Variation in stable isotope ratios of monthly rainfall in the Douala and Yaounde cities, Cameroon: local meteoric lines and relationship to regional precipitation cycle

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Abstract Hydrogen (D) and oxygen (^{18}O) stable isotopes in precipitation are useful tools in groundwater recharge and climatological investigations. This study investigated the isotopes in rainfall during the 2013 and 2014 hydrological years in the Douala and Yaounde urban cities. The objectives were to generate local meteoric water lines (LMWLs), define the spatial–temporal variations of the isotopes in rainwater and their relationship to the regional precipitation cycle, and determine the factors controlling the isotopic variation. The LMWLs in Douala and Yaounde were $\delta\text{D} = 7.92\delta^{18}\text{O} + 12.99$ and $\delta\text{D} = 8.35\delta^{18}\text{O} + 15.29$, respectively. The slopes indicate isotopic equilibrium conditions during rain formation and negligible evaporation effect during rainfall. Precipitation showed similar wide ranges in $\delta^{18}\text{O}$ values from -5.26 to -0.75 ‰ in Douala and -5.8 to $+1.81$ ‰ in Yaounde suggesting a common moisture source from the Atlantic Ocean. Enriched weighted mean $\delta^{18}\text{O}$ ($w\delta^{18}\text{O}$) values during the low pre- and post-monsoon showers coincided with low convective activity across the entire region. Enriched isotopic signatures also marked the West African monsoon transition phase during each hydrological year. Abrupt $w\delta^{18}\text{O}$ depletion after the transition coincided with the monsoon onset in the region. Peak periods of

monsoonal rainfall, associated with high convective activities, were characterised by the most depleted $w\delta^{18}\text{O}$ values. Controls on isotopic variations are the amount effect and moisture recycling. The stable isotope data provide a tool for groundwater recharge studies while the isotopic correlation with regional rainfall cycle demonstrate their use as markers of moisture circulation and detecting climatic changes in precipitation.

Keywords Stable isotope variation · Regional precipitation cycle · Douala–Yaounde meteoric water lines · Amount effect · Moisture recycling · Cameroon rainforest

Introduction

Increasing urbanisation in the two municipalities of Douala and Yaounde in Cameroon is putting pressure on water demand. Groundwater is a major source of water supply to most households in both cities. Recharge in these cities needs to be assessed and monitored as an important part of water resource management. Variation in stable isotopes of hydrogen (D) and oxygen (^{18}O) in precipitation forms primary background data for groundwater recharge investigations (Ingraham 1998; Gupta and Deshpande 2003; Kortelainen 2009; Gat 2010). These include the sources and timing of recharge, retention time and circulation of groundwater (Kortelainen 2009). Such a study will require long-term data of stable isotopes in rainfall (IAEA/WMO 2015). Regrettably, stable isotope data of precipitation in Douala and Yaounde are only available from 2006 to 2009 (Ketchemen-Tandia et al. 2013) and 2007 and 2008 (Kuitcha et al. 2012), respectively. The meteoric water line, which is important in groundwater recharge evaluation, has not been established in the city of Yaounde. For a

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comprehensive groundwater recharge assessment, there is a need for additional isotopic data of rainfall in both municipalities as well as the Yaounde meteoric line.

In tropical Africa, stable isotopes in precipitation are not only important in groundwater recharge studies (e.g., Mbonu and Travi 1994; Ketchemen-Tandia et al. 2007; Fantong et al. 2010; Wirmvem et al. 2015; Adomako et al. 2015). They are also useful in climatological studies including the study of atmospheric moisture circulation (Njitchoua et al. 1999; Taupin et al. 2000; Bony et al. 2008; Risi et al. 2008). Few studies in the region including the Douala and Yaounde urban cities have reported the significance of continental recycled moisture to precipitation and evidence of the amount effect (Njitchoua et al. 1999; Taupin et al. 2000; Risi et al. 2008; Kuitcha et al. 2012; Ketchemen-Tandia et al. 2013; Wirmvem et al. 2014). However, an in-depth analysis of the relationship between isotopic variations in rainfall and the known regional annual cycle of precipitation has not been appraised.

In the tropics, climate change is expected to result in increased frequency and intensity of extreme events such as rainstorm surges and floods (IPCC 2007). For example, coastal flooding constitutes an additional stress to already existing pressures within the coastal mangrove areas of Cameroon (Munji et al. 2013). Understanding rainfall patterns, particularly how they differ spatially and temporally, give information on regional and global hydrologic processes. The information enables better planning and preparation for potential future changes in climate (Sánchez-Murillo et al. 2013). In tropical Africa, such information is imperative given the dependence of the population on rain-fed agriculture. Variation in isotopic composition of precipitation offers a valuable tool to identify such changes in climate against response strategies. For example, during the monsoon onset, an abrupt increase in convective activity over the Sahel is associated with an abrupt change in isotopic composition of rain (Bony et al. 2008; Risi et al. 2008). Long-term isotopic data in the tropical Africa is useful in such studies. Unfortunately, like in other tropical areas, the data is limited in tropical Africa including the Cameroon rainforest.

This study investigated monthly D and ^{18}O characteristics of precipitation in the Douala and Yaounde cities (in the rainforest region Cameroon) from 2013 to 2014. The objectives were to (1) produce local meteoric water lines, (2) define the spatial–temporal variations of the isotopes and their relationships with the regional annual hydrological cycle, and (3) determine the factors controlling the isotopic composition of rain in both municipalities. The study provides additional stable isotope data for groundwater recharge studies in both localities (especially the first

meteoric line in Yaounde) and climatological investigations in tropical Africa.

