Key drivers controlling stable isotope variations in daily precipitation of Costa Rica: Caribbean Sea versus Eastern Pacific Ocean moisture sources

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A R T I C L E   H I S T O R Y

Received 28 October 2014
Received in revised form 7 August 2015
Accepted 24 August 2015
Available online 11 September 2015

ABSTRACT

Costa Rica is located on the Central American Isthmus, which receives moisture inputs directly from the Caribbean Sea and the Eastern Pacific Ocean. This location includes unique mountainous and lowland microclimates, but only limited knowledge exists about the impact of relief and regional atmospheric circulation patterns on precipitation origin, transport, and isotopic composition. Therefore, the main scope of this project is to identify the key drivers controlling stable isotope variations in daily-scale precipitation of Costa Rica. The monitoring sites comprise three strategic locations across Costa Rica: Heredia (Central Valley), Turrialba (Caribbean slope), and Cano Seco (South Pacific slope). Sporadic dry season rain is mostly related to isolated enriched events ranging from −5.8‰ to −0.9‰ δ18O. By mid-May, the Intertropical Convergence Zone reaches Costa Rica resulting in a notable depletion in isotope ratios (up to −18.5‰ δ18O). HYSPLIT air mass back trajectories indicate the strong influence on the origin and transport of precipitation of three main moisture transport mechanisms, the Caribbean Low Level Jet, the Colombian Low Level Jet, and localized convection events. Multiple linear regression models constructed based on Random Forests of surface meteorological information and atmospheric sounding profiles suggest that lifted condensation level and surface relative humidity are the main factors controlling isotopic variations. These findings diverge from the recognized ‘amount effect’ in monthly composite samples across the tropics. Understanding of stable isotope dynamics in tropical precipitation can be used to a) enhance groundwater modeling efforts in ungauged basins where scarcity of long-term monitoring data drastically limit current and future water resources management, b) improve the reconstruction of paleoclimatic records in the Central American land bridge, c) calibrate and validate regional circulation models.

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Notation list: 2H, deuterium isotope (%); 18O, oxygen-18 isotope (%); CAPE, convective available potential energy (J/Kg); CAPEv, convective available potential energy using virtual temperature (J/Kg); CIN, convection inhibition (J/kg); CLJJ, Caribbean low level jet; CHOCO, Colombian low level jet; D-xx, deuterium excess (%); GWML, global network of isotopes in precipitation; HYSPLIT, hybrid single particle Lagrangian integrated trajectory model; IAEA, international atomic energy agency; ITCZ, intertropical convergence zone; LCL, lifted condensation level (m); LCLp, lifted condensation level pressure (hPa); LCLI, lifted condensation level temperature (°C); LFC, level of free convection (m); LMWL, local meteoric water line; MR, mean layer mixing ratio; MLR, multiple linear regression; P, daily precipitation (mm); PW, precipitable water (mm); RH, mean daily relative humidity (%); T, mean daily air temperature (°C); VSMOW, Vienna standard mean ocean water; WMO, world meteorological organization; WS, mean daily wind speed (m/s).

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http://dx.doi.org/10.1016/j.quascirev.2015.08.028
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1. Introduction

Tropical regions cover approximately 50% of Earth’s landmass and are home to three-quarters of the world’s population. During the last decade, the scientific community, environmental institutions, governments, and communities have increased their awareness of the importance of current tropical climate variability based on the premise that changes in regional and global circulation patterns may lead to intensification of extreme events (i.e. floods or severe droughts). Past climate records of tree rings, speleothems, and coral reef formations in tropical environments offer a unique opportunity to a) examine previous abrupt climate changes and b) elucidate the hydrological responses to thermal and precipitation anomalies.

The use of stable isotopes of water, both δ2H and δ18O has provided novel insights in hydrological studies, ecological applications, understanding climate variability, and reconstructing paleoclimate (Lawrence et al., 2004; Johnson and Ingram, 2004; Risi et al., 2008; Lachniet, 2009a; Sturm et al., 2010; Tremoy et al., 2012; Moerman et al., 2013; Tremoy et al., 2014; Okazaki et al., 2015). Recently, the development of inexpensive instrumentation based on laser spectroscopy has enhanced our ability to achieve greater temporal and spatial resolution of isotopic data (Berden et al., 2000; Wen et al., 2008; Gupta et al., 2009; Munksgaard et al., 2012; 2015; Good et al., 2014; Munksgaard et al., 2015) and is greatly helping in development of new research avenues to study the atmospheric water cycle (e.g. 17O-excess; Berman et al., 2013). In particular, collection and analyses techniques of these naturally occuring tracers have shown to be useful in elucidating atmospheric moisture sources and their implications for the hydrological cycle (Araguás-Araguás et al., 2000; Bowen and Revenaugh, 2003; Aggarwal et al., 2012; Risi et al., 2013; Soderberg et al., 2013).

