Monthly $\delta^{18}\text{O}$, δD and Cl characteristics of precipitation in the Ndop plain, Northwest Cameroon: baseline data

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Abstract

Knowledge of stable isotopes and chemical tracers in meteoric water has been used as a valuable tool in various environmental studies. A systematic monthly sampling of precipitation, in the Ndop plain, was carried out to generate basic data on $\delta^{18}\text{O}$, δD and Cl , determine their seasonal variations and controlling factors to be used as baseline data in hydrological and climatological studies. The $\delta^{18}\text{O}$ - δD relationship of rainfall gives a regression line: $\delta\text{D} = 7.93 \delta^{18}\text{O} + 13.26$ ($R^2 = 0.99$), which represents the Ndop Meteoric Water Line (NMWL). The slope is similar to the Global Meteoric Water Line (GMWL), but, with a high d-excess, which suggests a contribution of continental recycled moisture to precipitation. Precipitation shows a wide variation, throughout the year (2012) in $\delta^{18}\text{O}$ and δD , from +3.86 and +38.62 ‰ in January to -7.98 and -53.18 ‰ in September, respectively. The volume-weighted mean of precipitation, which plots close to June rainfall, is -5.61 ‰

and -31.93 ‰ for $\delta^{18}\text{O}$ and δD , respectively. Light convective pre-monsoon and post-monsoon showers, under low relative humidity conditions, are isotopically more enriched than heavy orographic monsoon rain, under high relative humidity conditions. Chloride varies from 1.56 mg/l in the pre-monsoon to 0.06 mg/l during the monsoon rains; like $\delta^{18}\text{O}$ and δD , it shows high values in early and late rains. Apart from January, all d-excess values in monthly rains are >10 ‰. The high d-excess values at the beginning and end of the rainy season suggest the contribution of recycled moisture to precipitation during these periods, under low relative humidity conditions. Assuming a constant condensation temperature, the observed seasonal variation in isotopic composition of precipitation is probably as results of the (1) rain out of Atlantic moisture, (2) monthly rainfall amounts, (3) addition of inland recycled moisture, (4) rain formation mechanism, and (5) varied relative humidity. The varied Cl^- concentrations are due to anthropogenic and oceanic sources, and rainfall amounts.

Key words: *monthly rainfall events; stable isotopes; chloride; Ndop Meteoric Water Line; Cameroon*

1. Introduction

The stable isotopes of oxygen (^{18}O) and hydrogen (D) are integral parts of natural water molecules that fall as rain or snow each year over a watershed (Rozanski et al., 1993; Clark and Fritz, 1997; Kendall and Caldwell, 1998; Gat, 2010) and vary on spatial and temporal basis (Dansgaard, 1964; Jouzel et al., 1997). These variations result from the successive isotopic fractionation processes occurring at each phase change of water during its atmospheric cycle because of differences in physical properties of the isotopic species, HDO and H_2^{18}O , and of H_2^{16}O (Dansgaard, 1964; Gat, 1996; Jouzel et al., 1997; Gonfiantini et al., 1998; Coplen et al., 2000; Kendall and Doctor, 2011). As a consequence of the fractionation processes, atmospheric moisture and precipitation often develop unique isotopic compositions (ratios of heavy to light isotopes), making them ideal tracers of water (Rozanski et al., 1993; Clark and Fritz, 1997; Kendall and Caldwell, 1998; Gat, 2010). This has made stable isotopes an essential tool in hydrological and climatological studies (Ingraham, 1998; Gat, 1996; Gat, 2010; Liu et al., 2010). This includes their use to determine the origin of water vapour; its condensation and precipitation history (Gat and

Matsui, 1991; Mbonu and Travi, 1994; Taupin et al., 2000; Coplen et al., 2000; Kendall and Doctor, 2011) and groundwater recharge mechanism (Mukherjee et al., 2007; Negrel et al., 2011).

