Stable isotope characteristics of precipitation in Malaysia: Establishment of local meteoric water line

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Abstract

This paper discussed the use of stable isotope compositions of precipitation (d^2H and $d^{18}O$) to understand its characteristics and the parameters controlling meteorological conditions in Malaysia. The meteoric water line for Malaysia, or MMWL established in this study are $d^2H= (7.43±0.05)d^{18}O + (7.33±0.11)$ (n=595, r^2=0.97) for individual values, and $d^2H= (7.07±0.20)d^{18}O + (4.90±0.75)$ (n=51, r^2=0.96) for annual precipitation weighted means. No major variations in local meteoric water lines established between the stations, except for one (i.e., Cameron Highlands), which was found to be significantly different due to its high deuterium excess, or *d* value, attributed to moisture recycling (re–evapotranspiration) from the surrounding dense rainforest area. The precipitation moisture came from the two monsoon systems; the Northeast monsoon (NEM) and Southwest monsoon (SWM). They differ only slightly in their isotope signatures, where the NEM (winter monsoon) is 0.38‰ more negative than the SWM (summer monsoon), and the rainfall amount and temperature have a relatively weak influence on the stable isotopes in precipitation. Rainfall $d^{18}O$ is poorly correlated with the monthly rainfall amount and temperature, with very low r^2 values (–0.4‰/100mm; 0.09 and 0.7‰/°C; 0.06, respectively). The seasonal variability of isotopic compositions of precipitation in this region is controlled by the insubstantial but conspicuous inverse correlation amount effect. The seasonal patterns of d^2H and $d^{18}O$ are evident, with higher values observed during the NEM and lower values observed during SWM. However, the temporal variations of rainfall d^2H and $d^{18}O$ during NEM and SWM are almost indistinguishable due to local climatic conditions, prevailing atmospheric circulations, and sources of precipitation. The apparent sign of El Niño and La Niña events (2015 and 2017, respectively) of the El Niño–Southern Oscillation (ENSO) cycle were successfully identified from this study, indicated by the heavier $d^{18}O$ from the peaks in the annual precipitation amount versus $d^{18}O$ annual precipitation weighted mean plot, while La Niña corresponds to the lighter values of the rainfall isotopes.

Introduction

Isotope Hydrology is the use of isotopic tools and nuclear techniques to study water cycles. It was introduced just after the Second World War (Aggarwal et al. 2005). Stable isotope compositions in natural waters are typically measured using double–focused magnetic sector field mass spectrometers, which Alfred Nier initially designed in 1947 (Gourcy et al. 2005). His design remains the basis of stable isotope mass spectrometry, although modern instruments are equipped with multiple collectors for simultaneously measuring several isotope ratios.

Environmental isotopes are naturally occurring isotopes of elements found in abundance in the environment. However, only a few are of practical importance (H, C, N, O, and S) because they are the principal elements of hydrological, geological, and biological systems (Clark and Fritz 1997). The environmental isotopes can be divided into stable isotopes and radioisotopes; however, this article only discusses the latter. In a hydrological cycle, surface water and groundwater are derived from meteoric waters (atmospheric moisture and precipitation) evaporated from the ocean (Mook 2001; Mook 2006). Environmentally stable isotopes are ideal tracers of water and solutes in the environment, as they are incorporated in the water molecules and relatively conservative in their reactions with geological material. They can also be used to monitor processes (e.g., mixing and evaporation). Their behaviors and variations reflect the origin of and the hydrological and geochemical processes experienced by natural water bodies (Gonfiantini 1998), which is especially true of hydrogen (protium, deuterium, and tritium) and oxygen (oxygen–16, oxygen–17, and oxygen–18) isotopes in water, where the meteoric waters retain their distinctive isotopic fingerprint until they mix with waters with different compositions (Kendall and Caldwell 1998).

Isotope ratios of deuterium or $^2H/^1H$ (δ^2H) and oxygen–18,$^{18}O/^{16}O$ ($\delta^{18}O$) in precipitation are closely related, lying on a single line known as the Meteoric Water Line (MWL). Initially, the relationship between δ^2H and $\delta^{18}O$ in precipitation and non–marine surface waters, established from ~ 400 samples distributed from all over the world, is defined as:

$\delta^2H= 8\delta^{18}O + 10‰$ SMOW (Craig 1961)

and known as the Global Meteoric Water Line (GMWL). Later, based on the long–term annual weighted means of δ^2H and $\delta^{18}O$ values from 219 International Atomic Energy Agency and World Meteorological Organization (IAEA/WMO) stations network, the line was redefined as:

$\delta^2H= 8.20 (±0.07)\ \delta^{18}O + 11.27 (±0.65)$ ‰ VSMOW (Rozanski et al. 1993)

In order to determine the mean of freshwaters isotopic composition globally, Craig's (1961) equation describes distinctively the estimation of locus of the points, which then was also supported by Rozanski's et al. (1993) equation. However, developing a local meteoric water line for a specific study area is very important as $\delta^2H–\delta^{18}O$ relationship in precipitation varies spatially and region–dependent. Besides, identification of surface water and groundwater sources and effects of evaporation on water bodies can be obtained from the best–fit Local Meteoric Water Line (LMWL) which manifests the isotopic input functions for hydrological studies (Liu et al. 2014). Furthermore, meteorological factors (temperature, atmospheric humidity, precipitation amount, initial conditions and trajectory of the water vapor, rainout history of the air mass, secondary evaporation during rainfall and evapotranspiration effect) as well as environmental factors (geographical location, atmospheric circulation, weather system, and terrain) also affected the isotopic composition of local precipitation (Craig 1961; Peng et al. 2004; Hughes 2013; Jia et al. 2019).

Delineation of the deuterium excess in global precipitation using the *d* value was pioneered by Dansgaard (1964). The value *d* is defined for a slope of 8 and calculated for any precipitation sample using:

$d = \delta^2H – 8\delta^{18}O$ (Dansgaard 1964)

Primary information on the initial moisture source and secondary processes such as evaporation during precipitation and recirculation of moisture from large continental water bodies can be derived from deuterium excess (Dansgaard 1964; Araguas–Araguas et al. 1998; Araguas–Araguas et al. 2000; Gat 2000).

According to Jacob and Sonntag (1991), evaporation of raindrops under the cloud base and warm and dry conditions can be associated with low deuterium excess, while low humidity during evaporation at the moisture source (for example, sea surface) and evapotranspiration can be translated to high deuterium excess values (Hughes 2013).

International Atomic Energy Agency (IAEA) and World Meteorological Organization (WMO) started The Global Network of Isotopes in Precipitation (GNIP) program in 1958. The objective of the program was to collect spatial data of isotopic composition in precipitation globally to determine its spatial and temporal variations. GNIP also has strengthened its role to monitor and observe the network of stable hydrogen and oxygen isotope data for hydrological studies although its original goal was monitoring the atmospheric thermonuclear test fallout via the determination of the radioactive hydrogen isotope (tritium) since 1970s. As a result, global isotope data for hydrological studies such as water resources investigation, planning, conservation, and development have been derived from GNIP for the last 50 years. Therefore, over the past decade, more advanced scientific disciplines have leveraged the invaluable and exceptional isotope database for multiple applications which cover (i) validating and enhancing atmospheric circulation models, (ii) investigating global, regional, spatial, and temporal climate, (iii) examining the interactions of water between atmosphere and biosphere, or as an input to hydrological studies, and (iv) delivering baseline information for the authentication of commodities (such as food and plants), ecology, e.g., for tracking migratory species (birds, fish, and butterflies) and for forensic purposes (Baisden et al. 2016; IAEA 2019).

The lack of localized detailed investigations related to the use of stable isotopes, i.e., deuterium (^{2}H) and oxygen–18 (^{18}O) in water resources study conducted previously in Malaysia are mainly due to insufficient knowledge in isotope technique, unavailability of Isotope Ratio Mass Spectrometer (IRMS), and the lack of a database of stable isotope compositions of precipitation to act as a reference point. In light of the abovementioned facts, this study aims to develop a $\delta^{2}H$ and $\delta^{18}O$ database of precipitation to elucidate various components of the water cycle and groundwater evolutions. Stable isotope tracers of water can be used for this purpose due to their unique 'fingerprint' of sources often preserved within the subsurface. The precipitation process has a geographically–specific isotopic fingerprint inherited by the local groundwater (Kortelainen 2011). By collecting information, establishing a database on stable isotopes of hydrogen and oxygen of meteoric water, and analyzing the groundwater and surface water together with the hydrogeological information, an evaluation can be made to define the source and origin of groundwater, surface water, and groundwater interactions and groundwater dynamics. Recharge, sources of groundwater salinity, and the mass balance in the study area can also be determined (Yeh et al. 2009).