The global relationship between δ2H and δ18O in natural meteoric waters recognized by Craig (1961) and later defined as the GMWL (δ2H = 8•δ18O + 10) serves as a foundational reference to determine regional and local deviations (LMWL) from equilibrium processes and the potential origin of the water vapor. Other factors, such as the trajectory of air masses, latitude, altitude, precipitation amount, and distance from oceans, may also affect the spatial and temporal variations of δ2H and δ18O ratios in precipitation (Rozanski et al., 1982). Water losses due to evaporation, the incorporation of recycled atmospheric moisture, and mixing between isotopically-distinct reservoirs leave a unique water fingerprint that can be used to understand rainfall–runoff processes (Birkel et al., 2012), complex water flow paths (McGlynn et al., 2002), groundwater to surface water connectivity (Tetzlaff and Soulsby, 2008; Speed et al., 2010; Wassenaar et al., 2011), baseflow recession analysis (Sánchez-Murillo et al., 2015) and isotope-based paleoclimate reconstructions (Moerman et al., 2013). Light stable isotope compositions of tropical meteoric waters have proven to be an important indicator of modern climate variability (Araguás-Araguás et al., 1998; Vuille et al., 2000a,b; 2003; Cobb et al., 2007; Lachniet, 2009b; Lachniet and Paterson, 2009; Ishizaki et al., 2012; Moerman et al., 2013). In particular, δ18O values have provided novel insights into El Nino/Southern Oscillation dynamics (Vuille and Werner, 2005; Ichinayagi and Yamanaka, 2005; Lachniet et al., 2007; Panarello and Dapena, 2009).

Despite these advances to understand stable isotope precipitation dynamics in the tropics, a consensus exists regarding the urgent need for long-term monitoring networks, particularly in mountainous regions such as the Central America Continental Divide where orographic effects, local moisture recycling, canopy interception, intense evapotranspiration combined with complex microclimates may play an important role in influencing isotopic ratios (Lachniet and Paterson, 2009). Furthermore, recent studies have demonstrated that variations in the stable isotope composition of precipitation even occur during storm events (Celle-Jeanton et al., 2004; Coplen et al., 2008; Barras and Simmonds, 2009; Munksgaard et al., 2012), emphasizing the relevance of event-based and daily sampling. A physical understanding of the key

Fig. 1. Location of sampling sites. Sampling sites (Heredia, Turrialba, and Caño Seco) are denoted by black dots. The black arrows show the location of a) the Palma Depression (whereby trade winds reach the Central Valley of Costa Rica), b) the trade winds and Colombian low level jets, and c) the division of the country by the Continental divide in two main orographic slopes (Pacific and Caribbean). The inset shows a regional context within the Central American Isthmus. Elevation gradient is color coded. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
factors controlling stable isotope ratios of meteoric waters in the tropics will strengthen understanding of precipitation origin and transport (e.g. calibration and validation of Global and Regional Circulation Models), and provide contemporary isotopic data to enhance paleo-reconstructions and sustainable water resources management.

1.1. Isotopic variations in tropical meteoric waters

In temperate climates, stable isotope variations in meteoric waters have been successfully explained by the seasonal air temperature fluctuation, a relationship known as the ‘temperature effect’ (Dansgaard, 1964; Rozanski et al., 1993; Araguás-Araguás et al., 2000; Kurita et al., 2009; Wassenaar et al., 2011; Sánchez-Murillo et al., 2013). However, in tropical regions where temperature variability is muted, the isotopic ratios of meteoric waters only exhibit a weak correlation with surface air temperature. Instead for these regions, several studies have reported a negative correlation between precipitation amount and isotope values, a relationship commonly recognized as the ‘amount effect’ (Dansgaard, 1964; Rozanski et al., 1993; Araguás-Araguás et al., 2000; Kurita et al., 2009; Scholl et al., 2009; Sánchez-Murillo et al., 2013). The shift from air temperature to precipitation amount controlling isotopic ratios is generally noted around 30°N/S (Bowen, 2008). The ‘amount effect’ occurs as a result of rain-out processes of convective precipitation. The stronger the convective nature of a rainfall event, the greater is the total precipitation amount, and thus the lower the probability of moisture exchange during the drop travel time towards the surface (Vuille et al., 2003).