Precipitation is the ultimate source of water to catchments (Ingraham, 1998; Kortelainen, 2009). The isotopic composition of ^{18}O and D in local atmospheric precipitation forms primary background data in explaining the sources, retention times and circulation of groundwater, as well as the water-mineral interactions (Kortelainen, 2009). This information, often not accessible by means other stable isotope techniques, is valuable in the assessment and management of water resources (Gonfiantini et al., 1998; Kendall and Doctor, 2011). Thus, an understanding of how the stable isotopic composition is controlled by the formation of precipitation and knowledge of temporal and geographic variations in stable isotopic ratios of precipitation is relevant to the isotope hydrologists and critical for basin water balance studies (Ingraham, 1998; Coplen et al., 2000; Liu et al., 2010). Any isotopic study at the catchment basin scale must start with an understanding of the stable isotopic ratios of precipitation (Dansgaard 1964; Ingraham, 1998). Water resource investigations also require improved knowledge of solute inputs from rainfall such as Cl^- for water balance assessment (Goni et al., 2001; Negrel et al., 2011).

In tropical and semi-arid Africa, the regional mapping of the distribution of stable isotope contents of precipitation is of immense importance not only for use of the isotope data as a geochemical tool in groundwater investigations (e.g., Mbonu and Travi, 1994; Tanyileke et al., 1996; Goni, 2006; Fantong et al., 2010), but, also for describing atmospheric circulation patterns of air masses, and recycling of continental moisture (Njitchoua et al., 1995; Njitchoua et al., 1999; Taupin et al., 2000; Kebede and Travi, 2012). Although Cameroon is endowed with abundant rain and other water resources (Molua and Lambi, 2006), monthly stable isotopic data on rainfall, used in hydrological studies, is rare. Systematic monthly isotopic data in the entire country only include the 1972-1975 data in Mount Cameroon region (Fontes and Olivry, 1977; Gonfiantini et al., 2001) and July-September 1991 and June-August 1992 data in Garoua (Njitchoua et al., 1995), which are only for the rainy season precipitation, and March to November of 2006-2008 data from the Global Network of Isotopes in Precipitation (IAEA/WMO database on the web:

<http://isohis.iaea.org>) at the Douala-Hydrac station (GNIP code: 6491001), hereafter cited as IAEA/WMO Douala data. Thus, except for sporadic isotopic data (Tanyileke et al., Fantong et al., 2010), much of Cameroon remains a gap in the global isotopic data of precipitation, especially the entire Northwest Cameroon.

Given the significance of stable isotopes in hydrological studies and the lack of such data in Cameroon, an attempt has been made, for the first time, in the Ndop plain (Northwest Cameroon) to collect and analyse monthly rainfall for ^{18}O and D, as well as Cl^- . The objective of the investigation is to generate basic data on $\delta^{18}\text{O}$, δD and Cl^- characteristics, define their seasonal variations and controlling factors to be used as a baseline data in hydrological and climatological studies. While providing a first reference tool for understanding the relationship between the climate, hydrology and water resources in the entire region, the data will be a contribution to the global and limited national isotopic data in precipitation. The study is the first in Cameroon to provide a monthly record of isotopic and Cl^- composition in precipitation for up to 11 months in a year.

2. Location and climate of the study area

The Ndop plain (Fig. 1) is an inter-mountain basin, $\sim 1,100 \text{ km}^2$, in Northwest Cameroon. It lies between latitudes $5^\circ 42'$ and $6^\circ 10'$ N and longitudes $10^\circ 11'$ and $10^\circ 40'$ E and $\sim 1,200$ meters above sea level (m asl). The plain is bounded to the west, north and east by a chain of high altitude volcanoes. These form part of a 1,600 km long chain of Cenozoic volcanic centres that cut diagonally across Cameroon SW-NE, the Cameroon Volcanic Line, CVL (Tanyileke et al., 1994). The area falls under the humid tropical equatorial climate type. Located 244 km northeast from the Atlantic Ocean (Fig. 1), it is subjected to the northward and southward movement of the inter-tropical convergence zone (ITCZ) and associated air masses, mainly the southwest monsoon (SWM). These and the high altitude of the surrounding mountainous relief dictate its climate (Molua and Lambi, 2006, Ndzeidze, 2008). It has two distinctive seasons: a long rainy season (mid-March to mid-November) and a short dry season (mid-November to mid-March). Rain is uncommon in the dry season; annual rainfall and temperature in the plain range from 1,000 to 2,000 mm (Molua and Lambi, 2006) and 21.7 to 22.5°C , respectively. The plain has a warm climate, but, cooler

climate in adjacent high elevations, which record higher rainfall than within the plain (Ndzeidze, 2008).