In Malaysia, isotope hydrology techniques were introduced in the early 1980s. The Malaysian Meteoric Water Line (MMWL) was established in 1981 with 3 rainfall stations covering only the northern part of Peninsular Malaysia. There were no stations in East Malaysia or Borneo Island. The study continued in the 1990s until mid–2000s, with irregular sampling intervals resulting in intermittent data. The number of rainfall stations also varied during the entire study period, with only 5 stations remained by the end of the study, mostly located on the upper half of Peninsular Malaysia. Overall, the Malaysian Meteoric Water Line was established as:

$\delta^{2}H = 8\delta^{18}O + 13.255$ (Ayub 2006)

Efforts to strengthen the cooperation of the Malaysian Nuclear Agency (Nuclear Malaysia), the national nuclear research institute, formerly known as the Malaysian Institute for Nuclear Technology Research (MINT), with GNIP/IAEA was made possible by the former Director–General of Malaysian Nuclear Agency. Subsequent correspondence between the Division of Physical and Chemical Sciences, Isotope Hydrology Section (NAPC, IHS) and the Malaysian Nuclear Agency revealed the existence of a national precipitation isotope sampling network. However, these efforts were not pursued for several years starting mid–2000s and sampling activities resumed only in 2013. On the IAEA side, historical data was compiled, and precipitation isotope data from Malaysia were reviewed to identify potential overlap, and activities to be undertaken by IAEA alongside the Malaysian Nuclear Agency were recommended.

Unlike the mid–latitudes and high latitudes, this study is vital as the relation between the isotope signature of precipitation and climate is not well understood vis–à–vis the tropics (Araguas–Araguas et al. 1998). Consequently, it will result in a valuable database for hydrological studies in Malaysia and also Southeast Asia. Marryanna et al. (2017) highlighted the importance of stable isotope signals in precipitation water in their effort to conserve the tropical rainforests in Peninsular Malaysia. Stable isotope signals in precipitation water serve as indices of site–dependent rainfall and climate characteristics. These records can also serve as basic information for regional research and tools for monitoring possible climate change. The standard parameters related to climate change are surface air temperature, sea level, sea surface temperature, Arctic Sea ice, precipitation, and extreme weather occurrences. However, changes in Arctic Sea ice are irrelevant in the context of a tropical country. These indicators are distinguished by high temperature, high rainfall, dry spell, thunderstorm, and strong winds in Malaysia. According to Daniel Tang (2019), the accuracy of the review on temperature increase, rainfall variation, sea–level rise, and future projections on climate change is dependent on the accuracy of the data and simulation models adopted in the literature. Thus, the isotope technique can serve as a potential tool for defining the effect of climate change and help develop mitigating measures.

Poor correlation between $\delta^{18}O$ of rainfall and daily precipitation (amount effect) is consistently reported in studies conducted in East Malaysia. A study of extensive–scale climatic controls on rainfall at Gunung Mulu, Sarawak in northern Borneo by Cobb et al. (2007) showed that seasonal to interannual changes in large–scale precipitation is reflected in the $\delta^{18}O$ of rainwater, where the climate is dominated by monsoonal variability, and the precipitation is highly correlated to the Southern Oscillation Index (SOI). The study also found a low correlation ($r = 0.05$) between rainfall and precipitation, known as the local "amount effect" caused by the fractionation from the convective rain. On regional scales, the moisture transport path mainly determines $\delta^{18}O$ in rainwater (depleted or enriched) characteristics, degree of the rainout, and orographic effect. Again, a relatively weak but significant ($r = -0.19$) inverse correlation between rainfall $\delta^{18}O$ and daily precipitation was demonstrated when investigating the variability of northern Borneo rainfall $\delta^{18}O$ and its response to local and regional climate variations. However, the weak amount effect increased with increasing temporal averaging or running average (Moerman et al. 2013).

For the first time, besides developing a database of $\delta^{18}O$ and $\delta^{2}H$ and local meteoric water lines from monthly precipitation samples collected at the GNIP network stations throughout Malaysia, the moisture sources of the precipitation between monsoons will also be isotopically characterized and differentiated.

The seasonal and temporal behaviors of the isotopes and the relationship between isotope composition, temperature, and precipitation amount are also explained in this study. The need for reliable and detailed local MWL in Malaysia served as an impetus to the publication of this article.

Materials And Methods

Rainwater samples were collected monthly for 6 years (January 2013 to December 2018) from nine IAEA GNIP rainfall stations located in Kuching (Sarawak), Senai (Johor Bahru), Malaysian Nuclear Agency or MNA (Selangor), Kuantan (Pahang), Cameron Highlands (Pahang), Kuala Terengganu (Terengganu), Kota Kinabalu (Sabah), Kota Bharu (Kelantan), and Alor Setar (Kedah), as illustrated in Fig. 1. The stations' information is also tabulated in Table 1, organized ascendingly based on the order of the latitude. These stations were carefully selected and widely distributed throughout Malaysia. No stations in central East Malaysia were selected due to funding and logistical limitations. There are incomplete samples from all of the stations (one to five months) in the first year of the study due to early–stage project implementation problems such as the approval for hosting the sampler, the appointment of volunteers for handling the sampler, and unfamiliarity with the new technique used. The rain gauges were placed at the sampling area in the rainfall stations site on the first day of every month, and the monthly accumulated samples or composite samples of precipitation were emptied at the end of the month. The precipitation samples collected were analyzed for their isotope ratios, $^{2}H/^{1}H$ ($\delta^{2}H$) for deuterium and $^{18}O/^{16}O$ ($\delta^{18}O$) for oxygen–18. The monthly rainfall amount and air temperature were also measured.

Table 1
GNIP stations information

Stations	Latitude	Longitude	Elevation (m)	Distance from the coast (km)
Kuching	1˚ 29' N	110˚ 21' E	20.9	21
Senai	1˚ 38' N	103˚ 40' E	37.8	37
Malaysian Nuclear Agency	2˚54' N	101˚46' E	60	37
Kuantan	3˚ 46' N	103˚ 13' E	15.2	13
Cameron Highlands	4˚ 28' N	101˚ 23' E	1472	83
Kuala Terengganu	5˚ 23' N	103˚ 06' E	5.2	1
Kota Kinabalu	5˚ 56' N	116˚ 03' E	2.1	0.3
Kota Bharu	6˚ 10' N	102˚ 18' E	4.4	1.5
AlorSetar	6˚ 12' N	100˚24' E	3.9	15

Table 1 GNIP stations information

Study area

Peninsular Malaysia or West Malaysia is lined by the central mountain range (Titiwangsa Range), which runs roughly from north to south from the border of Thailand in the north and divides the peninsular to east and west coasts. It hosts the highest point, Mount Korbu (2183m), which is the second–highest peak in Peninsular Malaysia. In East Malaysia, situated in Borneo Island, the Crocker Range lies from the northeast to southwest of Sabah and separates its east and west coast. Here, the Mount Kinabalu with its peak of 4,101m, is the highest mountain in Malaysia. West Malaysia is separated from East Malaysia and Sumatra Island by the South China Sea and the Straits of Malacca, respectively (Fig. 2).

Generally, Malaysia experiences a warm and humid tropical climate all year round, with uniform temperatures between 25–32°C, high humidity, and significant rainfall. Malaysia has two monsoon regimes; (1) Northeast monsoon (NEM; November to March) or winter monsoon, and (2) Southwest monsoon (SWM; May to September), which is also known as the summer monsoon. The NEM brings heavy rains from November to January, especially to the east coast of Peninsular Malaysia, while SWM is a relatively drier period. Between these two monsoons are intermonsoon periods, which occur in April and October. The annual mean monthly rainfall retrieved from the Met Malaysia website (MMD 2020) is shown in Fig. 3.

The moistures from two prevailing monsoons for Malaysia's precipitation mainly originate from three different air masses, i.e., the polar air mass, equatorial–maritime air mass originating from the Indian Ocean, and equatorial–maritime air mass originating from the western Pacific Ocean. In NEM, the northeasterly begins from a dry cold surge developed over high–latitudinal Siberia in the Northern Hemisphere. The moisture is transported south due to the pressure difference on the Asian continent and gains air mass above the South China Sea before undergoing progressive rainout over the east coast of Peninsular Malaysia. During SWM, the abundant southwesterly moisture is sourced dominantly from the Indian Ocean, and low–level easterlies from the tropical western Pacific Ocean may also contribute to the source of moisture for precipitation (Araguas–Araguas et al. 1998; Aggarwal et al. 2004; Niwas et al. 2006; Endo et al. 2009).