While the ‘amount effect’ is the strongest relationship identified in the tropics, the majority of studies were based on monthly-composite samples, such as those recorded in the Global Network of Isotopes in Precipitation (GNIP) (http://www-naweb.iaea.org/napc/ih/IHS_resources_gnip.html) database overseen by the International Atomic Energy Agency (IAEA) and the World Meteorological Organization (WMO). This ‘amount effect’ appears to be stronger when examined over longer periods of time and not at shorter sampling intervals (Risi et al., 2008; Wu et al., 2015). Nevertheless, daily or event-based sampling of precipitation often does not show a strong correlation with precipitation amount (Vimeux et al., 2005; Wu et al., 2010, 2015). A vast majority of fractionation processes that may potentially influence the stable isotope composition of tropical precipitation occur along the convective vertical profile (Kurita, 2013); therefore, to further understand the key factors controlling stable isotope composition in tropical precipitation, a detailed analysis combining surface and sounding meteorological data is required.

This study examined daily isotopic variations at three strategic locations in Costa Rica for the year 2013: Heredia (Central Valley), which receives moisture inputs from both the Pacific and Caribbean), Turrialba (Caribbean Slope), and Caño Seco (South Pacific...

Table 1

<table>
<thead>
<tr>
<th>Site</th>
<th>Sub-region</th>
<th>Latitude (dec.deg)</th>
<th>Longitude (dec.deg)</th>
<th>Elevation (m.a.s.l.)</th>
<th>Total precipitation (mm)</th>
<th>Mean annual RH (%)</th>
<th>Mean annual temperature (°C)</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heredia</td>
<td>Central valley</td>
<td>10.0004</td>
<td>−84.1091</td>
<td>1173</td>
<td>2508</td>
<td>79.1</td>
<td>20.1</td>
<td>49</td>
</tr>
<tr>
<td>Turrialba</td>
<td>Caribbean slope</td>
<td>9.8970</td>
<td>−83.6570</td>
<td>1020</td>
<td>2006</td>
<td>84.9</td>
<td>19.6</td>
<td>46</td>
</tr>
<tr>
<td>Caño Seco</td>
<td>S. Pacific slope</td>
<td>8.7304</td>
<td>−82.9742</td>
<td>1037</td>
<td>2663</td>
<td>95.3</td>
<td>19.9</td>
<td>73</td>
</tr>
</tbody>
</table>

Fig. 2. Time series of monthly long-term precipitation means (A) and comparison of monthly standardized anomalies for 2013 for three locations Heredia (B), Turrialba (C), and Golfito (D) (20 km southwest of Caño Seco). Baseline precipitation periods are: Heredia (1982–2012), Turrialba (1942–2012), and Golfito (1998–2012). Normalized anomaly equals anomaly/standard deviation of the normal period at each site.

Fig. 3. LMWL constructed for the three study sites. The GMWL is shown as a reference. Note that only the equations of the LMWLs are given for clarity.
Isotope ratios were analyzed in combination with surface and convective meteorological data and HYSPLIT air mass back trajectories to i) investigate whether key drivers of isotopic variability can be identified, and ii) determine the precipitation moisture source.

2. Regional setting and previous isotopic studies

Costa Rica is located on the Central American Isthmus, between 8° and 12°N latitude, and 82° and 85°W longitude (Fig. 1). This narrow land bridge provides unique mountainous and lowland microclimatic systems (i.e. climate characteristics controlled by the strong influence of topographic features) across the country, which receives moisture inputs from two large water masses: the eastern tropical Pacific and the Caribbean Sea warm pools (Durán-Quesada et al., 2010). These microclimatic systems offer a unique opportunity to study isotopic variations in precipitation in a tropical setting where over 258 karst caves (Ulloa et al., 2011) remain basically unexplored for paleoclimatic records. Four regional air circulation processes predominantly control the climate of Costa Rica: northeast trade winds (i.e. alísios), the latitudinal migration of the Intertropical Convergence Zone (ITCZ), cold continental outbreaks (i.e. northerly winds or noroeste), and the seasonal influence of Caribbean cyclones (Waylen, 1986). These circulation processes produce two rainfall maxima, one in June and one in September, which are interrupted by a relative minimum between July–August known as the Mid-Summer Drought (i.e. intensification of the trade winds over the Caribbean Sea) (Magaña et al., 1999). In addition to these circulation processes, the Continental Divide (i.e. a mountainous range extending from northwest to southeast) also influences precipitation patterns across the country, dividing the territory into the Caribbean and Pacific drainage basins. Both basins exhibit distinct rainfall regimes in terms of magnitude and timing (Muñoz et al., 2002). In general, annual precipitation in Costa Rica varies from ~1500 mm in the drier northwestern region, ~2500 mm in the Central Valley, and up to ~7000 mm on the Caribbean side of the Talamanca range. Temperature seasonality is low throughout the country. The mean annual temperature on the coastal lowlands is around 27 °C, 20 °C in the Central Valley at around 1100 m.a.s.l., and below 10 °C at the summits of the highest mountain range (3820 m.a.s.l.) (Sánchez-Murillo et al., 2013).