3. Materials and methods

A weather station was installed at the centre of the study area (Fig. 1), 5°59'N and 10°25'E (1,178 m asl), to collect monthly rainfall samples, from January to December 2012, for stable isotope and Cl⁻ measurements. For better interpretation of the data, daily rainfall amounts, temperature and relative humidity were also recorded at the station. Rain samples were collected based on a method described by Negrel et al. (2011). On the last day of each month, water from the 5,000 ml low-density polyethylene (LDPE) container was properly shaken to mix and filled into a 100 ml LDPE bottle, tightly capped and stored in a cold dark-place prior to air-flight to Japan for analyses.

Laboratory analyses were carried out at Tokai University. Chloride content was determined by using a Dionex ICS-900 Ion Chromatography. Hydrogen and oxygen isotope ratios of water samples were measured using a Cavity Ring-Down Spectrometer analyser (model L2120-i from PICARRO) following the method described by Brand et al. (2009). The isotope ratio D/H and ¹⁸O/¹⁶O in water samples are expressed as per-mille deviation (‰) relative to the Vienna-Standard Mean Ocean Water (V-SMOW) as follows:

$$\delta(\text{‰}) = \frac{R(\text{sample})}{R(\text{V-SMOW})} \times 1000 \dots \dots \dots (1)$$

where R (sample) and R (V-SMOW) represent either the ¹⁸O/¹⁶O or D/H ratio of the samples and ¹⁸O/¹⁶O or D/H ratio of the V-SMOW, respectively. The oxygen and hydrogen isotope ratios are hereafter expressed as δ¹⁸O and δD, in that order, or collectively as δ-values. Total analytical precisions are better than ±0.03 ‰ (δ¹⁸O) and ±1.00 ‰ (δD). Analysed data was treated using Excel 2010. Given the usual 4 months of a dry season in the entire study area, the volume-weighted mean of δ-values (wδ¹⁸O and wδD) for each month and then the annual value at the weather station were computed from the formulation (IAEA, 1992):

$$w\delta = 1/P \sum^{12} (p_t \cdot \delta_t) \dots \dots \dots (2)$$

where P represents the annual amount of precipitation; p_t and δ_t are rainfall amounts and isotopic composition for each month. The same method was used to compute the volume-weighted mean of d-excess and Cl⁻.

4. Results and discussion

4.1. Isotopic and chloride characteristics in monthly precipitation

Table 1 presents the results of monthly rainfall isotopic data, Cl^- and corresponding measurements. There was no precipitation in December. The $\delta^{18}\text{O}$ - δD relationship for the 11 monthly rain samples (Fig. 2) gives the following regression line ($R^2 = 0.99$) that represents the Ndop Meteoric Water Line (NMWL):

$$\delta\text{D} = 7.93\delta^{18}\text{O} + 13.26 \dots\dots\dots(3)$$

The slope is very close to 8 of the GMWL: $\delta\text{D} = 8\delta^{18}\text{O} + 10$ (Craig, 1961), but plots slightly above the GMWL due to the high d-excess value, which suggest a contribution of recycled continental moisture to precipitation under low relative humidity conditions (Clark and Fritz, 1997). The similarity of the slope to the GWML suggests that (1) the rain formation process in the area occurs under conditions close to isotopic equilibrium (Dansgaard, 1964), and (2) the isotopic compositions of the investigated rains have not been significantly modified by evaporation during the descent of rain drops to the ground (Craig, 1961, Rozanski et al., 1993). Similar slopes with different d-intercepts have been obtained in Cameroon (Fontes and Olivry, 1977; Njitchoua et al., 1999; Gonfiantini, 2001; IAEA/WMO Douala data; Fantong et al., 2010), suggesting a common moisture source. The varied d-intercept reflects local climatic effects such as re-evaporation and relative humidity. The plot of pre-monsoon (January-April) and post monsoon (October-November) rains in the upper portion of the NMWL (Fig. 2) suggests that they may originate from isotopically enriched local moisture sources (such as evaporated surface water bodies). Except for May rains, all other monsoon rains (June-September) plot in the lower part of the NMWL, suggesting that the precipitated moisture has likely travelled a greater distance and had multiple fractions before precipitation (Mukherjee et al., 2007; Kendall and Doctor, 2011). The $\text{w}\delta^{18}\text{O}$ (-5.61‰) and $\text{w}\delta\text{D}$ (-31.93 ‰) are close to June precipitation (Fig. 2).

