, resulting in the development of a dry season (Hendon, 2003).

Current ability to monitor and analyse observed changes in the hydrological cycle under warming linked to ENSO development allows for the possibility of improving our knowledge of the global warming driven intensification of the hydrological cycle. In the context of long-term isotope monitoring (>5 years), stable isotopes are useful tracers of ENSO-induced anomalies (Sánchez-Murillo, Durán-Quesada, Birkel, Esquivel-Hernández, & Boll, 2017). Kurita et al. (2018) evidenced that ENSO modulates the frequency of synoptic conditions on a seasonal and longer time scale, showing a strong correlation between the seasonal isotopic anomalies and the Southern Oscillation Index. dos Santos et al. (2018) provided a comparison of daily stable isotope composition during the strongest ENSO event from the instrumental record (1997/1998) and the most recent strong event (2015–2016) in Brazil. The authors reported similar $\delta^{18}O$ and $\delta^{2}H$ values during the two ENSO events (on an annual basis), with significant *d*-excess changes. Their trajectory analysis indicated variations on the origins and moisture transportation pattern along the atmosphere (either from the Amazon Basin or the Atlantic Ocean), related to the atmospheric conditions and the formation of precipitation systems.

3 | LAND VEGETATION PROCESSES

The large dependency of groundwater reservoirs as the main water supply in the tropics invokes an urgent understanding of how rainfall dynamics (particularly ENSO-induced drought) may affect recharge volumes. In the absence of long-term hydrometric networks in the tropics (Riveros-Iregui, Covino, & González-Pinzón, 2018), water stable isotopes appear as a reliable, fast, and relatively low-cost technique (in comparison with hydrogeological studies involving expensive deep drilling) to study the interaction between rainfall inputs and surface/groundwater connectivity. Kirchheim, Gastmans, and Chang (2018) reviewed how stable isotope and noble gas methods have influenced the evolution of knowledge on the Guaraní aquifer (Brazil) groundwater circulation models in the past decades. Batista et al. (2018) studied groundwater and surface water connectivity within the recharge area of the same aquifer. Their isotopic mass balance and hydrograph separation estimated variations between 70% and 80% in the groundwater contribution during the last strong ENSO event coupled with a notable correlation of *d*-excess between surface and groundwater reservoirs. Similarly, Yang et al. (2018) quantified the relative recharge proportion within the Yinchuan basin (China) from the Yellow River and precipitation. On the basis of the isotope mass balance, the authors concluded that the Yellow River provided up to 87.5% of the total groundwater recharge.

In the coast aquifer of the Gulf of Urabá (Colombia), Villegas, Paredes, Betancur, Taupin, and Toro (2018) combined hydrogeochemical data and stable and radioactive isotopes to infer groundwater recharge processes in a highly important aquifer for agricultural production. ^{14}C and depleted $\delta^{18}O$ indicated a cooler recharge climate than the current conditions, corresponding to the last glacial period of the late Pleistocene. At the small catchment scale, Welsh, Boll, Sánchez-Murillo, and Roupsard (2018) analysed the seasonal and event-based hydrological responses in a coffee agroforestry catchment. On the basis of the results of this study, the authors concluded that this watershed is a baseflow-driven system. Spring baseflow response exhibited a mean transit time on the order of 1 year, whereas storm flow effects had a lagged response of approximately 1 hr. Furthermore, Hasselquist, Benegas, Roupsard, Malmer, and Ilstedt (2018) evaluated the canopy cover effects on the local soil water dynamics in the same agroforestry catchment. The authors proposed a new conceptual model that combines stable isotope and soil moisture measurements to assess potential mechanisms by which evaporation (of surface soil water and of canopy-intercepted rainfall) affects the relationship between surface soil water isotopic enrichment (*lc*-excess) and soil water content.

4 | SENSITIVE ECOSYSTEMS

Two studies looking at sensitive ecohydrological ecosystems (mangrove and Páramo) are also part of this special issue. Among mountainous tropical ecosystems, the Páramo (a tropical ecosystem that extends between 11°N and 8°S, roughly covering 35,000 km^2 along Central and South America; Hofstede et al., 2003) is of particular importance, with its high water and carbon storage capacity allowing it to act as an ecohydrological sentinel of climate change. Using stable isotopes and hydrometric data, Esquivel-Hernández et al. (2018) studied the tropical alpine glacial lakes of Chirripó, Costa Rica. The isotopic mass balance indicated seasonal variations in the evaporative conditions with low evaporation to inflow (E/I) ratios below 20% and water residence time of 0.53 ± 0.27 years. As Páramo ecosystems are the "water towers" of lowland urban areas in many tropical regions, understanding changes in water storage in a changing climate has become an imperative task.

On the other side, mangroves provide multiple ecosystemic services such as shoreline stabilization and storm protection, reservoirs of biodiversity, nutrient and sediment retention, export to marine ecosystems, carbon sequestration, food production, and groundwater replenishment and purification as well as a wide range of recreational and touristic activities. Over the past half century, mangrove surface area has declined by between 30% and 50% as a result of land clearing, aquaculture expansion and over harvesting, and urbanization (Donato et al., 2011). Samper-Villarreal, Cortés, and Polunin (2018) presented a trophic stable isotope study of ^{13}C and ^{15}N in the mangrove habitats of Golfo Dulce (Costa Rica). Although nutrient concentrations did not identify direct nutrient loading (despite the overall knowledge that untreated sewage is being delivered to the gulf at increasing rates), $\delta^{15}N$ values of mangrove leaves were more enriched at nutrient loaded locations, suggesting a more efficient uptake of dissolved nitrogen from anthropogenic discharges.