The study area

Location, climate and vegetation

The Douala and Yaounde municipalities in southern Cameroon are located in equatorial/tropical Africa at 4°3'N, 9°44'E and 3°52'N, 11°31'E, respectively. Both cities are situated northeast of the Gulf of Guinea in the Atlantic Ocean (Fig. 1a, b). Rainfall over the study area is controlled by the advection of moisture from the Gulf of Guinea in the low levels of the atmosphere (Sultan and Janicot 2000; Thorncroft et al. 2011). The location also subjects the area to the northward and southward oscillation of the inter-tropical convergence zone (ITCZ) and associated southerly monsoon winds (Sultan and Janicot 2000; Molua and Lambi 2006). The annual cycle of the monsoon is controlled by the hot Sahara and associated heat-low that develops in spring (April–June) and is hottest in summer (July–September), and the Atlantic cold tongue that also develops in spring and is coldest in summer. Consistent with the associated large-scale pressure gradient that exists between the hot Sahara and cold Atlantic, the flow of the southerly monsoon from the Atlantic Ocean bringing in the moisture-laden air towards land is in the spring and summer seasons (Thorncroft et al. 2011). Annual variation in rainfall peaks in both areas is linked to the annual shift in the position of the ITCZ and associated monsoon winds from the coast inland to around 10°N (Sultan and Janicot 2000; Janicot et al. 2008).

Despite the related moisture source and equatorial climatic regimes, both cities experience different seasonal patterns. The Douala coastal city has two main seasons. These are a long rainy season from March to November and a dry season from December to February (Ketchemen-Tandia et al. 2007). Meanwhile, Yaounde experiences four seasons. They include a rainy season from March to June, short dry season from July to August (transitional phase of the monsoon), rainy season from September to November and a dry season from December to February (Sighomnou 2004). In the dry season from December to February, rainfall depths are low compared to the rainy season. The low rainfall is because the southerly monsoon flow is weakened in this season. During this period, the entire area is alternatively influenced by north-easterly Harmattan winds (Thorncroft et al. 2011). Like the different seasonal patterns, the two municipalities present differences in elevation and distance from the Gulf of Guinea (Fig. 1a; Table 1). Differences also exist in atmospheric

Fig. 1 Altitude (a) and vegetation (b) maps of Cameroon showing the rain sampling points as red dots in the tropical evergreen rainforest region. Elevation map was modified after Sodalmelik (2007). Vegetation data is from GLC2000 (<http://bioval.jrc.ec.europa.eu/>)

Table 1 Location of rain sampling points, climatic variables and sampling period in the Douala and Yaounde urban cities

Location	Douala	Yaounde
Latitude of sampling point	4°5'4.12"N	3°55'3.03"N
Longitude of sampling point	9°39'32.49"E	11°28'49.03"E
Altitude (metres above sea level)	5	840
Distance from the Atlantic Ocean (km)	35	191
Mean annual rainfall (mm/year)	3867 ^a	1628 ^b
Average annual temperature (°C)	27 ^{a,b}	24 ^{b,c}
Mean relative humidity (%)	80 ^{a,b}	68 ^b
Evapotranspiration (mm/year)	1235 ^a	800 ^c
Data collection period	Jan 2013–Dec 2014	Jan 2013–Dec 2014
Number of monthly samples	24	19

^a Ketchemen-Tandia et al. (2013)

^b <http://www.climatemps.com>

^c Sighomnou (2004)

temperature, rainfall depth, relative humidity and evapotranspiration (Table 1).

At regional and continental scales over equatorial Africa, organized convection appears as coherent sequences or episodes. Zonal propagation speeds are similar

across continental regions and indicate common environmental conditions that favour increasingly organized precipitation regimes. A large fraction of convection episodes has their origin in the leeward side of Mountain ranges such as Mt Cameroon (Laing et al. 2011). The proximity of

Douala to Mount Cameroon as well as the Atlantic Ocean explains its high annual rainfall relative to Yaounde (Table 1).

Douala and Yaounde are covered by a dense, moist evergreen tropical forest (Fig. 1b) (Ketchemen-Tandia et al. 2013; Kuitcha et al. 2012). About 60–75 % of the rain that falls in the African tropical forest is re-evaporated as continental moisture (Monteny and Casenave 1989). Higher values (>80 %) have been reported in a zone within the tropical rainforest of Cameroon (Sigha-Nkamdjou 1993; Takounjou et al. 2011) which include the study area.

Geology and hydrogeology

Geologically, the low-lying coastal city of Douala is a sedimentary basin that is dominated by a Quaternary sandy formation at the top. Variation of elevation in the area does not exceed 100 m above sea level (m.a.s.l.) (Ketchemen-Tandia et al. 2007) as shown in Fig. 1a. On the contrary, Yaounde is characterized by an undulating relief with a network of hills. The highest altitude of 1060 m.a.s.l. is Mont Febe (Takounjou et al. 2011). Unlike Douala, Yaounde is made up of a crystalline metamorphic formation. It is dominated by gneissic rocks that are highly weathered (Temgoua et al. 2005; Takounjou et al. 2011). The high weathering is due to the high rainfall and warm climatic conditions. Both localities are characterized by dense dendritic drainage systems (Fig. 1b). Many rivers flow into the low-lying Douala sedimentary basin. The rivers include River Wouri, which flows to the Wouri estuary and subsequently join the Atlantic Ocean. In Douala, the gentle relief results to slow flowing rivers and development of wetlands. Yaounde is also drained by many rivers including Rivers Mfoundi, Mefou and Mfoulou (Kuitcha et al. 2012). The steep slopes in the city result in the rapid flow of run-off and streams with subsequent development of wetlands in the lowlands (Temgoua et al. 2005).