As for δD , the $\delta^{18}\text{O}$ of the monthly precipitation shows a wide variation, from lows of +3.86 ‰ at the peak of the dry season (January) to highs of -7.98 ‰ at the peak of the rainy season (September). Its mean of -2.96 ‰ (Table 1) is as expected for the latitude range of the study area (IAEA, 1992; Gat, 2010). Monthly d-excess, defined as $d = \delta\text{D} - 8*\delta^{18}\text{O}$ (Dansgaard, 1964), of precipitation range broadly from 7.73 (January) to 18.74 (April) with

a mean of 13.48 ‰. The 10 ‰ d-excess of Atlantic moisture (Dansgaard, 1964) falls between the d-excess ranges indicating the significance of the Atlantic Ocean as a vapour source for the Ndop plain. All months, except January have d-excess values >10 ‰. This suggests an additional source of moisture, besides the Atlantic moisture, and further indicates a minor evaporation during the descent of rain drops. From April, the $w\delta^{18}\text{O}$ and d-excess in the monthly rainfall events progressively show low values with an increase in rainfall amounts, forming V-shapes, i.e., high values at the beginning of the rainy season (April), low values during the rainy season (May-September) and again high values at the end of the rainy season (October-November) (Fig. 3a & b). The $w\delta^{18}\text{O}$ does not clearly show the decreasing pattern in the January to April precipitation, which are essentially light dry season showers (<89 mm of rainfall). On the contrary, d-excess shows a corresponding increase with an increase in rainfall amounts from January to April. These observations show distinctive characteristics of stable isotope composition and d-excess in the pre-monsoon, monsoon and post-monsoon rains. Similar wide variations in δ -values have been observed in Cameroon (Fontes and Olivry, 1977; Njitchoua et al., 1995; Gonfiantini et al., 2001; IAEA/WMO Douala data), the entire western Africa (Taupin et al., 2000) and elsewhere (Rhodes et al., 2006; Liu et al., 2010; Feng et al., 2013). The lack of correlation between temperature and δ -values (Table 1) is as expected for tropical low-latitudes (Rozanski et al., 1993).

As shown (Table 1), monthly Cl^- concentrations varies from 0.06 to 1.56, with a mean of 0.32 mg/l. Like $w\delta^{18}\text{O}$, the highest values are recorded during the pre-monsoon, but, contrary to the $w\delta^{18}\text{O}$, Cl^- clearly shows an inverse relationship with rainfall from January to April (Fig. 3c). It shows an even distribution during the rainy season (May-October); however, like $w\delta^{18}\text{O}$ and d-excess, shows relatively high values at the beginning (April) and end (November) of the rainy season (Fig. 3c). This shows the effects of evaporation. Thus, similar to δ -values and d-excess, Cl^- shows the distinctive seasonal characteristics in precipitation.

4.2. Factors controlling the seasonal isotopic and Cl^- variations in precipitation

January-April and October-November, which recorded the lowest rainfall amounts and days, have the most enriched δ -values. The low relative humidity during these months (Table 1) means that vapour below the cloud has not yet been exposed to the cooling process. This results to high isotopic exchange and partial evaporation between the falling rain drops and the environmental vapour (Dansgaard, 1964; Rozanski et al., 1993; Gat, 2010), hence, the relatively high δ -values in the rains, which plot in the upper portion of the NMWL (Fig. 2). The exceptional high positive δ -values in the January shower show a slight deviation from the NMWL. This can be explained after Rozanski et al. (1993) and Gat (2010) as due to high evaporation relative to other months given its unique low d-excess (Table 1). During the pre-monsoon, and post-monsoon, light convective showers of continental origin, under low relative humidity and warm air, probably dominant the rain formation process. Despite the relatively heavy February, April, October and November rains, their enriched isotopic compositions (Table 1) can as well be related to convective continental vapour sources (Taupin et al., 2000; Mukherjee et al., 2007). The observed positive δ -values in the pre-monsoon and post-monsoon precipitation have been observed elsewhere in the tropics (Mbonu and Travi, 1994; Njitchoua et al., 1999; Taupin et al., 2000; Goni et al., 2001; Rhodes et al., 2006), but, the very high values of the January shower are an exception, only comparable to arid zone precipitation (Taupin et al., 2000; Goni et al., 2001).

