Observational Research on Stable Isotopes in Precipitation over Indonesian Maritime Continent

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Abstract

The Indonesian Maritime Continent (IMC) is located in the tropics and consists of a number of islands and seas. This particular arrangement of land masses and seas produces unique weather and climate characteristics. Various hydrometeorology studies have been conducted exploring the variability of stable isotopes in precipitation over the IMC. Stable isotopes (δ18O and δD) in precipitation can be used to obtain information about atmospheric processes (e.g., precipitation, temperature and hydrological cycle). The Global Network of Isotopes in Precipitation, operated by the International Atomic Energy Agency, has been conducting worldwide monthly surveys of isotope levels in precipitation since 1961. To better understand the isotopic variability in the IMC, the Japan Agency for Marine-Earth Science and Technology began operating in the IMC region in 2001. There are three types of seasonal variation of stable isotopes in precipitation, depending on the level of precipitation amount and also stable isotopic value, namely, semiannual, anti-monsoonal and monsoonal. Negative correlations between the precipitation amount and stable isotope value (amount effect) were identified when using the monthly averages. The interannual variability of stable isotopes in precipitation was mainly because of El Niño Southern Oscillation activity, whereas intraseasonal variability was closely related to the Madden-Julian Oscillation. Stable isotope variability in short periods was found to be due to precipitation cloud types and post-condensation processes.

Key words: stable isotope, precipitation, Indonesian Maritime Continent, ENSO, MJO

I. Introduction

Ramage (1968) introduced the term “Maritime Continent”, which refers to a region in the tropics with many islands and peninsulas surrounded by numerous seas. The country that makes up most of the Maritime Continent is Indonesia; as such, this region is called the Indonesian Maritime Continent (IMC). The unique features of the IMC, namely, its location and topography, result in complex weather and climate variability in this region. The complex arrangement and interactions of land and sea produce significant seasonal and annual variations in the level of precipitation. Aldrian and Susanto (2003) divided the IMC into three climatological regions based on annual precipitation variability; in contrast, Hamada et al.
(2002) divided it into five climatological regions based on seasonal precipitation variability, which is mainly associated with the Asian–Australian monsoon. Along with seasonal and annual variability, the IMC also exhibits variability in several variables related to the level and pattern of precipitation, depending on different timescales, due to regional and/or local disturbances. Anomalous sea surface temperatures in the tropical Pacific Ocean can influence air–sea heat exchange related to the El Niño Southern Oscillation (ENSO), which can influence interseasonal variation in precipitation (Bjerknes, 1969; Cane and Zebiak, 1985; Hamada et al., 2002; Hendon, 2003). A phenomenon called the Madden-Julian Oscillation (MJO), which is characterized by 30–60 days of eastward propagation of a mass with both enhanced and suppressed precipitation that moves from the tropical Indian Ocean to the tropical Pacific Ocean, is known as the main factor behind intraseasonal variability in the level of precipitation, along with other phenomena, such as cold surges and synoptic weather systems (Chang et al., 2004, 2005). Another type of variability in precipitation on a shorter timescale in the IMC is diurnal variation. Renggono et al. (2001) differentiated between various types of precipitating cloud in West Java and west Sumatra using boundary layer radar and found that peak precipitation occurred in the afternoon and was dominated by convective clouds, but precipitating clouds that developed in the morning were dominated by stratiform clouds. Mori et al. (2004) further examined regional daily variability of rainfall in Sumatra and found that it was caused by the migration of the rainfall peak from the coastline inland in the daytime and offshore at night. In addition, Sakurai et al. (2005) and Qian et al. (2010) explained how ENSO intensified diurnal variability over Sumatra and Java, respectively.