Isotopic studies conducted in meteoric waters of Costa Rica have been limited to date. Sánchez-Murillo et al. (2013) analyzed historic monthly records from GNIP and provided the first comprehensive analysis of the variations in isotopic composition of precipitation in Costa Rica. The authors defined a country weighted-LMWL of δ²H = 7.6 δ¹⁸O +7.40. In particular, the authors determined an ‘amount effect’ of −1.6% δ¹⁸O per 100 mm of rain, which corresponds to a temperature effect of −0.37% δ¹⁸O/°C. Rhodes et al. (2006a,b) and Guswa et al. (2007) conducted studies of the isotopic composition of precipitation in the Monteverde Cloud Forest Reserve, identifying that water evaporated from land is an important moisture flux during the transitional and dry seasons with dominating winds from the Caribbean. Additional studies (Lachniet and Patterson, 2002; Reynolds and Fraile, 2009; Melchiorre et al., 2009) on stable isotopes in surface waters and groundwaters did not examine the factors that influence the isotopic composition of precipitation.

3. Materials and methods

3.1. Sampling sites

A daily sampling campaign was conducted during 2013 at three sites: Heredia (Central Valley), Turrialba (Caribbean slope), and Caño Seco (Pacific slope) (Fig. 1 and Table 1). Heredia is located within the Central Volcanic Range at 1173 m.a.s.l. Mean annual precipitation (period 1982–2012) is 2452 mm with two rainfall maxima between May–June and September–October and a clear dry season from December to April. Precipitation events in Heredia are composed of moisture transported from the Caribbean lowlands through the Palma Depression and the Pacific Ocean. Turrialba is located on the Caribbean slope at 1020 m.a.s.l. (Coffee-Flux Observatory, Aquiraes station, 9 km northwest of Turrialba, Gómez-Delgado et al., 2011). Mean annual precipitation is 2712 mm (period 1942–2012). A precipitation maximum occurs between November and January due to the increasing strength of northeast trade winds. Isotopic studies conducted in meteoric waters of Costa Rica have been limited to date. Sánchez-Murillo et al. (2013) analyzed historic monthly records from GNIP and provided the first comprehensive analysis of the variations in isotopic composition of precipitation in Costa Rica. The authors defined a country weighted-LMWL of δ²H = 7.6 δ¹⁸O +7.40. In particular, the authors determined an ‘amount effect’ of −1.6% δ¹⁸O per 100 mm of rain, which corresponds to a temperature effect of −0.37% δ¹⁸O/°C. Rhodes et al. (2006a,b) and Guswa et al. (2007) conducted studies of the isotopic composition of precipitation in the Monteverde Cloud Forest Reserve, identifying that water evaporated from land is an important moisture flux during the transitional and dry seasons with dominating winds from the Caribbean. Additional studies (Lachniet and Patterson, 2002; Reynolds and Fraile, 2009; Melchiorre et al., 2009) on stable isotopes in surface waters and groundwaters did not examine the factors that influence the isotopic composition of precipitation.