Progressive low $w\delta^{18}\text{O}$ values from April to September (Fig. 3a) reflect the gradual influence of the ITCZ and SWM over the area, bringing in warm moisture-laden winds from the Gulf of Guinea (GoG) in the Atlantic Ocean. Because of the high altitude of the immediate surrounding mountainous relief, deep cooling by high lifting of the winds result to increasing orographic rainfall from April and the number of rainy days (Table 1). The moisture-laden winds and subsequent rainfall result in progressively high relative humidity (Table 1), that is, saturated air. As a consequence, the isotopic exchange between the falling rain drops and atmospheric vapour decreases (Dansgaard, 1964; Ingraham, 1998; Gat, 2010), resulting to increasingly negative $w\delta^{18}\text{O}$ values from April to September as rainfall increases. The slight rainfall decrease in June, which causes a minor change in $w\delta^{18}\text{O}$ slope from May to June (Fig. 3a), probably marks a temporary southward retreat of the ITCZ. However, because the meteorological equator shifts towards the north, which is linked to the

strengthening of the SWM (Molua and Lambi, 2006), the area still receives considerable rainfall from June (Fig. 3a). The lowest $w\delta^{18}\text{O}$ value in September, which corresponds to the highest rainfall, indicates the northward migration of ITCZ and its strongest influence, in association with the SWM, in the area. An abrupt increase in $w\delta^{18}\text{O}$, which parallels a sharp decrease in rainfall, from September to October (Fig. 3a) possibly mark the retreat of ITCZ.

The observed inverse relation between the monthly rainfall amounts and $w\delta^{18}\text{O}$ (Fig. 3a) is in agreement with amount effect characteristic of tropical low latitude rains (Dansgaard, 1964; Rozanski et al., 1993). This has been observed in Cameroon (Njitchoua et al., 1995; Njitchoua et al., 1999; Gonfiantini et al., 2001), and elsewhere (Mbonu and Travi, 1994; Goni et al.; Rhodes et al., 2006; Liu et al., 2010; Kebede and Travi, 2012). As shown (Fig. 3a), the $w\delta^{18}\text{O}$ showed less variability in light convective showers (January-April) than in heavy rains (May-September), indicating that the amount effect is less significant in light convective showers. Similarly, light convective summer rains have shown less variability in $w\delta^{18}\text{O}$ than heavy winter rains (Jaeschke et al., 2010). This is contrary to the observation in Ethiopia rains (Kebede and Travi, 2012), where the amount effect is visible only for small rain events. This disparity may be due to varied local climates and vapour sources in the two regions; and the anomalous stable isotope composition of Ethiopia rainfall that has long been recognised (Dansgaard, 1964).

The annual variation in $w\delta^{18}\text{O}$ gives a similar V-shape observed in south Cameroon (Njitchoua et al., 1999) and the entire western Africa; this is attributed to evidence of moisture from the Atlantic Ocean (Taupin et al., 2000). It appears that this annual V-shape (Fig. 3a) is similar to that of a single rain event due to a combination of rain out and the amount effect (Gat, 2010). The $w\delta^{18}\text{O}$ of precipitation, in this study, is compared with the few related studies in Cameroon as a function of distance from the coast. As shown (Fig. 4), the $w\delta^{18}\text{O}$ of -1.5 ‰ in rainfall at Kribi, near the Atlantic coast (Njitchoua et al., 1999) and -3.43 ‰ from IAEA/WMO Douala data show a steep gradient. Further inland, from Douala to the study area, there is a gentle $\delta^{18}\text{O}$ gradient (Fig. 4). Therefore, as the Atlantic air mass moves northward, to higher altitudes and latitudes, across Cameroon, there is progressive removal of vapour as rainout by Rayleigh type distillation mechanism of an open system. This is in agreement with continental, altitude, and latitude effects (Dansgaard, 1964; Gat,