Sample Collection

Monthly composite precipitation samples were collected using a rain gauge, which was permanently installed by the Malaysian Nuclear Agency at all of the GNIP rainfall stations at the Malaysian Meteorological Department (MetMalaysia) state office compound together with their meteorological instruments. Generally, the main precautions in precipitation sampling for isotopic analysis are evaporation prevention or exchange with atmosphere and representativeness of the sample to ensure reliable isotopic data. Sample evaporation occurs during sample collection, as the collector is left for one month on–site, and exposure of a precipitation sample to the atmosphere could result in evaporation that alters the isotopic composition of the water sample. Therefore, the collected rainwater sample should represent the integrated natural precipitation of the targeted sampling period, which is one calendar month. Rainwater flowing out of a collector from extreme rain events such as monsoon also results in the loss of an essential part of a month's precipitation (IAEA 2014). The rainwater collection apparatus for this study utilizes a tube–dip–in–water totalizer collector with pressure equilibration for excellent evaporation protection (Fig. 4). A stainless–steel table–tennis–sized–ball and debris screen were placed in the collection funnel for extra protection against evaporation and to help seal the collector bottle against any debris, respectively. Another advantage of using this type of collector is that it facilitates low–cost unattended monthly sampling and eliminates the need for paraffin oil. However, the disadvantage of this collector is the amount of rainfall need to be determined volumetrically when there is no rain amount recorded on site. This method compared favorably with the paraffin oil and performed better than collecting daily rain gauge samples overall (Hughes 2013).

A funnel with a known diameter is used for a site where no precipitation amount is recorded (e.g., Malaysian Nuclear Agency). The rain amount is estimated using the equation below:

$$Rainfallamount(mm) = \frac{10V}{\pi r^2}$$

where V = volume of rainwater collected (ml) and r = funnel radius (cm). For other stations, the meteorological data (rainfall and temperature) was obtained from MetMalaysia headquarters.

100ml high–density polyethylene bottles (HDPE) were used for rainwater stable isotope sampling and storage. The sampling bottle was filled with the rainwater sample from the monthly accumulation collector and tightly–sealed for proper storage and shipment. Samples were sent to IAEA, Vienna, for stable isotope analysis (δ^2H and δ^{18}O) at the Isotope Hydrology Section Laboratory using LGR Liquid–Water Isotope Analyzer.

Sample Measurement

Stable isotope compositions were determined for 595 samples and reported as δ values and denoted as ‰ or permil/per mill, which is relative to a standard of known composition (e.g., Vienna Standard Mean Ocean Water, VSMOW for δ^2H and δ^{18}O analyses). The δ values are calculated using the equation below, for example, in this case, ^{2}H:

$$\delta^2 H(‰) = \frac{R_{Sample} - R_{Standard}}{R_{Standard}} x1000$$

where R represents the ratio of heavy to light isotope (^{2}H/^{1}H), and R_{Sample} and $R_{Standard}$ are the isotope ratios in the sample and the standard, respectively. The sample is described as depleted (more negative) if the δ values are lower, and enriched (more positive) if the δ values are higher with respect to a reference (IAEA 1983; Clark and Fritz 1997; Kendall and Caldwell 1998).

Weighted Means

The weighted arithmetic mean is similar to an ordinary arithmetic mean, except that instead of each of the data points contributing equally to the final average, some data points contribute more than others, i.e., the isotope data are weighed in this study by the amount of precipitation. Weighted means of the isotope data are calculated by multiplying the isotope values by the amount of precipitation monthly or annually. The weighted mean values can be calculated using the equation below (IAEA 1992):

$$\bar{\delta}_{Weighted} = \frac{\sum_{i=1}^{n} P_i \delta_i}{\sum_{i=1}^{n} P_i}$$

where P_i and δ_i represent the daily or monthly precipitation and its δ value, respectively. The weighted means are taken in the specific context of hydrology, where the rainfall input function constitutes the weighted mean of a specific period. They were calculated by considering only if more than 70% of precipitation of a given isotope was analyzed in a particular year to ensure that it is isotopically characterized. This means that the monthly isotope data must construct at least 70% of the total annual precipitation. In addition, a full 12 months precipitation amount for a particular year must be available to establish this precipitation coverage fraction. However, if the precipitation amount was unavailable for specific months for a given year, the long–term mean value can be used to estimate the percentage (IAEA 1992). Later, the long–term weighted means can be calculated based on this precipitation percentage where a year, with values less than 70%, is ignored.

Results And Discussion

Isotopic composition of water

The annual weighted means and long–term annual weighted means of $\delta^{18}O$, $\delta^{2}H$ and deuterium excess for the precipitation samples of the Malaysian GNIP stations are summarized in Tables 2 and 3, respectively. Most of the discussions of stable isotope characteristics in precipitation will be focused on $\delta^{18}O$ as $\delta^{2}H$ values will involve those with similar relationships and therefore will not be shown here.

Table 2

Annual precipitation weighted means of $\delta^{18}O$, $\delta^{2}H$, and deuterium excess (*d*)

	2013			**2014**			**2015**			**2016**			**2017**		
	$\delta^{18}O$ (‰)	$\delta^{2}H$ (‰)	*d* (‰)	$\delta^{18}O$ (‰)	$\delta^{2}H$ (‰)	*d* (‰)	$\delta^{18}O$ (‰)	$\delta^{2}H$ (‰)	*d* (‰)	$\delta^{18}O$ (‰)	$\delta^{2}H$ (‰)	*d* (‰)	$\delta^{18}O$ (‰)	$\delta^{2}H$ (‰)	*d* (‰)
Alor Setar	–5.30	–36.30	6.1	–5.91	–34.34	13.0	–3.32	–18.41	8.2	–6.51	–42.37	9.7	–8.14	–53.33	11.8
MNA	–6.74	–44.64	9.3	–7.08	–44.39	12.3	–5.52	–32.27	11.9	–7.01	–44.93	11.1	–7.87	–50.98	12.0
Senai	–5.50	–37.07	6.9	–6.27	–40.45	9.7	–4.43	–25.54	9.9	–5.46	–34.36	9.3	–7.39	–49.47	9.6
C. Highlands	–3.32	–19.30	7.3	–7.28	–45.30	12.9	–7.34	–43.50	15.2	–8.27	–51.87	14.3	–9.66	–62.64	14.6
Kota Bharu	–3.57	–23.53	5.0	–4.90	–32.86	6.4	–5.60	–31.78	13.0	–5.88	–36.29	10.7	–6.34	–40.07	10.7
Kuala Terengganu	–4.90	–31.87	7.3	–6.13	–39.75	9.3	–4.63	–27.73	9.3	–5.73	–35.31	10.5	–6.86	–44.02	10.9
Kuantan	–5.74	–38.89	7.0	–6.13	–37.72	11.3	–5.10	–31.99	8.8	–6.03	–38.29	9.9	–7.37	–47.90	11.0
Kuching	–4.86	–31.83	7.1	–6.08	–38.41	10.3	–6.81	–44.35	10.1	–6.38	–39.28	11.7	–8.19	–55.18	10.4
Kota Kinabalu	–4.32	–24.72	9.8	–5.69	–34.20	11.3	–4.67	–26.74	10.6	–5.60	–31.27	13.6	–7.71	–50.26	11.4

Table 3

Summary of long–term annual precipitation weighted means of $\delta^{18}O$, $\delta^{2}H$, and deuterium excess

	$\delta^{18}O$ (‰)					**$\delta^{2}H$ (‰)**					**Deuterium excess, *d*(‰)**				
	Min	Max	SD	Wt. mean	SD	Min	Max	SD	Wt. mean	SD	Min	Max	SD	Wt. mean	SD
AlorSetar	–11.34	0.05	2.28	−6.04	1.65	–78.1	5.5	16.7	−38.13	11.75	−0.3	15.0	3.6	10.2	2.7
MNA	–11.19	0.31	2.44	−6.83	0.76	–76.3	4.4	18.8	−43.36	6.11	2.0	15.0	2.4	11.3	1.1
Senai	–13.61	–1.43	2.14	−5.85	0.99	–95.2	–3.5	16.5	−37.19	7.82	−1.8	13.8	2.6	9.6	1.6
C. Highlands*	–13.83	–1.24	2.25	−8.10	0.97	–96.4	4.2	18.4	−50.57	7.52	6.9	17.4	1.8	14.2	0.9
Kota Bharu*	–10.28	–0.79	2.22	−5.65	0.52	–71.4	1.3	16.4	−34.67	3.49	−2.8	15.6	3.5	10.6	2.5
Kuala Terengganu	−8.96	1.92	2.27	−5.60	0.82	–61.8	14.2	16.7	−35.10	5.93	−1.2	15.3	2.6	9.7	1.4
Kuantan	–10.25	0.55	2.30	−6.11	0.75	–70.8	0.1	16.7	−39.20	5.14	–10.3	18.8	3.8	9.7	1.6
Kuching*	–11.52	–1.68	2.41	−6.95	0.83	–83.2	–1.5	18.9	−44.91	6.81	2.3	15.8	2.7	10.7	0.7
Kota Kinabalu	–13.91	1.62	2.74	−5.49	1.21	–95.5	17.9	20.9	−32.62	9.26	3.8	16.9	3.1	11.3	1.2

*2013 data were not included for overall Min, Max, and Weighted Mean values calculation due to percentage of available annual precipitation < 70%.