Sampling and analysis of rainwater

Two rain sampling devices were installed in Douala and Yaounde at different elevations and distances from the Gulf of Guinea (Fig. 1a; Table 1). Forty-three monthly samples of rainwater were collected from both areas over a period of two hydrological years from 2013 to 2014 (Table 1). The rain sampling followed the method described in Wirmvem et al. (2014). Collected samples in 50 ml polyethylene bottles were tightly capped and stored at 4 °C in a refrigerator before periodic dispatch to Japan for analysis. The samples were analysed at Ohba Laboratory in

Tokai University for the stable isotopes of hydrogen and oxygen. A Cavity Ring-Down Spectrometer analyser model L2120-i from PICARRO was used to analyse the isotopes following the method described by Brand et al. (2009). Conventionally, the isotope ratios of D/H and $^{18}\text{O}/^{16}\text{O}$ in the water samples were expressed as per mille (‰) deviation relative to the Vienna-Standard Mean Ocean Water (V-SMOW):

$$\delta(\text{‰}) = (R_{\text{sample}}/R_{\text{V-SMOW}} - 1) \times 1000 \quad (1)$$

where R represents the ratio of heavy to light isotopes (D/H or $^{18}\text{O}/^{16}\text{O}$) in the sample and standard, respectively. The oxygen and hydrogen isotope ratios are henceforth expressed as $\delta^{18}\text{O}$ and δD , in that order, or collectively as δ values. Total analytical precisions were better than $\pm 0.05 \text{‰}$ for $\delta^{18}\text{O}$ and $\pm 0.12 \text{‰}$ for δD . Given that some months in the study areas experience the dry season, the volume-weighted mean of δ values denoted as $w\delta^{18}\text{O}$ and $w\delta\text{D}$ were calculated for comparison (Dansgaard 1964). The $w\delta$ value for each month and the annual value for each locality were computed from the formulation (Dansgaard 1964; IAEA 1992):

$$w\delta = \frac{1}{p} \sum_{t=1}^{12} (pt \times \delta t) \quad (2)$$

where p represents the annual amount of precipitation; pt and δt are rainfall amounts and isotopic composition for each month, respectively. Deuterium excess (d-excess) was calculated from the following equation (Dansgaard 1964):

$$d = \delta\text{D} - 8 \times \delta^{18}\text{O}. \quad (3)$$

Results and discussion

Variation in stable isotopes of rainfall

Despite the high annual rainfall in the coastal city of Douala compared to Yaounde at 191 km from the coast, the isotopic signatures of monthly precipitation in both localities showed similar wide variations during the two hydrological years (Table 2). In Douala at 5 m.a.s.l., the $\delta^{18}\text{O}$ values of rain ranged from -5.22 to -0.75‰ in 2013 and from -5.26 to -1.28‰ in 2014. At 840 m.a.s.l. in Yaounde, the $\delta^{18}\text{O}$ values of rainfall varied from -5.20 to $+1.81 \text{‰}$ in 2013 and -5.86 to -0.66‰ in 2014. Mean $\delta^{18}\text{O}$ values were -2.90‰ ($n = 24$) and -2.86‰ ($n = 19$) in Douala and inland Yaounde, respectively. The mean values were as expected for the latitude range of the study areas (IAEA/WMO 2015). Similarities in $\delta^{18}\text{O}$ and δD of rain during the 2013 and 2014 hydrological years in both localities suggests similar annual controls on

Table 2 Stable isotope composition of monthly rainfall and weather records in the tropical urban cities of Douala and Yaounde in Cameroon