1996; Jouzel et al., 1997; Coplen et al., 2000; Liu et al., 2010) as would be expected due to progressive fractionation along a coast-to-inland gradient and lower temperatures with increasing altitude (Clark and Fritz, 1997; Kendall and Doctor, 2011). However, despite the high altitude difference between Douala and the Ndop plain (Fig. 4), the relatively small isotopic gradient of $-1.08 \text{ ‰ } 100 \text{ km}^{-1}$ reflects a gradual lack of continental effect with increasing distance from the coast, that is, a ‘partially closed system’ (Ingraham, 1998). Similar observations (Salati et al., 1979; Njitchoua et al., 1999; Taupin et al., 2000) have been attributed to a contribution of inland recycled moisture to precipitation. This influence can be corroborated by the d-excess parameter.

Deuterium-excess shows a degree of the kinetic effect and is quite useful in distinguishing source vapour (Gat, 1996; Clark and Fritz, 1997; Kortelainen, 2009). About 91 % of the monthly samples have d-excess $>10 \text{ ‰}$ of continental precipitation from oceanic moisture (Dansgaard, 1964) by a $\sim 3.48 \text{ ‰}$ increase. The weighted mean value is 12.99 ‰ (Table 1). Recycled inland vapour usually results to $>10 \text{ ‰}$ d-excess in precipitation (Salati et al., 1979; Gat and Matsui, 1991; Clark and Fritz, 1997; Gat, 2010). Thus, the observed high mean, weighted mean and monthly d-excess values further confirm a contribution of inland recycled moisture to precipitation in the Ndop plain. The recycling is favoured by rising of inland moisture such as from the Bamendjin dam and numerous rivers to the immediate surrounding mountain chain (Fig. 1) leading to precipitation. Such high d-excess values have also been reported from inland hydrological systems where moisture recycling plays a significant role in the water cycle (Salati et al., 1979; Gat and Matsui, 1991; Mbonu and Travi, 1994; Njitchoua et al., 1999; Kebede and Travi, 2012; Feng et al., 2013).

The annual V-shape of d-excess (Fig. 3b) indicates that the contribution of recycled vapour is mainly in early April and late October-November light convective showers, under low relative humidity conditions, in agreement with enriched δ -values during these months (Table 1). The convective showers tend to recycle local atmospheric vapour instead of being a source of new vapour to the region (Ingraham, 1998). On the contrary, the steady decrease in d-excess from 18.74 ‰ in April rains to $\sim 10 \text{ ‰}$ during the main rainy season (Fig. 3b) shows the gradual contribution of the Atlantic moisture to precipitations under high relative humidity conditions given the depleted δ -values. The total amount of convective showers

from January to April and October to November is 379 mm (25 %) of the total rainfall (1,540 mm). The May to September monsoon rains is 1161 mm (75 %) of the total rainfall in the study area. Based on the d-excess and δ -values, it can be postulated that 75 % of moisture, largely from May to September, originates from the Atlantic Ocean, and 25 % of vapour (mainly January-April and October-November) is from recycled inland moisture.

The observed d-excess pattern has been observed in the entire western Africa (Taupin et al., 2000) and elsewhere in the tropics (Rhodes et al., 2006). Similarly, low winter precipitation amounts have been shown to have extremely higher d-excess values than abundant summer precipitation in Urumqi River Basin, China (Feng et al., 2013). Therefore, assuming a constant condensation temperature, the observed seasonal variation in isotopic composition of precipitation in the Ndop plain is probably influenced by the (1) rain out of Atlantic moisture, (2) monthly rainfall amounts, (3) addition of recycled moisture given the ca. 244 km distance northeast from the Atlantic Ocean, (4) rain formation mechanism (convective and orographic systems), and (5) varied relative humidity.