$\delta^{18}O$ and $\delta^{2}H$

Generally, all of the stations (except Cameron Highlands, which is a continental station) can be considered as coastal stations based on the definition stating that coastal is the land margin within 100 km of the coastline or less than 100 m above mean low tide, whichever comes first (Christian and Mazzilli 2007). Therefore, the coastal stations can be further classified into west coast (Alor Setar, MNA, and Senai) and east coast (Kota Bharu, Kuala Terengganu, and Kuantan) of Peninsular Malaysia and East Malaysia (Kuching and Kota Kinabalu).

Overall, the annual weighted means value for δ^2H varies between − 62.64 and − 19.30‰, while $\delta^{18}O$ ranges from − 9.66 to − 3.32‰. The long–term weighted means value for δ^2H and $\delta^{18}O$ stretches from − 50.57 to − 32.62‰ and − 8.10 to − 5.49‰, respectively. In Peninsular Malaysia, the long–term weighted means isotopic composition for the east coast region (δ^2H and $\delta^{18}O$ range from − 39.20 to − 34.67‰ and − 6.11 to − 5.60‰, respectively) is enriched compared to the west coast (δ^2H and $\delta^{18}O$ range from − 43.36 to − 37.19‰ and − 6.83 to − 5.85‰, respectively). This is mainly due to the significant difference in rainfall magnitude or degree of rainout from both regions (where more rainfall in east coast especially during NEM) and other factors which will be discussed later. Cameron Highlands, the only continental station located at the high altitude with relatively low temperature surrounded by dense rainforest, has a quite significant depleted δ^2H and $\delta^{18}O$ values (−50.57 and − 8.10‰, respectively). Contrarily, although Kuching receives considerable amounts of rain (almost double of the magnitude) than Kota Kinabalu, its δ^2H and $\delta^{18}O$ values (−44.91 and − 6.95‰, respectively) was found to be more depleted relative to Kota Kinabalu (−32.62 and − 5.49‰, respectively) in East Malaysia.

Deuterium excess, d

The deuterium excess annual weighted means and long–term weighted means values expand from 5.0 to 15.2‰ and 9.6 to 14.2‰, respectively. There was no considerable deviation in deuterium excess values among all stations, except for Cameron Highlands, which was significantly different in its high deuterium excess value (14.2‰). The high deuterium excess value (> 10‰) is an indicator of a different source of rainfall, i.e., mixed evaporated vapor from continental basins and oceanic air mass (Araguas–Araguas et al. 1998; Araguas–Araguas et al. 2000; Gat 2000). On a local scale climate, high deuterium excess in Cameron Highlands can be attributed to weather processes such as recycling moisture from the dense rainforest area of the mountainous range situated in central Peninsular Malaysia. Re–evapotranspiration of moisture being recycled into new precipitation was considered a possible source of higher deuterium excess value. The rest of the stations reported deuterium excess values of 9.6–11.3‰.

Table 2 Annual precipitation weighted means of $\delta^{18}O$, δ^2H, and deuterium excess (*d*)

Table 3 Summary of long–term annual precipitation weighted means of $\delta^{18}O$, δ^2H, and deuterium excess

Precipitation sources and transport

The annual and seasonal mean monthly rainfall for each station and its isotopic composition are tabulated in Table 4. Data of the intermonsoon periods were not included for a seasonal calculation to avoid overlapping seasonal signals. Generally, the seasonal weighted mean values and rainfall amount are higher (except for MNA) on the windward side of the Peninsular Malaysia relative to the leeward side on each season, which means that the west coast stations are more enriched in the isotopic composition during SWM compared to NEM. Similarly, the isotope values for the east coast stations were enriched in NEM than SWM. Kuching shares similar characteristics with Peninsular Malaysia. However, the conditions are different in Kota Kinabalu, which can be attributed to its geographical location. As for deuterium excess, the values for all stations were higher during SWM relative to NEM.

Table 4
Isotopic composition of annual and seasonal mean monthly rainfall of SWM (summer monsoon) and NEM (winter monsoon)

Region	Station	Annual (mm)	Monsoon	Seasonal (mm)	Weighted mean values (‰)		
					$\delta^{18}O$	$\delta^{2}H$	*d*
P. Malaysia:							
West coast	Alor Setar	2325.6	SWM	1123.5	−5.88	−34.36	11.4
			NEM	748.0	−6.81	−44.57	9.9
	MNA	2372.4	SWM	699.6	−6.99	−43.60	12.3
			NEM	1080.8	−7.22	−46.76	11.0
	Senai	2476.6	SWM	946.0	−5.76	−35.36	10.8
			NEM	899.7	−6.64	−43.04	10.0
East coast	Kota Bharu	2703.1	SWM	752.5	−6.62	−40.22	12.7
			NEM	1534.8	−5.75	−34.88	11.1
	K. Terengganu	2717.6	SWM	628.7	−6.13	−38.06	11.0
			NEM	1654.6	−5.65	−35.48	9.7
	Kuantan	2854.8	SWM	819.0	−6.18	−38.25	11.2
			NEM	1526.3	−6.59	−42.41	10.3
Central	C. Highlands	2530.8	SWM	1004.1	−8.30	−50.90	15.5
			NEM	885.0	−8.88	−58.13	12.9
E. Malaysia:							
	Kuching	4210.2	SWM	1307.1	−6.44	−40.68	10.9
			NEM	2019.2	−7.52	−49.46	10.7
	K. Kinabalu	2634.2	SWM	1297.5	−6.12	−36.81	12.1
			NEM	818.0	−5.86	−36.32	10.6

The total value of annual mean monthly rainfall includes intermonsoon periods, i.e., April and October.

Table 4 Isotopic composition of annual and seasonal mean monthly rainfall of SWM (summer monsoon) and NEM (winter monsoon)

It can also be seen that Alor Setar has the highest rainfall (1123.5 mm) in the west coast region during SWM due to the phenomenon known as squall, where it receives a direct source of moisture from the Andaman Sea via the opening of the Straits of Malacca in the north. Squall−line is a term used for describing moving lines of thunderstorms. They are hundreds of kilometers in length and have a life span of several hours, which is considerably longer than its component thunderstorms. Therefore, squall−lines generate gusty winds and heavy rains, which are more intense and extensive than individual thunderstorms (MMD 2020). The higher rainfall amount received in Kuching during NEM is due to direct rainout compared to Kota Kinabalu, which is virtually sheltered by the mountainous terrain (Crocker Range) on its east side, resulting in the rainfall amount in Kota Kinabalu (818 mm) being lower than Kuching (2019.2 mm).

Two main factors, i.e., vapor trajectories (shorter during NEM and longer in SWM) and the terrain (Titiwangsa Range), play an essential role in determining the isotopic value in precipitation and the significant difference of rainfall amount received between the east coast and west coast regions (Fig. 5) in Peninsular Malaysia. This explains why the long−term weighted means isotopic composition for the east coast region is more enriched than its western counterpart. The evidence is more apparent when differentiating between the two monsoon seasons.

The shorter moisture pathway of water vapor slightly after gaining its air mass above the South China Sea combined with the higher degree of rainout with a significant amount of rain over the east coast region (average of 1571.9 mm) during NEM, causing the precipitation to be enriched in $\delta^{2}H$ and $\delta^{18}O$ (average of − 37.59 and − 6.00‰, respectively) compared to the west coast (average rainfall amount is 909.5 mm; an average of $\delta^{2}H$ and $\delta^{18}O$ are − 44.79 and − 6.89‰, respectively). The remaining depleted water vapor will be carried further by the northeasterly winds crossing the mountain range stretching from the north to south in central Peninsular Malaysia (Titiwangsa Range) before undergoing the second phase of a rainout on the west coast. This fractionation mechanism is known as the orographic effect (Saravana Kumar et al. 2010) (Fig. 6).

Similarly, this effect can be seen during the SWM when the source of moisture from the Indian Ocean underwent the first phase of the rainout process when it met with the orographic features of the Sumatran Island, which resulted in the heavy isotope depletion of the residual vapor that later moves towards the west coast (average rainfall amount is 923 mm; an average of $\delta^{2}H$ and $\delta^{18}O$ are − 37.77 and − 6.21‰, respectively) and east coast (average rainfall amount is 733.4 mm; average of $\delta^{2}H$ and $\delta^{18}O$ are − 38.84 and − 6.31‰, respectively) of Peninsular Malaysia.

In East Malaysia, with only two stations for comparison, it can be concluded that the main factor causing the isotope difference in rainfall is the amount effect. Thus, higher rainfall amounts in Kuching (2019.2 mm) and Kota Kinabalu (1297.5 mm) during NEM and SWM, respectively, caused the precipitation to be depleted in δ^2H and $\delta^{18}O$.

The lower deuterium excess value for all stations during NEM than SWM indicates a relatively more humid moisture source due to the first phase rainout after a shorter moisture transport trajectory.