Month	2013					2014					Mean annual	
	$\delta^{18}\text{O}$ (‰)	δD (‰)	d-excess (‰)	Rainfall (mm)	Rainy days	$\delta^{18}\text{O}$ (‰)	δD (‰)	d-excess (‰)	Rainfall (mm)	Rainy days	Temp ^a (°C)	RH ^a (%)
Douala												
January	−1.26	+1.02	11.11	34	02	−1.28	+3.23	13.45	23	01	28	74
February	−1.02	+2.30	10.43	57	03	−1.39	+2.75	13.91	34	01	28	75
March	−2.53	−5.29	14.95	57	05	−2.88	−6.23	16.80	170	13	28	76
April	−3.28	−14.71	11.51	113	10	−3.73	−12.52	17.34	283	16	28	76
May	−4.31	−20.24	14.21	170	15	−5.26	−27.33	14.73	339	17	27	79
June	−2.86	−9.37	13.47	396	18	−3.04	−8.76	15.53	622	19	26	82
July	−2.94	−10.61	12.87	339	27	−1.86	−0.10	14.75	600	23	25	86
August	−2.18	−6.52	10.95	656	28	−2.73	−8.17	13.67	905	29	25	84
September	−3.92	−21.31	10.07	679	27	−5.08	−27.90	12.77	453	22	26	84
October	−5.22	−31.23	10.53	305	25	−4.05	−21.27	11.13	396	12	26	83
November	−3.03	−12.97	11.30	226	15	−3.80	−14.48	15.93	113	02	27	80
December	−1.84	−1.78	12.96	57	10	−1.99	−1.85	14.09	57	01	27	78
Minimum	−5.22	−31.23	10.07	34	2	−5.26	−27.90	11.13	23	02	25	74
Maximum	−1.02	+2.30	14.95	679	28	−1.28	+3.23	17.34	905	29	28	86
Mean	−2.87	−10.89	12.03	3088 ^b	185 ^b	−3.09	−10.22	14.51	3994 ^b	156 ^b	27	80
Weighted mean	−3.19	−13.95	11.56	–	–	−3.87	−14.31	16.67	–	–	–	–
Yaounde												
January	–	–	–	–	–	–	–	–	–	–	24	62
February	+1.81	+26.68	12.17	57	3	–	–	–	–	–	25	62
March	−1.02	+10.29	18.43	170	14	−0.66	+11.63	16.89	96	6	25	65
April	−3.12	−7.93	17.03	255	22	−4.02	−14.95	17.20	283	21	25	67
May	−3.29	−11.47	14.86	198	20	−1.01	+5.19	13.25	311	19	24	70
June	−1.92	+0.69	16.02	96	15	−3.11	−9.81	15.05	141	15	23	73
July	−5.14	−28.73	12.39	74	10	−2.12	−1.41	15.52	45	1	23	74
August	−3.52	−16.57	11.58	17	4	−4.39	−23.06	12.06	57	2	23	75
September	−3.71	−18.07	11.58	102	10	−5.82	−34.94	11.60	226	20	23	73
October	−5.20	−28.18	13.42	255	20	−5.86	−32.94	13.90	141	18	23	72
November	−1.78	+4.66	18.87	141	15	–	–	–	–	–	24	66
December	−1.64	+5.34	18.46	113	10	–	–	–	–	–	24	60
Minimum	−5.20	−28.73	11.58	17	3	−5.86	−34.94	11.60	45	1	23	60
Maximum	+1.81	+26.68	16.68	255	20	−0.66	+11.63	17.20	311	21	25	74
Mean	−2.59	−5.75	14.19	1476 ^b	143 ^b	−3.37	−12.54	14.43	1301 ^b	102 ^b	24	68
Weighted mean	−2.77	−7.50	14.69	–	–	−3.41	−12.91	14.38	–	–	–	–

The average $\delta^{18}\text{O}$ are −2.90 ‰ in Douala and −2.86 ‰ in Yaounde for the two hydrological years (2013–2014)

The 2-year weighted mean of the isotopic values are −3.26 ‰ ($\delta^{18}\text{O}$), −13.01 ‰ (δD) and 13.07 ‰ (d-excess) in Douala

In Yaounde, the 2-year weighted mean isotopic values are −3.07 ‰ ($\delta^{18}\text{O}$), −10.04 ‰ (δD) and 14.55 ‰ (d-excess)

^a Temp is Temperature and RH is relative humidity from <http://www.climatemps.com>

^b Sum

precipitation including a common moisture source from the Gulf of Guinea. The observed wide ranges in δ values of precipitation for each year depict varied controls on the

stable isotope composition of rainfall such as seasonality. The distinctive variations in monthly isotopic signatures offer a tool to determine the timing of groundwater

recharge in both localities as applied in other studies (e.g., Taylor and Howard 1996; Njitchoua et al. 1997; Wirmvem et al. 2015).

The seasonal variations in $\delta^{18}\text{O}$ and δD of rainfall were obvious in the Douala and Yaounde municipalities. Enriched values were mainly associated with low dry season showers and depleted values with heavy monsoon showers (Table 2) suggesting an amount effect. The weighted mean $\delta^{18}\text{O}$ and δD for 2 years did not show the expected decrease inland from Douala to Yaounde (Table 2). In both localities, d-excess values varied widely from 10.07 to 17.34 ‰ with a mean value of 13.70 ‰. As shown in Table 2, the annual mean d-excess values in precipitation were above 10 ‰ of the Atlantic Ocean moisture (Dansgaard 1964). The values increased from 11.94 ‰ in 2013 to 14.51 ‰ in 2014 for Douala rainfall. On the contrary, the d-excess values were relatively constant (~ 14 ‰) for Yaounde precipitation in 2013 and 2014 (Table 2). The high values (>10 ‰) suggest an additional source of moisture such as moisture recycling as will be discussed later.

Local meteoric water lines

Conventional $\delta^{18}\text{O}$ – δD graphs of the 2-year data gave the following regressions lines that represent the local meteoric water lines for Douala (Fig. 2a) and Yaounde (Fig. 2b), respectively:

$$\delta\text{D} = 7.92\delta^{18}\text{O} + 12.99 \quad (R^2 = 0.97, n = 24) \quad (4)$$

$$\delta\text{D} = 8.35\delta^{18}\text{O} + 15.29 \quad (R^2 = 0.99, n = 19) \quad (5)$$

Equations 4 and 5 show similar slopes to the Global Meteoric Water Line (GMWL) of Craig (1961) but relatively high d-intercepts. Similarities of slopes in both localities to the GMWL indicated that the process of rain formation in the tropical rainforest region of Cameroon occurred under equilibrium conditions (Dansgaard 1964). The slopes also suggest that the falling rain drops were not significantly affected by the evaporation effect (Craig 1961; Dansgaard 1964; Rozanski et al. 1993) including the small and enriched rain events in February, November and December of 2013 and March and July of 2014 with high d-excess values in Yaounde (Table 2). Such enriched events with high d-excess values account for the slope above 8 of the GMWL in Yaounde (Eq. 5; Fig. 2b) as earlier reported in Costa Rica by Sánchez-Murillo et al. (2016). Different d-intercepts in the local meteoric water lines (Eqs. 4, 5) may be attributed to changing conditions at the source of atmospheric moisture (Ingraham 1998; Gonfiantini et al. 2001) and local climatic effects such as re-evaporation (Taupin et al. 2000; Liu et al. 2014). The observed slopes are similar to those reported across

Fig. 2 Conventional $\delta^{18}\text{O}$ – δD relationships of monthly rainfall from 2013 to 2014 in the study areas. The relationships in **a** and **b** show the Douala and Yaounde meteoric water lines, respectively

Cameroon (Njitchoua et al. 1999; Gonfiantini et al. 2001; Fantong et al. 2010; Ketchemen-Tandia et al. 2013; Wirmvem et al. 2014; Kamtchueng et al. 2015) and elsewhere in the tropics (Mbonu and Travi 1994; Gonfiantini et al. 2001; Sánchez-Murillo et al. 2013, 2016; Rai et al. 2013). The generated local meteoric water lines are useful in assessing the origin and mechanism of groundwater recharge in both localities.