Table 2

<table>
<thead>
<tr>
<th>Site</th>
<th>δ¹⁸O (%)</th>
<th>δ²H (%)</th>
<th>d-excess (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry season</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heredia</td>
<td>−2.52</td>
<td>−4.96</td>
<td>15.2</td>
</tr>
<tr>
<td>Turrialba</td>
<td>−3.24</td>
<td>−5.47</td>
<td>20.4</td>
</tr>
<tr>
<td>Caño Seco</td>
<td>−3.90</td>
<td>−19.40</td>
<td>11.8</td>
</tr>
<tr>
<td>Wet season</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heredia</td>
<td>−9.31</td>
<td>−60.18</td>
<td>14.3</td>
</tr>
<tr>
<td>Turrialba</td>
<td>−7.07</td>
<td>−48.39</td>
<td>8.2</td>
</tr>
<tr>
<td>Caño Seco</td>
<td>−9.42</td>
<td>−65.09</td>
<td>10.2</td>
</tr>
<tr>
<td>Annual</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heredia</td>
<td>−8.34</td>
<td>−52.29</td>
<td>14.4</td>
</tr>
<tr>
<td>Turrialba</td>
<td>−6.20</td>
<td>−39.99</td>
<td>10.6</td>
</tr>
<tr>
<td>Caño Seco</td>
<td>−8.84</td>
<td>−60.42</td>
<td>10.3</td>
</tr>
</tbody>
</table>
The influence of atmospheric trajectory on daily precipitation isotope composition was studied using the Hybrid Single-Particle Lagrangian Trajectory (HYSPLIT) model (Draxler and Rolph, 2015) developed by the National Oceanic and Atmospheric Administration (NOAA). HYSPLIT provides meteorological variables on hourly basis over the trajectory requested using a three-dimensional Lagrangian air mass velocity algorithm. Air parcel trajectories were modeled 48 h backwards in time due to the proximity of the Caribbean Sea and the Pacific Ocean. To compute a trajectory, the HYSPLIT model requires a starting time, location, and altitude as well as NOAA meteorological data files (e.g., GDAS1, global data assimilation system, 1×1°, 2006-present, Su et al., 2015). Based on meteorological conditions (T and RH) at each sampling, the altitude was entered as the LCL (m) using Lawrence’s (2005) approximation. For the purpose of this analysis, a daily trajectory for each rain sample in Heredia (n = 49), Turrialba (n = 46), and Caño Seco (n = 73) was computated. Trajectories were further divided into dry (December–April) and wet (May–November) seasons.

3.4. Statistical analysis

Spaenr’s rank correlation analysis was performed to assess potential relationships between daily precipitation data and surface meteorological and sounding data at the three sites. The correlation results were reported as correlation matrices or bivariate plots. The latter additionally were used to visualize frequency distribution histograms of the data; the resulting correlation coefficients r scaled to increasing size for different significance levels and scaled kernel regression smoothing indicate potential linear and non-linear relationships. Simple linear regression analysis was performed to construct a LMWL for each site. We also applied the machine learning technique Random Forests (randomForests R package) to analyze the isotopic data in relation to meteorological variables (see detailed description of the method in Breiman, 2001). This method can be used for classification, prediction and relative importance assessment of predictors. Random Forests was developed to improve predictions of regression trees by avoiding overfitting and was also reported to be more robust than simple linear regression, specifically for large datasets (e.g. Lawler et al., 2006). We attempted to construct parsimonious multiple linear regression (MLR) models using Random Forests to self-select predictors with a physical meaning. The relative importance of selected predictors in the regression models and their performance is reported using the mean squared error (MSE) and the % increase of the MSE for model selection. Furthermore, the % explained variance derived from the adjusted coefficient of determination ($R^2$) allows realistic comparison of different models as an increased number of parameters are penalized:

$$\text{adj} R^2 = 1 - \frac{n - 1}{n - p - 1} \left(1 - r^2\right)$$  \hspace{1cm} (1)
packages (R Development Core Team, 2014). In addition, a Kruskal-Wallis non-parametric test was conducted to determine significant differences in the $\delta^{2}H$ and $\delta^{18}O$ median ratios of the three study sites.

4. Results and discussion

4.1. Precipitation anomalies in 2013

Fig. 2A shows an overview of monthly precipitation regimes in the Central Valley (Heredia, 1982–2012), the Caribbean slope (Turrialba, 1942–2012), and the South Pacific slope (Golfito, 20 km southwest of Caño Seco, 1998–2012) based on available long-term records (National Meteorological Institute, 2014). The rainiest months in the Central Valley correspond to May–June and September–October; the same pattern occurs within the South Pacific. However, the influence of a persistent low pressure system located south of the Panama coast influences the precipitation regime in Golfito resulting in abundant precipitation events throughout the year, but primarily between May and November. The intensification of the easterlies during the boreal winter carries moisture from the Caribbean Sea producing a precipitation maxima in Turrialba in November and December. The orographic effect from the continental divide serves as a ‘precipitation barrier’ for the Central Valley resulting in a clear dry season from December to April. Fig. 2B–D shows the 2013 monthly precipitation standardized anomalies. In the South Pacific and the Caribbean slopes, precipitation amounts were substantially lower throughout 2013. Even though Caño Seco is not directly comparable to the Golfito long-term data due to a significant elevation difference, 2013 was the driest year of the three-year record from Caño Seco. In Heredia, negative standardized anomalies were observed predominantly at the beginning of the wet season and during the Mid-Summer Drought months (i.e. a precipitation deficit between August and July; Magaña et al., 1999) with above average rainfall from September to December.