Precipitation isotope characteristics

The oceanic air masses forming the two monsoon systems; South China Sea in NEM and Indian Ocean (together with the Pacific Ocean) during SWM differ inconsiderably in their isotope signatures, as demonstrated by the average $\delta^{18}O$ of rainfall, which in the NEM (winter monsoon) is 0.38‰ more negative than in the SWM (summer monsoon). In tropical areas, the temperature has a weak influence on stable isotopes in precipitation (Gat 1996 and Araguas–Araguas et al. 1998), which is true as the range of the monthly temperature observed in all of the stations (except for Cameron Highlands) from 2013–2018 was very small (24.9–30.3°C) with the overall average varying between 26.9 to 27.8°C. There is no temperature data for MNA; however, its profile is expected to be similar to that of the other stations. Meanwhile, Cameron Highlands, located at a high altitude (1472m), have a lower monthly average temperature, varying between 14.6°C and 23.3°C (Weather Atlas 2020). Generally, the plot of $\delta^{18}O$ also shows a very poor correlation with the monthly rainfall amount (–0.4‰/100mm) and temperature (0.7‰/°C), with very low r^2 values (0.09 and 0.06, respectively), indicating that not only temperature but precipitation amount also has a weak but considerable influence on the isotopic composition of precipitation in Malaysia (Fig. 7). The weak amount effect was still found in this study even though the monthly and regional scale precipitation method was carried out instead of daily sampling, which is quite intriguing, as the amount effect is expected in tropical regions. However, this finding is supported by the variations of unweighted means (δs – δw) of summer and winter, which will be discussed further in the next section.

Seasonal and temporal variations

Seasonal variations

Seasonal variations in the isotopes and their relation with the surface air temperature and the precipitation amounts can be shown using the (δs – δw) values, where δs and δw denote the unweighted means of the summer and winter months, respectively (Dansgaard 1964). The author also demonstrated that the values vary from negative values (–6.5) in low latitude areas to high positive values (+ 8.6) in high latitude areas. The negative values reflect the amount effect, while the high positive values are due to the temperature effect. The (δs – δw) values of the precipitation from Malaysia GNIP stations, which are all located at low latitudes, range from − 1.95 to 0.43 (Table 5). These small negative values (close to zero) of (δs – δw), which lie in the middle between the low negative values and high positive values mentioned above, also indicate an insubstantial but conspicuous amount effect.

Table 5
Seasonal variations of unweighted means (δs – δw) of summer and winter

Region	Station	$\delta_s - \delta_w$ (‰)
Peninsular Malaysia:		
West coast	Alor Setar	−0.18
	MNA	−0.45
	Senai	−0.28
East coast	Kota Bharu	−1.05
	Kuala Terengganu	−1.95
	Kuantan	−0.24
Central	Cameron Highlands	−0.74
East Malaysia:		
	Kuching	0.43
	Kota Kinabalu	−1.15

Table 5 Seasonal variations of unweighted means (δs – δw) of summer and winter

Figure 8 (a–i) illustrates the seasonal variability of long–term monthly means (2013–2018) of $\delta^{18}O$ composition in precipitation related to rainfall amount. As discussed earlier, the seasonal variability of $\delta^{18}O$ in this region is controlled by the weak but significant inverse correlation amount effect. The relationship of long–term monthly means between $\delta^{18}O$ and temperature is not shown, as the overall temperature average difference was minimal (~2°C). Generally, the seasonal patterns of $\delta^{18}O$ are pretty clear and distinguishable, with higher $\delta^{18}O$ values observed during the NEM or winter monsoon and lower $\delta^{18}O$ during SWM. The seasonal fluctuation of $\delta^{18}O$ behavior is evident due to the rainy summer and dry winter (except for the east coast and Kuching).

The rainy period in November–January is associated with the southward movement of the Intertropical Convergence Zone (ITCZ). The ITCZ is the zone where the northeast trade winds of the Northern Hemisphere and southeast trade winds from the Southern Hemisphere converge near the equator and circle the earth. As these winds converge, moist air is forced upward due to the equator's intense sun and warm water. As the air rises, it expands and cools and releasing the accumulated moisture resulting in a band of heavy precipitation. Therefore, seasonal shifts in the location of the ITCZ affect the rainfall resulting in the wet and dry seasons of the tropics. This coincides with the maximum south extent of the ITCZ in the region during NEM (Fig. 9). Thus, the arrival of the monsoon is manifested by increased rainfall, followed by a subsequent drop of rainfall $\delta^{18}O$ value. Also, the second rainy period in April and May is due to the northward movement of the ITCZ.

Temporal variations

The temporal variations trend over the period examined (Fig. 10) is inconsistent, suggesting differences in local climatic conditions, prevailing atmospheric circulations, and precipitation sources that determine the rainfall's isotopic composition. The trends of $\delta^{18}O$ fluctuations are obscure even at stations with very clear rainfall distribution patterns, i.e., the east coast region of Peninsular Malaysia (Kota Bharu, Kuala Terengganu, and Kuantan). Overall, the temporal variations of $\delta^{18}O$ during NEM and SWM are barely clear and indistinguishable.

El Niño and La Niña are complex weather patterns resulting from variations in ocean temperatures in the Equatorial Pacific and are opposite phases of what is known as the El Niño–Southern Oscillation (ENSO) cycle. El Niño is sometimes referred to as the warm phase of ENSO and La Niña as the cold phase. Although their frequency can be erratic, El Niño and La Niña events occur on average every two to seven years (NOAA 2020). El Niño has enormously contributed to the hot weather in 2015, while La Niña happened in 2017 (MMD 2017; Wang et al. 2019). This apparent sign of El Niño in 2015 is indicated by heavier $\delta^{18}O$ from the peaks in the annual precipitation amount and $\delta^{18}O$ annual precipitation weighted mean graph (Fig. 11), while La Niña corresponds to the lighter values of $\delta^{18}O$ in 2017. The increment of ^{18}O–enriched precipitation is due to the atmospheric circulation generally known as the trade wind, which is associated with the ENSO cycle. This trade wind plays a vital role in transporting ^{18}O–enriched or ^{18}O–depleted water vapor, resulting in heavier or lighter values of $\delta^{18}O$ through a rainout process following the Rayleigh distillation equation (Tan 2014).

The δ^2H–$\delta^{18}O$ linear relationship and Local Meteoric Water Line (LMWL)

Based on the 595 precipitation samples collected from nine stations of the International Atomic Energy Agency (IAEA) Global Network of Isotopes in Precipitation (GNIP), the Malaysian meteoric water lines (MMWLs) established in this study are $\delta^2H = (7.43 \pm 0.05)\delta^{18}O + (7.33 \pm 0.11)$ ($n = 595$, $r^2 = 0.97$) for individual values (Fig. 12a) and $\delta^2H = (7.07 \pm 0.20)\delta^{18}O + (4.90 \pm 0.75)$ ($n = 51$, $r^2 = 0.96$) for annual precipitation weighted means (Fig. 12b). A close relationship between δ^2H and $\delta^{18}O$ is evident, as most of the samples' plots are very close to the global meteoric water line, indicating that the precipitation condensed under saturated conditions from the ocean water–sourced vapor. Slightly lower slope values relative to GMWL imply small variations in precipitation temperature under the Rayleigh process at liquid–vapor equilibrium and some sub–cloud raindrops secondary evaporation (Dansgaard 1964; Liu et al. 2014; Crawford et al. 2017). In contrast, the noticeable low intercept values indicate a significant evaporation process occurred at the water vapor source regions, i.e., South China Sea and Indian Ocean. During NEM, the continental dry cold air of the polar air mass originating from the north inducing the evaporation process above the South China Sea before progressive rainout over the east coast part of Peninsular Malaysia.

The SWM (summer) and NEM (winter) MWLs also show similar characteristics as the MMWL with seasonal meteoric water line of $\delta^2H = 7.18\delta^{18}O + 6.21$ ($n = 54$, $r^2 = 0.94$) and $\delta^2H = 7.48\delta^{18}O + 6.98$ ($n = 54$, $r^2 = 0.96$), respectively (Fig. 13). The vague differences between these seasonal MWLs are due to the small temperature deviations on a seasonal basis. Despite the small temperature difference, the evaporation effect is more prominent during SWM as shown by the lower intercept value of its MWL. Vapor source conditions are the main factors that give the precipitation its unique isotope value (Kumar et al. 2010). Most of the isotopic compositions of precipitation for Cameron Highlands, located further inland at a high altitude and subjected to relatively cooler temperatures, are distributed at the lower part of the GMWL plot. The data was scattered parallel above the GMWL, indicating the effect of moisture recycling, as discussed in the previous section. Moisture recycling is also a sign of inland or continental vapor sources, i.e., dense rainforest.

This relationship is crucial regionally and locally, as it serves as a database that can provide isotopic input functions for hydrological studies, such as identifying the origin, interrelation, and evaporation effects of surface water and groundwater sources.

The regression values for the local meteoric water lines (LMWLs) of each station from this study are listed in Table 6. The slopes and intercepts range from 7.15 to 8.13 and 5.11 to 15.59, respectively, with Cameron Highlands the highest (8.13 and 15.59, respectively).