A combination of the 34 monthly samples from 2006 to 2009 (Ketchemen-Tandia et al. 2013) with the 24 monthly samples in this study from Douala (Table 2) showed similar wide variations (Fig. 3). This similarity indicates related controls on rain formation during the past few years. The combined data gave the following regression line for Douala precipitation:

$$\delta\text{D} = 8.10\delta^{18}\text{O} + 12.94 \quad (R^2 = 0.94, n = 58). \quad (6)$$

Temporal-seasonal variations in stable isotopes: Relation to the regional rainfall cycle

Monthly $\text{w}\delta^{18}\text{O}$ patterns of the investigated rains showed apparent seasonal variations in rainfall during the two

Fig. 3 A $\delta^{18}\text{O}$ – δD relationship of 58 monthly rainfall records in Douala showing the Douala meteoric water. The 2006–2009 data is from Ketchemen-Tandia et al. (2013) while 2013–2014 data is from this study

hydrological years in Douala and Yaounde (Fig. 4a, b). In Douala, precipitation in each hydrological year generally gave a single V-shaped evolution of $w\delta^{18}\text{O}$ (Fig. 4a). Enriched $w\delta^{18}\text{O}$ values were associated with lighter rains at the beginning and end of the wet seasons while the peaks of the rainy seasons in September 2013 and August 2014 were characterized by the most depleted values (Fig. 4a). Hence, the single V-shaped patterns indicating the recurrent single rainy and dry seasons during a hydrological year in Douala. On the contrary, rainfall during each hydrological year in Yaounde gave two V-shaped patterns of $w\delta^{18}\text{O}$ (Fig. 4b). Like in Douala, the peaks of the two rainy seasons in April and October of 2013 and May and September of 2014 had the most depleted $w\delta^{18}\text{O}$ values (Fig. 4b). Meanwhile, low rainfall amounts of the two dry seasons in the months of July to August and December to February for each hydrological year were characterized by enriched $w\delta^{18}\text{O}$ values. These patterns give the observed

Fig. 4 Monthly variation of rainfall and weighted mean $\delta^{18}\text{O}$ ($w\delta^{18}\text{O}$) for 2013 and 2014 hydrological years in Douala (a) and Yaounde (b). Monthly rainfall in Douala shows a similar single V-shaped evolution of $w\delta^{18}\text{O}$ in 2013 and 2014 (a) while Yaounde monthly rain shows a double V-shaped pattern in 2013 and 2014 (b). The $w\delta^{18}\text{O}$ variations from January to February of 2013 and January to March and October to December of 2014 in Yaounde are simply extrapolations. Error bars represent standard deviations with only the plus direction

two V-shaped patterns of $\delta^{18}\text{O}$ (Fig. 4b) representing the typical two rainy and dry seasons during a hydrological year in Yaounde. The annual V-shaped isotopic patterns in precipitation during each hydrological year are typical of precipitation in Cameroon (Njitchoua et al. 1999; Wirrmvem et al. 2014; Kamtchueng et al. 2015) and across the entire western Africa (Taupin et al. 2000). In this section, the isotopic patterns have been used to describe the annual evolution of the regional precipitation cycle.

In the Douala coastal city at $4^{\circ}03'\text{N}$, there is a gradual depletion in $\delta^{18}\text{O}$ with increasing rainfall during the two hydrological years from January to June. May and June recorded high rainfall depths with corresponding isotopic depletion compared to January–April showers in both years (Fig. 4a). According to Sultan and Janicot (2003), during the second half of May and in June, the ITCZ remains at a quasi-stable location around 5°N . Thus, its proximity to Douala explains the high rainfall in May and June. Decreases in rainfall depths and subsequent distinct isotopic enrichments from June to July in 2013 and 2014 (Fig. 4a) mark the rapid shift in the position of the ITCZ and resultant rainfall peak to a quasi-stable state around 10°N where it remains until about the end of August (Sultan and Janicot 2000; Thorncroft et al. 2011). The July rainfall reduction and resultant $\delta^{18}\text{O}$ enrichment in both areas correspond to the typical transition phase of the summer monsoon onset in the region (Sultan and Janicot 2003; Thorncroft et al. 2011). This change is also consistent with a reduction in sea-surface temperatures in the coastal areas (Sultan and Janicot 2003). However, remarkably, the shift in the ITCZ only has a minor effect in Douala compared to Yaounde from July to August as these months still record high rainfall depths suggesting considerable convection activity (Fig. 4a). The negligible effect may be due to the proximity of Douala to Mount Cameroon where large fractions of convective episodes have their origin on the leeward side (Laing et al. 2011). Another reason could be its nearness to the primary source of moisture, the Gulf of Guinea.