5 | FUTURE CHALLENGES

Although tracer hydrology studies are increasingly undertaken in the tropics, significant challenges remain, and several aspects of ecohydrological processes are still poorly understood (Vuille, 2018), such as (a) physically based meaning of *d*-excess and ^{17}O-excess variations, (b) precipitation formation (i.e., deep and shallow convective development, stratiform fractions, and in-cloud fractionation kinematics) and its correlation with isotope variations in the context of high-resolution data, (c) coordination of continuous long-term stable isotope monitoring stations (precipitation, surface water, and groundwater), (d) standardization of isoscaping modelling and spatial coverage of sampling efforts, (e) appropriate incorporation of stable isotope measurements into global circulation models and paleoclimatic reconstructions, (f) high-frequency measurements during extreme events such as tropical cyclone passages, and (g) incorporation of tracer hydrology courses in a wide range of related university majors. The main goal of the present special issue is to widen the use of isotopes for tropical hydrological studies in order to build upon the current knowledge of rain-producing systems and ecohydrological interactions and to support the improvement of modelling towards a better representation of physically based processes within the hydrological cycle in a changing climate.

5.1 | Contributions to the special issue

5.1.1 | Atmospheric–ocean processes

1. The role of fog, orography, and seasonality on precipitation in a semiarid, tropical island

Sarah R. Schmitt, Diego A. Riveros-Iregui, Jia Hu

2. Continuous real-time analysis of the isotopic composition of precipitation during tropical rain events: Insights into tropical convection

He Shaoneng , Nathalie F. Goodkin, Dominik Jackisch, Maria Rosabelle Ong,
Samanta Dhrubajyoti.

3. The isotopic signature of monsoon conditions, cloud modes, and rainfall type

Costijn Zwart, Niels C. Munksgaard, Alain Protat, Naoyuki Kurita, Dionisia Lambrinidis, Michael I. Bird

4. Interpretation of El Niño–Southern Oscillation-related precipitation anomalies in north-western Borneo using isotopic tracers

Naoyuki Kurita, Mayumi Horikawa, Hironari Kanamori, Hatsuki Fujinami, Tomoomi Kumagai, Tomonori Kume, Tetsuzo Yasunari

5. Isotopic composition of precipitation during strong ENSO events in the southeastern region of Brazil

Vinícius dos Santos, Marcelo Dias de Oliveira, Jan Boll, Ricardo Sánchez-Murillo, Luiz Fellipe Gozzo, Didier Gastmans.

5.1.2 | Land vegetation processes

7. Isotope hydrology of a tropical coffee agroforestry watershed: Seasonal and event-based analyses

Kristen Welsh, Jan Boll, Ricardo Sánchez-Murillo, Olivier Roupsard

8. Canopy cover effects on local soil water dynamics in a tropical agroforestry system: Evaporation drives soil water isotopic enrichment

Niles J. Hasselquist, Laura Benegas, Olivier Roupsard, Anders Malmer, Ulrik Ilstedt

9. Groundwater and surface water connectivity within the recharge area of Guarani aquifer system during El Niño 2014–2016

Ludmila Vianna Batista, Didier Gastmans, Ricardo Sánchez-Murillo, Bárbara Saeta Farinha, Sarah Maria Rodrigues dos Santos, Chang Hung Kiang

10. Groundwater evolution and mean water age inferred from hydrochemical and isotopic tracers in a tropical confined aquifer

Pedro Villegas, Vanesa Paredes, Teresita Betancur, Jean D. Taupin, Luis E. Toro

11. Quantitative evaluation of groundwater recharge and evaporation intensity with stable oxygen and hydrogen isotopes in a semi-arid region, Northwest China

Qingchun Yang, Haokun Mu, Hao Wang, Xueyan Ye, Hongyun Ma, Jordi Delgado Martín

12. How isotopes influenced the knowledge evolution of the groundwater circulation models of the Guarani Aquifer System

Roberto Eduardo Kirchheim, Didier Gastmans and Hung Kiang Chang.

5.1.3 | Sensitive ecosystems

13. Isotopic evidence of subtle nutrient enrichment in mangrove habitats of Golfo Dulce, Costa Rica

Jimena Samper-Villarreal, Jorge Cortés, Nicholas V.C. Polunin

14. Insight into the stable isotopic composition of glacial lakes in a tropical alpine ecosystem: Chirripó, Costa Rica

Germain Esquivel-Hernández, Ricardo Sánchez-Murillo, Adolfo Quesada-Román, Giovanny Mosquera, Christian Birkel, Jan Boll.

5.1.4 | Invited commentary

15. Current state and future challenges in stable isotope applications of the tropical hydrologic cycle

Mathias Vuille

5.1.5 | Preface

16. Stable isotopes in hydrological studies in the tropics: Precipitation, groundwater and ecohydrological perspectives in a changing climate

Ricardo Sánchez-Murillo and Ana M. Durán-Quesada.

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