4.2. $\delta^{2}H$ and $\delta^{18}O$ in precipitation

A Kruskal–Wallis non-parametric test revealed a significant difference ($p < 0.001$) in the $\delta^{2}H$ and $\delta^{18}O$ median ratios of the three study sites; therefore, all LMWLs were analyzed separately. The linear relationships of $\delta^{2}H$ and $\delta^{18}O$ ratios of precipitation samples collected in Heredia ($n = 49$), Turrialba ($n = 46$), and Caño Seco ($n = 73$) during 2013 are presented in Fig. 3 and compared to the GMWL. The $\delta^{2}H$ and $\delta^{18}O$ ratios of precipitation in Heredia ranged from $-114.7\permil$ to $-7.3\permil$ and $-15.3\permil$ to $1.5\permil$, respectively. A least squares regression of the precipitation isotope data resulted in a highly significant LMWL for Heredia: $\delta^{2}H = 8.65 \cdot \delta^{18}O + 19.8$ ($r^2 = 0.97$, Fig. 3), with a mean annual $\delta^{18}O$ of $-8.3\permil$. The $\delta^{2}H$ and $\delta^{18}O$ ratios in Turrialba varied from $-115.9\permil$ to $-13.7\permil$ and $-15.3\permil$ to $0.85\permil$, respectively. A least squares regression of the precipitation isotope data resulted in a significant LMWL for Turrialba: $\delta^{2}H = 8.72 \cdot \delta^{18}O + 17.9$ ($r^2 = 0.98$, Fig. 3), with mean $\delta^{18}O$ of $-6.3\permil$. In Caño Seco, $\delta^{2}H$ and $\delta^{18}O$ ratios ranged from $-135.9\permil$ to $-5.6\permil$ and $-18.7\permil$ to $-0.89\permil$, respectively. A least squares regression of the precipitation isotope data resulted in a significant LMWL for Caño Seco: $\delta^{2}H = 8.21 \cdot \delta^{18}O + 12.2$ ($r^2 = 0.98$, Fig. 3), with a mean annual $\delta^{18}O$ of $-8.9\permil$. 
Isotope ratios in sporadic dry season (Dec–April) rainfall events are mostly related to small enriched events (Fig. 4A, Table 2). By mid-May, when the ITCZ travels over Costa Rica, a sharp depletion in isotope ratios was observed (Table 2). Shifting of the ITCZ to the north and the prevalence of Mid-Summer Drought conditions across Central America increases the isotopic variability throughout the wet season. The high slopes of the LMWL (8.2–8.7) observed at the three sites are an artifact introduced by the dry season sample values which exhibited high δ-excess values. Others have explained high intercepts and slopes to enhanced moisture recycling processes, such as localized strong convective events fed by evapotranspiration fluxes, whereby δ-excess increases as a result of increased evaporate content (Gat and Matsui, 1991; Froehlich et al., 2002). Mean annual δ-excess values ranged from +10.3‰ (Cano Seco) and +10.6‰ (Turrialba) up to +14.4‰ (Heredia). Although temperature seasonality was similar among the three sites (Fig. 4B), Cano Seco and Turrialba exhibited a greater relative humidity than Heredia (close to saturation during the wet season) (Fig. 4C). The precipitation anomalies mentioned above resulted in similar annual cumulative precipitation volumes (Fig. 4D). Surface meteorological conditions were used to further evaluate the isotopic variations.

4.3. δ¹⁸O, δ²H, and surface meteorological and sounding data

An exploratory Spearman’s correlation analysis was conducted between surface meteorological variables and daily isotope composition to determine whether the empirical ‘amount effect’ or other relationships may be present on a daily-scale (Fig. 5A, B, and C). Overall, precipitation amounts and δ¹⁸O exhibited a non-significant negative correlation among the three sites, suggesting that other physical processes may control the isotopic variations. In Heredia and Turrialba, there is a significant positive correlation between wind speed and isotope ratios (based on surface meteorological observations) most likely related to the influence of strong trade winds and moisture transport from the Caribbean lowlands to the Central Valley through the Palma Depression. Since the analysis of convective system organization at meso and large scales have been proposed as a rationale to better understand isotopic variations (Kurita, 2013), surface meteorological and available sounding data were combined to further explore the influence of these convective processes. Significant Spearman’s correlation coefficients between precipitation isotopes and LCL (0.37 < r < 0.48) at both sites support the notion of the importance of sounding profiles to enhance understanding of precipitation isotopic variations (Table 3).