From August to September in 2013 and July to August in 2014, the $\delta^{18}\text{O}$ signatures in rain changed abruptly (Fig. 4a). The July 2014 $\delta^{18}\text{O}$ abrupt change coincides with the end of the monsoon transition period and increasing influence of the ITCZ during its retreat from around 10°N equatorward (Janicot et al. 2008; Thorncroft et al. 2011). This transition period occurred late in the previous year, i.e., in August 2013 (Fig. 4a). The most isotopically depleted heavy September 2013 and August 2014 rainfall mark the strongest impact of the ITCZ (with associated monsoons winds) in Douala. These months are peak periods of the monsoon rains in Douala during the two hydrological years. Strong convective updrafts carry condensed water upward at a faster rate such that moisture

derived from the updraft is much richer in heavy isotopes; hence, depleted than a parcel of air that would rise slowly (Bony et al. 2008). Thus, the depleted September 2013 and August 2014 rainfall were mainly formed from strong convective activities. They correspond to periods during which the city of Douala experiences the highest flood events. A decrease in rainfall depth with subsequent isotopic enrichment marks the gradual retreat of the ITCZ towards the equator after September (Fig. 4a).

In Yaounde (at $3^{\circ}52'\text{N}$), the $\delta^{18}\text{O}$ of rainfall showed abrupt changes from March to April in 2013 and 2014 (Fig. 4b). Similar abrupt changes were observed from September to October in 2013 and August to September in 2014 (Fig. 4b). These abrupt changes mark the end of the two dry seasons during each hydrological year in Yaounde. During April and the first half of May, the ITCZ is centred between the equator and the southern coast of West Africa. This period corresponds to the initial phase of the first rainy season over the Guinea coast region (Sultan and Janicot 2003). The peak period of this first part of the rainy season in Yaounde is marked by the most isotopically depleted high precipitation of April 2013 and 2014. The high rainfall records mark an increase in convective activity during this period (Fig. 4b). During the second half of May and in June, the ITCZ remains at a quasi-stable location around 5°N (Sultan and Janicot 2000; Sultan and Janicot 2003). Yaounde still records significant rain during this second part of the first rainy season, but with slightly enriched isotopic signatures (Fig. 4b). The decrease in rainfall during the second and short dry season from July to August in 2013 and 2014 is marked by enriched $\delta^{18}\text{O}$ values (Fig. 4b). Like in Douala, this period corresponds to the typical transition phase of the summer monsoon onset when the ITCZ shifts to a second quasi-stable state around 10°N (Sultan and Janicot 2000; Janicot et al. 2008; Thorncroft et al. 2011). Meanwhile, the most isotopically depleted rains in October 2013 and September 2014 (Fig. 4b) mark the equatorward retreat of the ITCZ and its strongest influence in Yaounde. The heavy October 2013 and September 2014 rains represent peak periods of the monsoon in Yaounde. Similar to Douala rain, the most depleted isotopic signatures during these months (Fig. 4b) reflect precipitation moisture formed from high convective activity (Bony et al. 2008). Like in Douala, the southward retreat of the ITCZ after the October rains is characterised by a sharp enrichment of $\delta^{18}\text{O}$ (Fig. 4b). Thus, discernible isotopic changes clearly mark the observed variation in transition and peak periods of the monsoon in 2013 and 2014 in both localities. The variations are evidence of changes in annual cycles of rain-formation processes including changes in convection or environmental conditions at a regional scale. This inference supports the observation in Niger by Risi et al. (2008) that $\delta^{18}\text{O}$ records

a regional signal of convection variability. Thus, the isotopes can be used as a climatological tool in monitoring changes in known annual hydrological cycles. Such knowledge is very important in tropical Africa where rain-fed agriculture is a major source of sustenance for a majority of the population.

The observed heavy and depleted $\delta^{18}\text{O}$ content in the rain during some months (Fig. 4a, b) are associated with the higher vertical velocity of ascending air masses and smaller effect of exchange between atmospheric air and the falling raindrops (Rozanski et al. 1993). Meanwhile, enriched isotopic values at the edges of the rainy season are likely due to large exchange with atmospheric vapour, and partial evaporation of the rain drops during precipitation (Rozanski et al. 1993; Taupin et al. 2000; Gat 2010; Rai et al. 2013). An apparent inverse relationship between rainfall depths and $\delta^{18}\text{O}$ from Fig. 4a and b and Fig. 5 is in agreement with the so-called amount effect, i.e., the greater the volume of rainfall, the lower the $\delta^{18}\text{O}$ or δD content (Dansgaard 1964; Coplen et al. 2000). The amount effect, which is a characteristic of tropical low-latitude precipitation (Dansgaard 1964), have also been observed in Cameroon (Njitchoua et al. 1999; Kuitcha et al. 2012; Wirmvem et al. 2014; Kamtchueng et al. 2015), western Africa (Mbonu and Travi 1994; Taupin et al. 2000; Risi et al. 2008; Adomako et al. 2015), East Africa (Kebede and Travi 2012), Costa Rica (Sánchez-Murillo et al. 2013) and the Bhagirathi River Basin in India (Rai et al. 2013).