Table 6
Local Meteoric Water Lines (LMWLs) established for all the stations of Malaysia's IAEA GNIP network

Region	Station	LMWL	r^2	n
Peninsular Malaysia:				
West coast	Alor Setar	$\delta^2H = (7.22 \pm 0.17)\delta^{18}O + (5.41 \pm 0.33)$	0.97	67
	MNA	$\delta^2H = (7.66 \pm 0.11)\delta^{18}O + (8.91 \pm 0.34)$	0.99	71
	Senai	$\delta^2H = (7.62 \pm 0.14)\delta^{18}O + (7.44 \pm 0.35)$	0.98	69
East coast	Kota Bharu	$\delta^2H = (7.26 \pm 0.19)\delta^{18}O + (6.55 \pm 0.37)$	0.97	54
	Kuala Terengganu	$\delta^2H = (7.33 \pm 0.11)\delta^{18}O + (6.57 \pm 0.31)$	0.98	66
	Kuantan	$\delta^2H = (7.15 \pm 0.18)\delta^{18}O + (5.11 \pm 0.33)$	0.96	65
Central	Cameron Highlands	$\delta^2H = (8.13 \pm 0.11)\delta^{18}O + (15.59 \pm 0.48)$	0.99	59
East Malaysia:				
	Kuching	$\delta^2H = (7.74 \pm 0.14)\delta^{18}O + (8.99 \pm 0.39)$	0.98	59
	Kota Kinabalu	$\delta^2H = (7.56 \pm 0.14)\delta^{18}O + (8.97 \pm 0.28)$	0.98	62

Table 6 Local Meteoric Water Lines (LMWLs) established for all the stations of Malaysia's IAEA GNIP network

Conclusions

The need for a database of δ^2H, $\delta^{18}O$ of precipitation and local meteoric water lines led to this study, and the results garnered from this study contribute to the current demand in closing the knowledge gaps in isotope hydrology research in Malaysia. Besides the database, this study also successfully delineated the meteorological and environmental factors of the climatic conditions locally and regionally; for example, rainfall amount and temperature manifested poor correlation but considerable influence with the stable isotope signals in precipitation. Moisture sources between the two monsoons were also differentiated, where the NEM was slightly more negative than the SWM. Isotope values in precipitation were characterized by the water vapor transport trajectories, where longer pathways resulted in more depleted values, similar to the fractionation mechanism caused by the orographic effect. The seasonal behavior of the isotopes was quite clear with an insubstantial amount effect, in contrast with the temporal variations, which are indistinguishable. This study also captured the clear signals of El Niño and La Niña events indicated by heavier and lighter rainfall isotopes, respectively.

It is strongly recommended that the precipitation in Malaysia is continuously monitored and that long–term findings are published from time to time. There is also a need for more monitoring stations to be established, especially in Sabah and Sarawak, for better spatial coverage. In addition, high frequency and event–based precipitation sampling should be considered for more comprehensive results.

Declarations

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Contributions: RM collected data, analyzed data, and wrote the manuscript. KS commented and improved on the manuscript. All authors read and approved the final manuscript.

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Figures

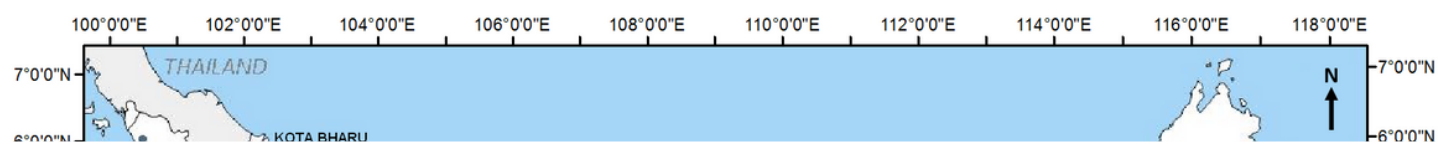

Figure 1

GNIP rainfall sampling stations

Figure 2

Physical map of Malaysia. The brownish color indicates the mountainous area with higher elevation

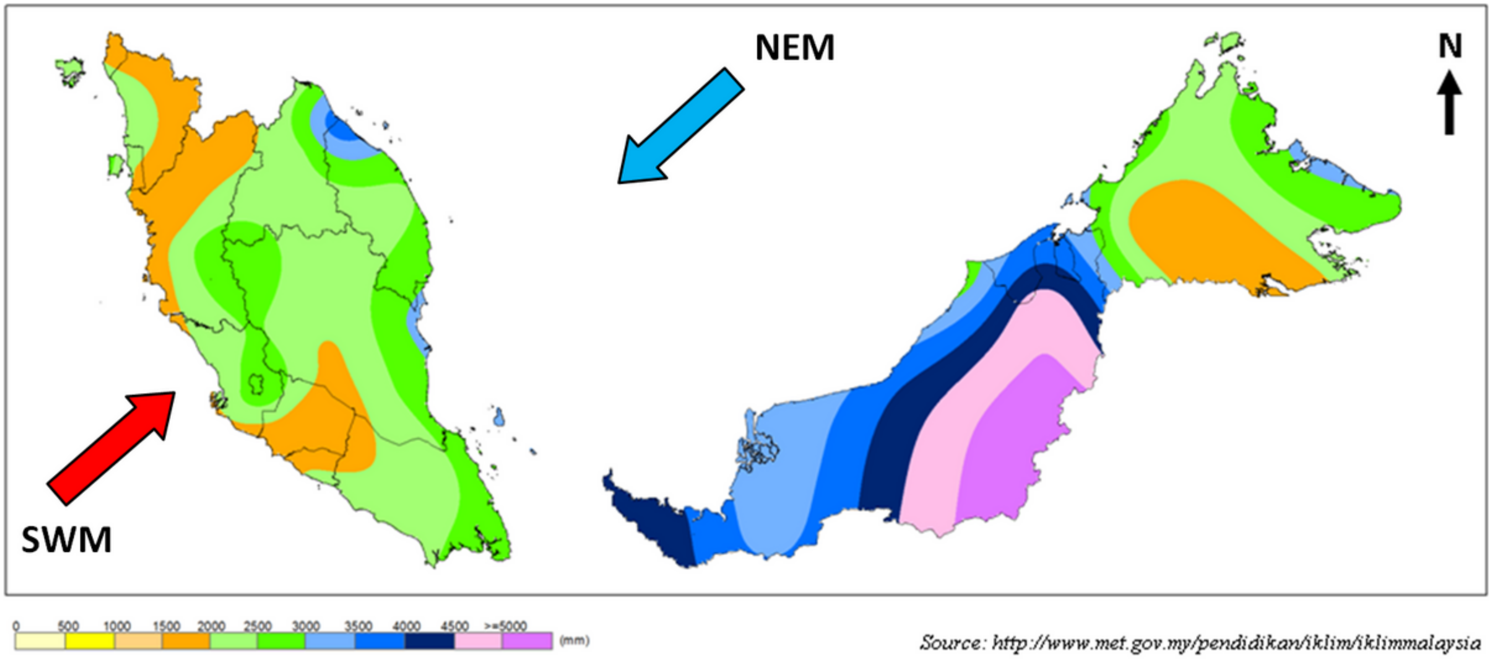

Figure 3

Mean monthly rainfall (annual). Arrows indicate the direction of the two precipitation moisture sources of the monsoon, which dominate the climate, i.e., SWM and NEM. The precipitation and wind data were sourced from the MetMalaysia website at http://www.met.gov.my/pendidikan/iklim/iklimmalaysia

Figure 4

Rainwater tube–dip–in–water totalizer collector with pressure equilibration for isotopic analysis