The best-performing and most parsimonious Random Forests MLR models included as expected identical predictor variables for both isotopes, but different models were selected for the Heredia and Cano Seco site reflecting the spatial variability of influencing microclimatic systems. The precipitation isotopes collected at the South Pacific slope (Cano Seco) site were most significantly related to RH, LCL, and T (ordered according to relative importance, Fig. 6a). These self-selected predictor variables reflect the near-surface (RH, T) and vertical (LCL) atmospheric processes related to potential isotopic exchange and can therefore, be considered physically meaningful. This three-parameter MLR model resulted in a MSE = 5.3 and 67.9% overall explained variance for δ¹⁸O and in a MSE = 341 and 61.4% overall explained variance for δ²H. In comparison, for the isotopes at Heredia a four-parameter (from most to least important: LCL, PW, RH, and P) MLR model was selected. Additionally to RH and LCL this model uses the amount of PW over the vertical profile together with the near-surface precipitation volumes to explain the isotopic composition of rain waters. The Heredia model consists of one additional parameter compared to the Cano Seco model, but can still be considered physically meaningful as all included variables relate to isotopic exchange processes near the surface and over the vertical profile. The latter model resulted in a MSE = 15.1 and 47.3% explained variance for δ¹⁸O and for δ²H in a MSE = 1146.4 and 42.2% of explained variance (Fig. 6b). Generally, the model selected for Cano Seco outperformed the Heredia model and δ¹⁸O models seem to be more accurate compared to δ²H. The model performance is further visualized using an x–y plot of predicted against observed isotopes at both sites and the simulated deuterium isotope time series at Heredia (Fig. 7). The models clearly match the seasonal dynamics correctly simulating more enriched isotopic values during the dry and early rainy season and much more depleted values towards the end of the rainy season in November. Despite reproducing the general trends quite well, the models are not capable of matching the most extreme (enriched and depleted) isotope values.

4.4. Parental moisture source: HYSPLIT air mass back trajectories

The identification of the parental moisture source of daily precipitation events sampled in the three study sites was computed using an analysis of air mass back trajectories. Fig. 8A and B shows the HYSPLIT trajectories for the dry and wet season in 2013, respectively. The wind direction and velocity in the study region is greatly influenced by the seasonal migration of the ITCZ. During the dry season, when the ITCZ is located south of Costa Rica, air masses travel in a northeasterly direction across the country (Fig. 8A); as the air masses enter the continental Caribbean lowlands the moisture transport is affected mainly by the Central Volcanic Range

<table>
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<th>Variables</th>
<th>δ¹⁸O</th>
<th>δ²H</th>
<th>D-Xs</th>
<th>CAPE</th>
<th>CAPEv</th>
<th>CIN</th>
<th>LFC</th>
<th>LFCv</th>
<th>LCLt</th>
<th>LCLp</th>
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<th>MR</th>
<th>PW</th>
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water molecules experience orographic distillation when crossing the Palma Depression. The Palma Depression is a pass between two main volcano massifs with altitudes ranging from 2906 m.a.s.l. (Irazú Volcano). Moisture derived from the Caribbean Sea basin travels across this pass where significant distillation (~2‰/km of air mass lifting) has been reported by Sánchez-Murillo et al. (2013) (Fig. 1B). Wind direction during the dry season is controlled by a regional moisture transport mechanism, the Caribbean Low Level Jet (CLLJ) (Duran-Quesada et al., 2010). This water vapor transport pattern is associated with enriched rainfall events whereby recycled evapotranspiration fluxes mix with the air masses travelling along the Caribbean lowlands (Fig. 8A). During the wet season, the precipitation regime is controlled by the presence of the ITCZ across Central America. When the ITCZ moves northward, cross-equatorial winds from the southern hemisphere recurve to become southwesterly and transport Pacific parental moisture to Costa Rica combined with a weakening of trade winds (Lachniet et al., 2007). As a result, intensification in the genesis and development of deep convection systems on the Pacific coast of Costa Rica occurs; generally this phenomenon is associated with the presence of the ‘Chorro del Occidente Colombiano’ or CHOCO jet (Fig. 8B) (Duran-Quesada et al., 2010). Because of its location on the Pacific Slope, Caño Seco received abundant precipitation events under the influence of this convection system, whereas Heredia and Turrialba are topographically isolated from this influence during most of the wet season (Fig. 8B). In addition, precipitation events arriving to the Central Valley from the Pacific Ocean undergo a noticeable orographic distillation when the air masses are lifted over the Continental Divide barrier (Sánchez-Murillo et al., 2013), resulting in depleted isotopic samples in Heredia (mean = −8.3‰) and Caño Seco (mean = −6.3‰). In Caño Seco, the influence of the Talamanca range (See Fig. 1) (highest altitude 3820 m.a.s.l.) induces strong orographic distillation resulting in a mean annual δ18O ratio of −8.8‰ (Table 2).