Spatial variation in stable isotopes and moisture recycling

In precipitation, the stable isotopes of $\delta^{18}\text{O}$ and δD decrease as a function of distance from the ocean

Fig. 5 Cross-plot of monthly rainfall amounts as a function of weighted mean $\delta^{18}\text{O}$ in the Douala and Yaounde precipitation from 2013 to 2014 ($n = 43$). There is an inverse relationship between rainfall depths and weighted mean $\delta^{18}\text{O}$ with a negative slope

(continental effect) (Dansgaard 1964; Gat and Matsui 1991; Coplen et al. 2000). The isotopes also decrease with increasing altitude (altitude effect) (Fontes and Olivry 1977; Gonfiantini et al. 2001; Gat 2010). The average and weighted mean of δ values did not decrease from the low altitude of 5 m.a.s.l. in the coastal city of Douala to the comparatively high altitude of 870 m.a.s.l. in Yaounde at 191 km from the coast (Table 2). This observation indicates a deviation from the expected Rayleigh fractionation with distance and altitude (Dansgaard 1964; Coplen et al. 2000). This deviation, which shall be discussed later on a regional scale, suggests that the Cameroon rainforest is a ‘partially closed system.’ In such a system, evapotranspired moisture is returned to the atmosphere and recycled (Ingraham 1998). The added moisture counteracts the isotopic depletion due to rainout (Gonfiantini et al. 2001; Gat 2010).

Deuterium excess can further explain the effect of recycled moisture to rainfall. The Atlantic Ocean moisture results in continental precipitation with d-excess close to 10 ‰ (Dansgaard 1964). However, in hydrological systems where moisture recycling plays a significant role, higher d-excess values (>10 ‰) have been reported (Salati et al. 1979; Gat and Matsui 1991; Sánchez-Murillo et al. 2013; 2016; Liu et al. 2014) including the Cameroon rainforest (Njitchoua et al. 1999; Kuitcha et al. 2012; Ketchemen-Tandia et al. 2013). During evaporation, d-excess decreases in residual moisture and will accordingly increase in the evaporated moisture such that precipitation from such moisture will be characterized by high d-excess (Salati et al. 1979). In this study, 98 % of the samples had d-excess values >10 ‰ (Table 2; Fig. 6a, b). Despite the proximity of the Douala sampling point the Gulf of Guinea, which is the primary source of moisture, its high two-year d-excess value of 13.22 ‰ was comparable to 14.29 ‰ in Yaounde. The high d-excess values further indicate the significance of moisture recycling in both localities from the tropical evergreen rainforest and a network of rivers through successive evaporation and precipitation cycles in the region.

The inference above confirms the significance of moisture recycling in the equatorial rainforest of Cameroon (Njitchoua et al. 1999; Sigha-Nkamdjou 1993; Takounjou et al. 2011; Ketchemen-Tandia et al. 2013). However, the lowest d-excess values (close to 10 ‰) were recorded in the rain during the months of August, September and October in Douala (Table 2; Fig. 6a). These months are peak periods of the monsoon and are associated with increased convection activity. Higher convective activity is expected to be associated with less rain re-evaporation and thus higher d-excess (Bony et al. 2008). Such an inverse relationship has been observed in Niamey (Risi et al. 2008). According to Taupin et al. (2000), during such periods, surfaces processes like the partition of

Fig. 6 Variation of d-excess as a function of monthly rainfall for each year in Douala (a) and Yaounde (b). High d-excess values are mainly associated with early and late dry season showers while the peak of the monsoon from August to October recorded the lowest d-excess in Douala (a). On the contrary, the lowest d-excess values are associated with the short dry season from July to August (except July 2013) and the September monsoon rains in Yaounde (b). The d-excess variations from January to February of 2013 and January to March and October to December of 2014 in Yaounde are simply extrapolations. Error bars represent standard deviations with only the plus direction

evapotranspiration into evaporation and transpiration may exert control on d-excess. The low d-excess also indicates the dominance of the Gulf of Guinea as main the source of moisture during the height of the monsoon and limited supply of inland recycled moisture to rainfall during this period. Despite the low rainfall amounts (except in September 2014), August to September rains in Yaounde showed low d-excess signatures approaching 10 ‰ (Table 2; Fig. 6b). The low values also suggest a limited supply of continental moisture to precipitation and/or the effect of surface processes on d-excess during the said months. Thus, using d-excess, it can be possible to determine the relative contributions of inland moisture and oceanic moisture to groundwater recharge as well as the conditions of recharge.

Comparison with other studies in Central Africa

The weighted mean δ values in this study were compared with those of few studies in the Central African region located at different elevations and distances from the Gulf of Guinea (Table 3). Despite the varied sampling periods and number of samples, precipitation at higher elevations was associated with depleted weighted mean values (Table 3; Fig. 7a) in agreement with the altitude effect. An exceptional case was the Yaounde rain (Fig. 7a) where the altitude effect is likely obliterated by the addition of inland recycled moisture to rainfall.

From the low latitude in Sao Tome to the high latitude in inland Ndjamena, there is no discernible depletion of $w\delta^{18}\text{O}$ in precipitation with distance from the Gulf of

Table 3 Comparison of weighted mean $\delta^{18}\text{O}$ and δD values in this study with those of other studies in the Central African region as a function of altitude and approximate distance from the Gulf of Guinea in the Atlantic Ocean

Location	Period	Latitude	Altitude (m asl)	Distance (km)	$\delta^{18}\text{O}$ (‰)	δD (‰)	# Of samples ^a	References
Douala (Cameroon)	2013–2014	04°01'N	5	35	−3.26	−13.01	24	This study
Sao Tome (S and P) ^b	1962–1976	00°38'N	8	0	−3.40	−17.44	123	IAEA/WMO (2015)
Bakingili (Cameroon)	1972–1975	04°13'N	10	0.6	−3.02 ^c	–	–	Gonfiantini et al. (2001)
Douala (Cameroon)	2006–2009	04°05'N	18	35	−3.55	−16.67	34	Ketchemen-Tandia et al. (2013)
Ndjamena (Chad)	1960–1995	12°13'N	294	1105	−3.78	−19.87	86	IAEA/WMO (2015)
Yaounde (Cameroon)	2013–2014	03°55'N	840	191	−3.07	−10.04	19	This study
Nyos (Cameroon)	2013	06°28'N	900	301	−4.00	−23.30	08	Kamtchueng et al. (2015)
Ndop plain (Cameroon)	2012	05°59'N	1178	244	−5.61	−31.93	11	Wirmvem et al. (2014)
Mt. Cameroon summit	1972–1974	04°13'N	4050	22	−9.52 ^c	–	–	Fontes and Olivry (1977)