While moisture supply from the GoG has been reported in the study area, from climatological evidence (Molua and Lambi, 2006, Ndzeidze, 2008), greater details regarding the hydrologic inputs, during the pre-monsoon, monsoon and post-monsoon, have been acquired through the use of stable isotopes. Thus, in addition to variations in δ -values, d-excess can be used, as geochemical tools, to determine the relative contribution of re-evaporated moisture (early and late rains) and Atlantic moisture (the rainy season) to precipitation and subsequent groundwater recharge studies in the study area.

Like the $w\delta^{18}\text{O}$, the distribution of Cl^- in the monthly rainfall events generally decreases with an increase in rainfall amounts (Fig. 3c). Based on the annual distribution of Cl^- and linear $\delta^{18}\text{O}$ - Cl^- relationship (Fig. 5), two sources of Cl^- are possible. The high Cl^- values can be explained by rainout of dry deposition from non-marine sources. Similar high Cl^- values in the early rains have also been reported elsewhere in the tropics (Goni et al., 2001; Akoto et al., 2011). A second source of Cl^- is likely moisture from the Atlantic Oceanic during the monsoon rains; it shows similar values during these rains (Fig. 3c), even with the change $\delta^{18}\text{O}$ values (Fig. 5), consistent with the continuous supply of the moisture by the ITCZ and SWM. The low homogenous nature of Cl^- values during this monsoon period are similar to

1992 precipitation in Garoua (Njitchoua et al., 1995), and the 1990s precipitation in northern Nigeria (Goni et al., 2001). This has been attributed to the advanced state of emptying of vapour reservoir, induced by a relatively slow northward migration of ITCZ and associated SWM (Njitchoua et al., 1995). The low weighted mean of Cl^- (Table 1) relative to semi-arid precipitation (Njitchoua et al., 1995; Goni et al., 2001; Fantong et al., 2010) may be due to the high amount of rainfall in the study area which results in atmospheric dilution, hence, the higher the rainfall, the lower the Cl^- content.

5. Summary and conclusions

The geographical location of the study area (tropical low-latitude, 244 km inland and northeast from the Atlantic Ocean) is reflected in the isotopic composition of precipitation. The mean $\delta^{18}O$, δD and d-excess values and their relations reveal a contribution of vapour from the GoG in the Atlantic Ocean (75 %) by the ITCZ and associated SWM given the proximity to the Atlantic coast. When compared with other studies in Cameroon, there is gradual lack of continental effect with increasing distance from the coast as has been observed in the entire western Africa (Taupin et al., 2000). This, in addition to the high d-excess, at the beginning and end of the rainy season reflect a contribution of inland recycled moisture (25 %) to precipitation. Lighter pre-monsoon and post-monsoon showers are isotopically enriched relative to heavier monsoon precipitation, in agreement with the so called ‘amount effect’ characteristic of lower-latitude tropical rains (Dansgaard, 1964). This also suggests the origin of pre-monsoon and post-monsoon precipitated moisture mainly from isotopically enriched local sources under low relative humidity conditions. The monsoon vapour has likely travelled a greater distance from the Atlantic Ocean and had multiple fractionations before precipitation, hence, relatively depleted.

For the first time, a baseline stable isotopic and Cl^- data of precipitation for future hydrological and climatological studies has been made available in the entire Northwest Cameroon. The average $\delta^{18}O$ and δD relationship for all the 11 monthly rain samples gives the following regression line that represents the Ndop Meteoric Water Line (NMWL): $\delta D = 7.93\delta^{18}O + 13.26$ ($R^2 = 0.99$) with a similar slope to the GMWL; but, higher d-excess, due to a contribution of recycled moisture to precipitation. The average $\delta^{18}O$ and δD in

precipitation vary widely from +3.86 and +38.62 in January (peak of the dry season) to -7.98 and -53.18 ‰ in September (peak of the rainy season), respectively. Since precipitation is the major source of groundwater recharge, the distinctive seasonal variation in δ -values, d-excess and Cl^- can be used as reference tools in groundwater studies, in the region, such as in the determination of recharge mechanism, quantification and timing. Assuming a constant condensation temperature, the factors causing the observed seasonal variation in isotopic composition of precipitation, in the Ndop plain, can be summarised as the (1) rain out of Atlantic moisture, (2) monthly rainfall amounts, (3) addition of recycled moisture, (4) rain formation mechanism (convective and orographic systems), and (5) the varied relative humidity. The varied Cl^- concentrations are due to rainfall amounts and non-marine and oceanic sources. While the study covers only one year of precipitation sampling, it is the first in Cameroon to provide a record of isotopic composition and Cl^- for up to 11 monthly samples in a year, hence, constituting a basis for subsequent studies. Further studies are highly recommended given significance of isotopic composition of oxygen and hydrogen of precipitation in hydrological, as well as climatological studies.