4.5. Assessing key drivers of isotopic composition in precipitation

Since the pioneering work by Dansgaard (1964), the key drivers affecting δ18O and δ2H ratios in maritime and continental meteoric waters have been debated. Regularly, the monthly cumulative precipitation volume has been strongly correlated with isotopic variations. The rationale behind the empirical ‘amount effect’ relies on the idea that isotopic equilibration with the enriched vapor below the cloud base is more complete with the small raindrops associated with light rains. Water vapor near the surface has higher δ18O because of the effect of δ18O enriched vapor from surface evaporation. Therefore, lighter rainfall events (i.e. lower volume) will favor isotopic exchange with surrounding moisture and are subject to a more effective secondary evaporation below the cloud base. During heavy rainfall events (i.e. large volume), relative humidity below the cloud base is greater (indicated by bivariate plots, Fig. 5A–C) and thus the moisture exchange is lower as well as the probability of secondary evaporation as water falls to the surface. This explanation has been successful when analyzing monthly composite samples that may represent more regional precipitation patterns. Nevertheless, in tropical regions such as Central America, our findings suggest that convective systems are often attributed to localized moisture recycling; therefore, the ‘amount effect’ relationship is no longer useful to explain the observed isotopic variations. The insignificant ‘amount effect’ is further emphasized analyzing seasonal d-excess variations among the three sites (Fig. 9). High d-excess (mean = +17.8‰, ranging from +9.8‰ up to +26.6‰) among all the three sites were observed during the dry season months (December–April) when evaporation occurs under conditions of lower relative humidity (Fig. 4C) and a higher LCL (Heredia, mean LCL 487 m). During the dry season, on daily timescales independent of precipitation amount the longer the molecule travel time from the cloud base to the surface the greater the isotopic enrichment. During the rainy season, local convective systems have lower LCL heights (Caño Seco, mean LCL 278 m), therefore, a shorter molecule travel distance under humidity conditions close to saturation reduces the change of secondary evaporation resulting in depleted ratios.
5. Conclusions

In this study we report on the isotope composition of daily precipitation at three sites across Costa Rica for the year 2013. This was done with the aim of assessing the key drivers controlling isotope variability within this region of Central America. Contrary to the previously reported monthly 'amount effect', precipitation volume plays a rather minor role explaining daily-scale isotope variability in tropical meteoric waters. The most important drivers (as assessed by Spearman's rank correlation and Random Forests
MLR analyses) were the lifted condensation level and relative humidity. Both variables explained over 70% of the variance in MLR models that predict daily precipitation isotope time series. The self-selected MLR models resulted in parsimonious (<4 parameters) and physically-ground explanations of the isotopic composition of precipitation patterns. Together with HYPLIT air mass back trajectories we were able to further relate the diverse origin of moisture and transport mechanisms to the observed daily isotopic variability. The results of this study help to better understand the factors influencing daily-scale precipitation isotopes here and elsewhere within Central America with strong implications for water resource management. Furthermore, the results of this study could help identify the likely origin of rainfall recharging groundwater and the aquifer’s susceptibility to drought induced by a prolonged Pacific dry season as well as improving the reconstruction of paleoclimatic records in the Central America land bridge.

Acknowledgments

This project was supported by International Atomic Energy Agency grant CPR-19747 to RSM under the initiative “Stable isotopes in precipitation and paleoarchives in tropical areas to improve regional hydrological and climatic impact models.” Sampling conducted in Turrialba (Coffee-Flux Observatory, http://www6.montpellier.inra.fr/ecosols/Recherche/Les-projets/CoffeeFlux) was supported by a National Science Foundation-IGERT Fellowship (Grant no. 0903479), US Borlaug Fellowship in Global Food Security to KW and by SOERE-FORE-T network of observatories. Ecosys project (ANR-10-STA-003-001), Macacc project (ANR-13-AGRO-0005) and CIRAD-IRD SAFSE-Project. CB and RAM would like to thank various helping hands in the field (Carlos Mendez Blanco, Gonzalo Salazar Salazar) and support from the University of Costa Rica (project VI-B2235 and 217-B4-239) and the University of Aberdeen (Doerthe Tetzlaff and Josie Geris).

References


Fig. 9. Seasonal variation of d-excess (%) (three sites combined) and δ2H (%) during 2013. Blue dots and red squares represent the wet and dry seasons, respectively. The mean d-excess in the wet season is +11.7%, which increases in the dry season to a mean of +17.8%. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)


Lachniet, M., Paterson, W., 2009. Oxygen isotope values of precipitation and surface waters in northern Central America (Belize and Guatemala) are dominated by temperature and amount effects. Earth Planet. Sci. Lett. 284, 435–446.