^a Number of monthly samples^b Sao Tome and Principe (An Island in the Gulf of Guinea)^c Mean values

Guinea (Table 3; Fig. 7b). This is contrary to the expected stable isotope depletion with increasing latitude and inland due to the latitude/continental effect (Dansgaard 1964; Coplen et al. 2000). The slight isotopic enrichment of rainfall with increasing distance from the sea in the segment from Sao Tome to inland Yaounde shows an apparent lack of continental effect. The lack of this effect further supports the significance of inland recycled moisture to rainfall in the Cameroon rainforest (Sigha-Nkamdjou 1993; Njitchoua et al. 1999; Takounjou et al. 2011). Thus, the Cameroon rainforest acts like a ‘partially closed system’. The steep slope of $\delta^{18}\text{O}$ from Yaounde to the Ndop plain (Fig. 7b) with deciduous shrubs and sparse trees suggests the interplay of altitude and continental effects. This steep $\delta^{18}\text{O}$ gradient indicates the dominance of precipitation over evapotranspiration (Ingraham 1998). On the contrary, the steep rise in $\delta^{18}\text{O}$ from the Ndop plain through Nyos to Ndjamena (Fig. 7b) in the semi-arid region suggests the dominance of evapotranspiration over rainfall. Evapotranspiration doubles the mean annual precipitation as reported by Njitchoua et al. (1997) in Garoua, which is along this segment.

A regression line for the data across the Central African region (including this study) shows a higher d-intercept above 10 ‰ of the GMWL (Fig. 8). The higher d-intercept further reflects an additional supply of recycled continental moisture across the region. The observed lack of continental effect is probably due to the added inland moisture from vegetation and numerous water bodies in the region to precipitation. This finding confirms the lack of continental effect that has previously been observed in Sub-Saharan Africa (Joseph et al. 1992; Taupin et al. 2000).

Conclusions

Stable isotopes in monthly rainfall records during the 2013 and 2014 hydrological years in the Douala and Yaounde urban cities have been investigated. Results showed wide and distinctive stable isotope variations that ranged from −5.86 to +1.81 ‰ for $\delta^{18}\text{O}$ and −34.94 to +26.68 ‰ for δD . Rain formation processes in both areas, as reflected by the slopes of the local meteoric water lines of $\delta\text{D} = 7.92\delta^{18}\text{O} + 12.99$ in Douala and $\delta\text{D} = 8.35\delta^{18}\text{O} + 15.29$ in Yaounde occurred under isotopic equilibrium conditions with minor evaporation effect in the course of precipitation. The distinctive monthly variations in stable isotope composition and local meteoric lines are tools for groundwater recharge assessment. The monthly isotopic variations have been used to describe known regional annual cycle of precipitation and atmospheric moisture circulation. Isotopically enriched and depleted rains were mainly associated with precipitation during the dry seasons (pre- and post-monsoons) and rainy seasons (monsoon), respectively. The isotopic enrichments characterised low convective activity before and after the onset of the monsoon in both localities. Like the dry seasons, the West African monsoon transition phase during each hydrological year was clearly marked by enriched isotopic signatures. The abrupt isotopic change (depletion) after the transition phase marked the monsoon onset in the region. At the peaks of the rainy seasons, the strongest influence of the ITCZ and associated monsoons winds in both cities were marked by the most depleted isotopic signatures. High convective activity during the monsoon peaks was characterised by isotopic depletions. Two primary processes influencing the isotopic composition of rainfall in

Fig. 7 Plots of weighted mean $\delta^{18}\text{O}$ ($w\delta^{18}\text{O}$) values in rainfall of Central Africa as a function of altitude (a) and distance from the Gulf of Guinea (b). There is a decrease in $w\delta^{18}\text{O}$ following an increase in elevation. An exceptional case is in the Yaounde and Bakingili rains. Only the mean $\delta^{18}\text{O}$ values represent Bakingili and the Mt. Cameroon summit data (a). From Sao Tome at 8 m in the Gulf of Guinea to Yaounde at 191 km, there is a gentle rise in isotopic slope. The slope decreases steeply to the Ndop plain at 244 km and steeply rises to Nyos at 301 km from the coast. From Nyos, it rises gently to Ndjamenana at 1105 km from the Gulf of Guinea. Only data from Table 3 with weighted mean values are considered (b). *Sao Tome and Principe

Fig. 8 A $\delta^{18}\text{O}$ – δD relationship of the average weighted mean of rainfall in the Central African region. The plot shows a similar slope to the Global Meteoric Water Line (GMWL) of Craig (1961)

both areas are the amount effect and addition of inland recycled moisture from the Cameroon rainforest. The added moisture explains the lack of continental and altitude effects from the Douala coastal city to inland Yaounde. Besides offering a tool for groundwater recharge assessment, the data is useful in climatological investigations in the region. However, long-term stable isotope records in the study areas and across Cameroon are highly recommended as a tool for a better water resource evaluation and climatic studies especially in a changing climate.

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