Acknowledgements

The paper constitutes part of ongoing PhD research of the corresponding author, sponsored by the Japanese Government under the Monbukagakusho Scholarship from the Ministry of Education, Culture, Sports, Science and Technology (MEXT). Material support is provided by Japan Science and Technology Agency (JST) and Japan International Cooperation Agency (JICA) under the Science and Technology Research Partnership for Sustainable Development (SATREPS) project titled: Magmatic Fluid Supply into Lakes Nyos and Monoun, and Mitigation of Natural Disasters in Cameroon. The authors are grateful to the editor and anonymous reviewers for their valuable comments and suggestions which have modified this paper.

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Fig. 1. Map of the study area showing the drainage, relief and rain sampling point.

Fig. 2. $\delta^{18}\text{O}$ - δD relationship of monthly rainfall events in the Ndop plain. The produced Ndop Meteoric Water Line (NMWL) has a similar slope to the Global Meteoric Water Line (GMWL). Pre-monsoon (January-April) and post-monsoon (October-November) rains are isotopically enriched than the monsoon (May-September) precipitation.

Fig. 3. Inverse relationships between monthly rainfall amounts and (a) weighted mean $\delta^{18}\text{O}$, (b) d-excess except January to April (dry season) and (c) Cl^- except May-Oct. These parameters record the highest values during the dry season showers, lowest values during the monsoon rains (May-September) and high values in the post-monsoon precipitation (November).

Fig. 4. A spatial distribution of weighted mean $\delta^{18}\text{O}$ in rainfall as a function of distance and elevation from the Atlantic Ocean showing altitude and continental effects; but a gradual lack of these effects further inland. The plot shows two systems: Kribi-Douala (an open system) and Douala-Ndop plain (a partially closed-system).

Fig. 5. $\delta^{18}\text{O}$ - Cl^- linear relationship of monthly rainfall events.

Table 1 Isotopic and Cl⁻ composition of monthly rainfall and weather records in the Ndop plain in 2012 showing a progressive decrease in $\delta^{18}\text{O}$, δD and Cl⁻ with an increase in rainfall amounts.

Month	$\delta^{18}\text{O}$	δD	<i>d</i> -excess	Rainfall	Rainy days	RH (%)	Temp (°C)	Cl ⁻ (mg/l)
January	+3.86	+38.61	07.73	03	01	33	29.10	1.56
February	-0.15	+11.67	12.87	63	08	36	24.31	0.40
March	+0.58	+15.69	11.04	10	04	45	25.55	0.73
April	-0.54	+14.44	18.74	89	12	50	24.90	0.21
May	-2.89	-08.34	14.78	139	16	55	25.40	0.79
June	-4.97	-25.38	14.39	112	11	54	24.51	0.07
July	-7.09	-43.10	13.60	151	10	68	24.73	0.06
August	-7.64	-50.66	10.42	278	14	79	24.21	0.06
September	-7.98	-53.18	10.70	481	11	81	23.00	0.10
October	-2.84	-5.88	16.87	133	06	50	25.92	0.08
November	-2.91	-6.21	17.10	81	4	40	27.50	0.22
December	-	-	-	-	-	38	28.80	-
Mean	-2.96	-10.21	13.48	1540	Sum = 97	53.73	25.54	0.32
vwm	-5.61	-31.93	12.99	-	-	-	-	0.11

$\delta^{18}\text{O}$, δD and *d*-excess are in ‰, Rainfall (mm); RH, relative humidity; vwm, volume-weighted mean value; Altitude: 1178 meters above sea level; distance from the Atlantic Ocean, ca. 244 km.

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5