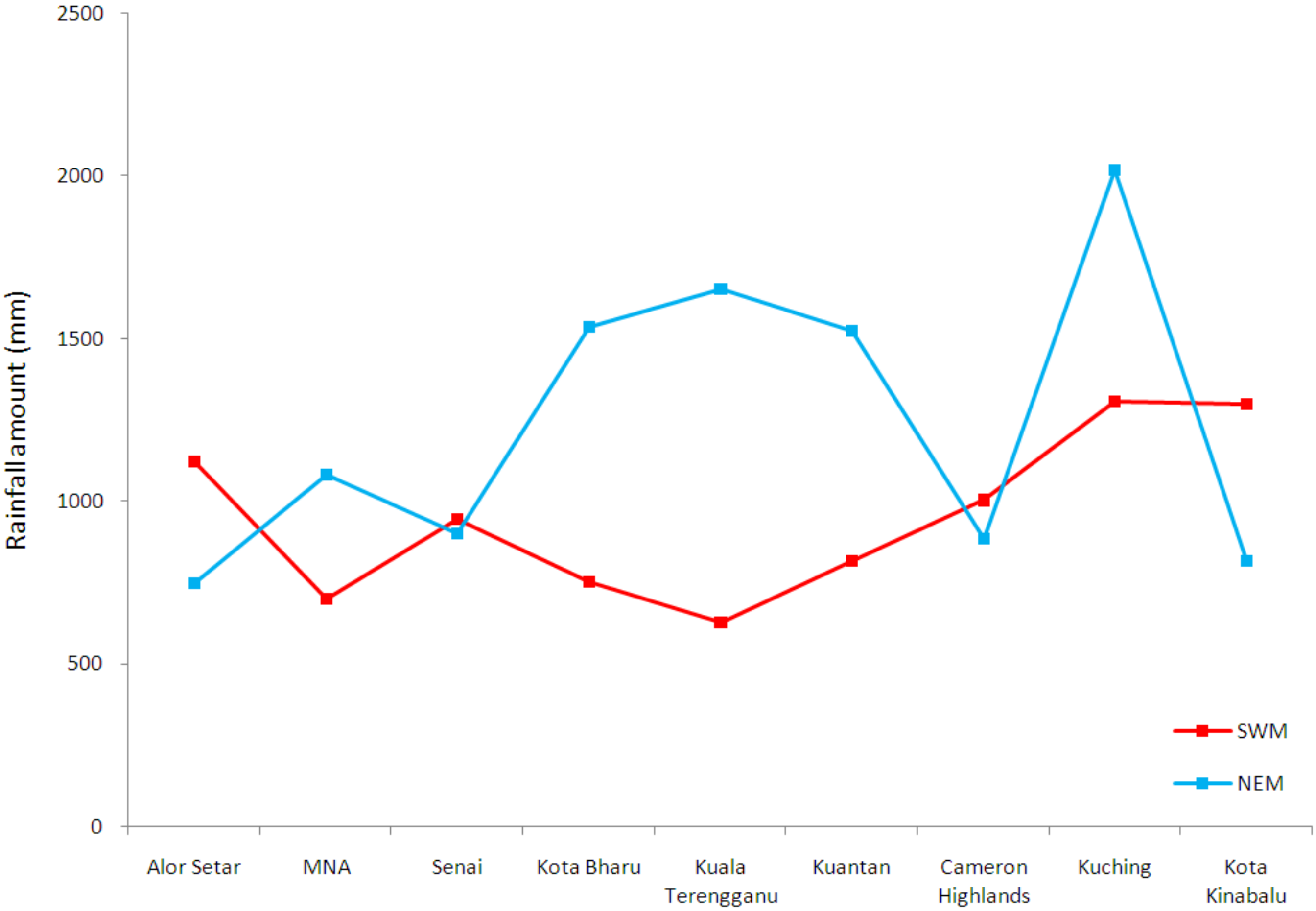

Figure 5

Difference of the seasonal mean monthly rainfall between SWM and NEM of the west coast (Alor Setar, MNA, and Senai), east coast (Kota Bharu, Kuala Terengganu, and Kuantan), central (Cameron Highlands), and East Malaysia (Kuching and Kota Kinabalu) of the GNIP stations

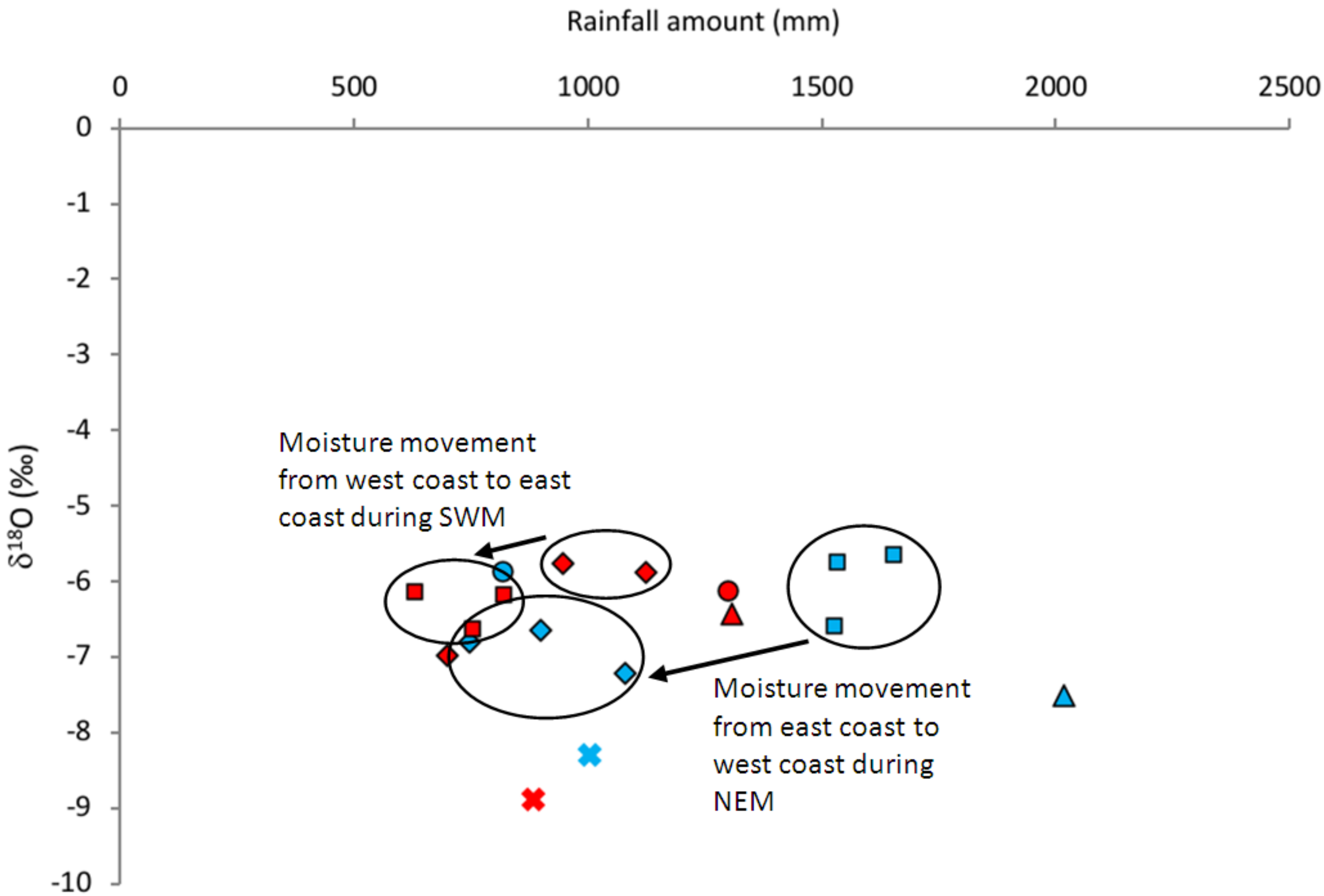

Figure 6

Relationship between long–term weighted seasonal means of precipitation $\delta^{18}O$ and seasonal mean monthly rainfall. West coast (diamond), East coast (rectangle), Central (cross), Kuching (triangle), and Kota Kinabalu (circle). The red and blue colors of the plot marker indicate SWM and NEM, respectively

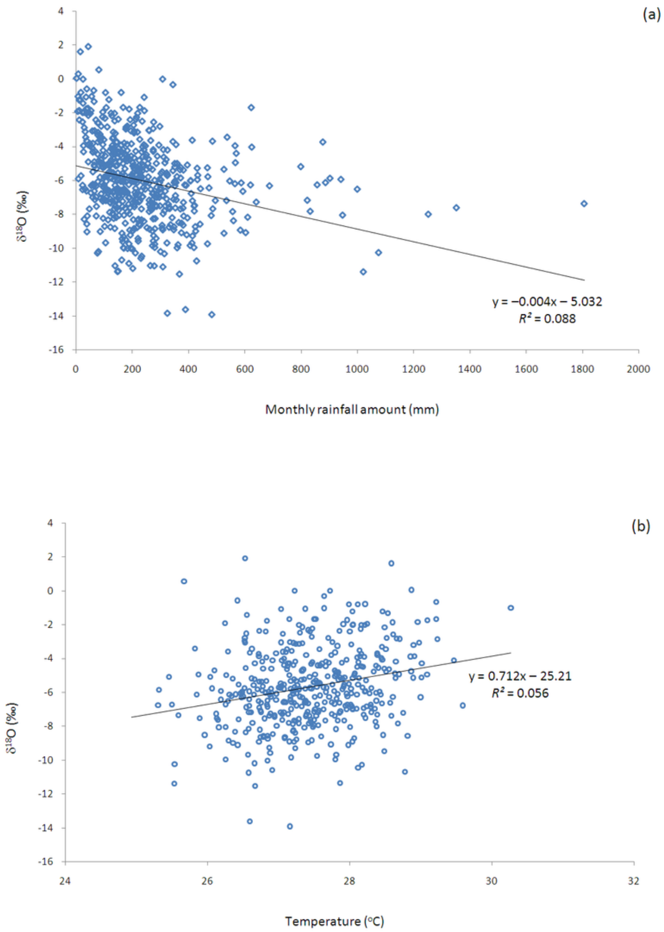

Figure 7

Correlation between $\delta^{18}O$ and (a) monthly rainfall amount (b) temperature

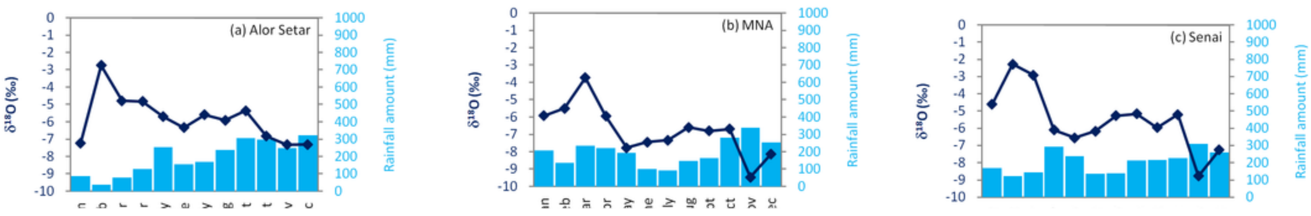

Figure 8

Seasonal variations of rainfall $\delta^{18}O$ for the Malaysia GNIP stations

Figure 9

The maximum extent of the Intertropical Convergence Zone (ITCZ) in the region during NEM and SWM

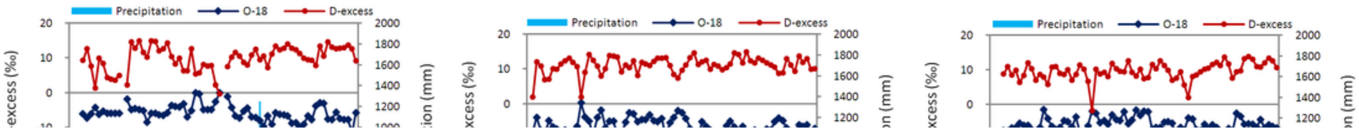

Figure 10

Temporal variations of rainfall δ^{18}O for the Malaysia GNIP stations

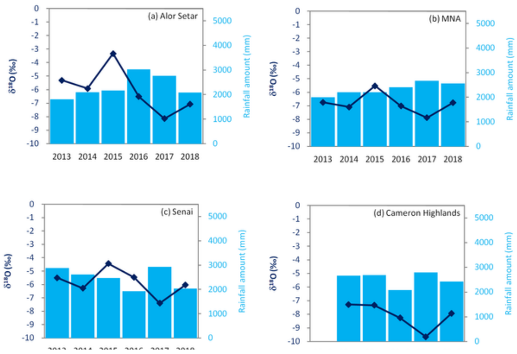

Figure 11

Time series plot of annual precipitation amount and $\delta^{18}O$ annual precipitation weighted mean

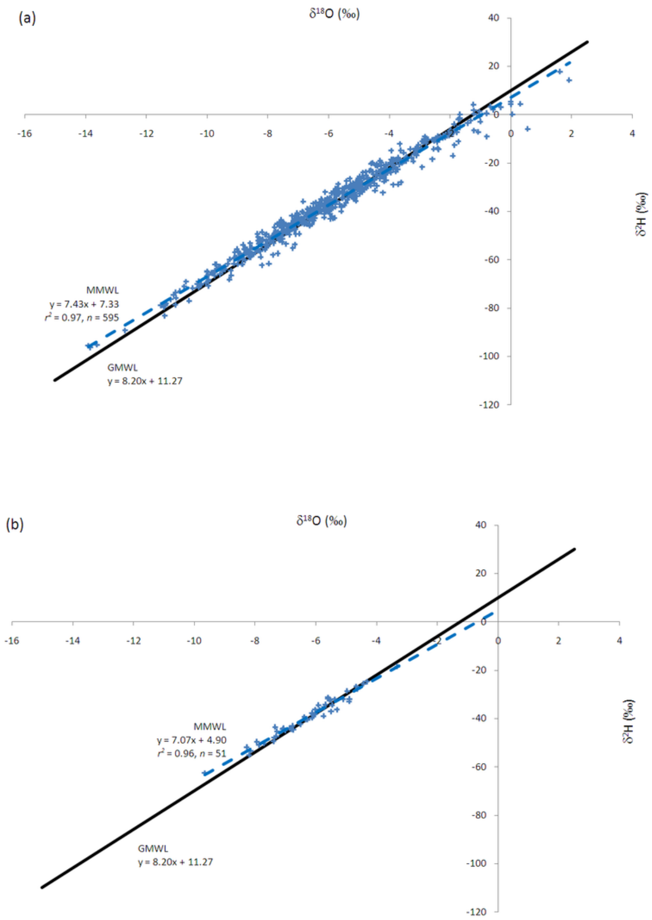

Figure 12

δ^2H–$\delta^{18}O$ linear relationship for precipitation derived from all the Malaysian IAEA GNIP network stations (a) Individual values, and (b) Annual precipitation weighted means

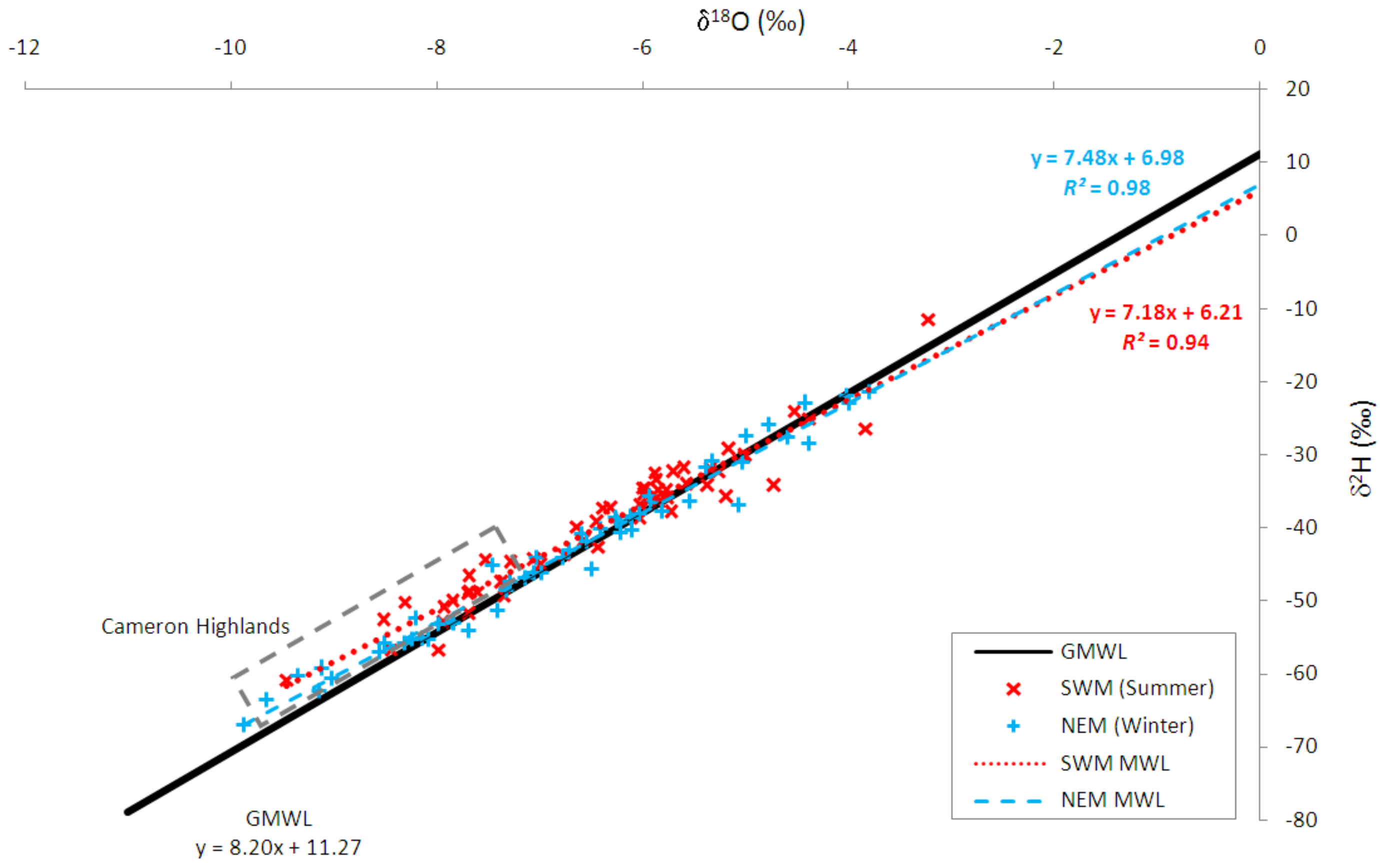

Figure 13

Seasonal variations of amount−weighted δ^2H−$\delta^{18}O$ linear relationship. The red and blue colors of the plot marker indicate summer and winter, respectively