These meteorological factors and different timescale variability in the level of precipitation may produce unique variability in the isotopes found in precipitation. The term ‘precipitation isotope’ refers to the stable water isotopes in precipitation. Water molecules consist of an oxygen atom and two hydrogen atoms (H₂O). Hydrogen and oxygen have several naturally occurring isotopes; the stable isotopes of oxygen are ¹⁶O, ¹⁷O and ¹⁸O and those of hydrogen are ¹H and ²H [i.e. deuterium (D)]. Stable water isotopes are a combination of an oxygen isotope and two hydrogen isotopes (e.g., HDO, H₂¹⁸O). A heavy water/stable water isotope (HD₁⁶O, H₂¹⁸O) has greater mass (atomic weight) than normal water (¹H₂¹⁶O), and molecules with different masses tend to have different reaction rates. This leads to isotope partitioning or fractionation (Clark and Fritz, 1997). The fractionation process, a term describing the separation of heavier and lighter isotopes, is commonly influenced by evaporation and condensation. In the case of evaporation, lighter isotopes evaporate more easily than heavier ones. Thus, H₂¹⁶O water molecules can more easily escape from the surface of water in the form of vapor than H₂¹⁸O and HD¹⁶O, due to their lower mass and higher vapor pressure. These processes, favoring the loss of ¹⁶O and/or ¹H, result in the enrichment of ¹⁸O and D in the remaining water body. In the case of condensation, the reverse process occurs. Specifically, a heavier isotope in water vapor will more easily enter the liquid phase, but lighter isotopes will remain as water vapor. Briefly, the journey of a water molecule can be traced from its source to a given catchment (hydrological cycle) based on
fractionation ratios. Dansgaard (1964) reported a comprehensive analysis of the global distribution of isotopic content in precipitation and identified a number of “effects” on isotopic variation due to several meteorological and geological parameters, such as latitude, altitude, distance from the sea, level of precipitation, and temperature. Air masses lose water content when they move to more tropical or polar regions (the “latitude effect”), from the ocean to more inland areas (the “continental effect”) and from lower to higher elevations (the “altitude effect”).

Another effect that was specifically found in the tropical region where the IMC is located is the “amount effect” (Dansgaard, 1964; Rozanski et al., 1993; Araguás-Araguás et al., 1998). The amount effect refers to the negative correlation between the amount of precipitation and the value of stable isotopes. The processes controlling the amount effect were summarized as the rain-out process of deep convective clouds, isotope exchange and partial evaporation of raindrops below the cloud base, and changes in the isotopic composition of vapor in the source region (Rozanski et al., 1993). This amount effect occurs in all seasons in tropical regions and in the summer in regions at intermediate latitudes, but not in polar regions, where temperature is the dominant factor affecting the isotopic value (Dansgaard, 1964). Studies on the amount effect in the IMC showed that it occurred because of the fractionation process that occurs across large regions and long time periods (Cobb et al., 2007; Risi et al., 2008; Kurita et al., 2009, 2011; Moerman et al., 2013; Suwarman et al., 2013). In addition, although the amount effect was observed at a shorter timescale in tropical regions (Risi et al., 2009), isotopic content in precipitation was not correlated well with the amount of precipitation in short timescales (Risi et al. 2008; Kurita et al., 2009).

An important point to note is that the isotopic signal in precipitation is influenced by not one but a combination of factors, such as level of precipitation, temperature, vapor source and atmospheric circulation (Vuille et al., 2003). In addition, the region from which moisture is derived may control the interannual isotopic variability (Cole et al., 1999), so it is essential to investigate the factors that control the changes in precipitation isotopes if we want to analyze isotopic variability due to atmospheric circulation, such as ENSO, MJO and monsoons.

Studies on the isotopic content of precipitation using observational data from the IMC have been reported (Ichiyanagi et al., 2005a; Kurita et al., 2009; Fudeyasu et al., 2011; Suwarman et al., 2013). Other observational research on stable isotopes in the IMC has also been performed, such as that exploring the diurnal to interseasonal isotopic variability (Araguás-Araguás and Froehlich, 1998; Ishizaki et al., 2012; Moerman et al., 2013), the correlation between the stable isotope ratio in vapor (HDO in vapor) derived from satellite measurements and MJO (Berkelhammer et al., 2012; Kurita et al., 2011), as well as the variability of the stable isotope ratio regarding the region from which moisture is derived and has been transported (Munksgaard et al., 2012). Paleoclimatology research has revealed that the isotopic content (δD) of terrestrial plant waxes from Lake Lading on Java can be used as a proxy to reconstruct precipitation levels and shown that precipitation on Java has steadily increased over the last millennium (Konecky et al., 2013).

This paper aims to review the history of observational research on stable isotopes in the
IMC and also to review research discussing stable isotopes in precipitation in the Maritime Continent and other tropical regions at different time scales. Research was conducted at different time scales to identify the effects of different meteorological and climatological phenomena, such as monsoons (annual and seasonal), ENSO (interannual), MJO (intra-annual) and torrential rain (short term), on the variability of stable isotopes in precipitation value in the IMC.

II. Stable Isotopes in Precipitation in the IMC

The International Atomic Energy Agency (IAEA) initiated a program called Global Network of Isotopes in Precipitation (GNIP) in 1958, which became operational in 1961. GNIP was established for the systematic collection of basic spatial data on the isotope content of precipitation on a global scale. GNIP has been conducting a worldwide monthly survey of isotope content in precipitation from observational stations across the globe (IAEA/WMO, 2015). Around Indonesia, GNIP collected rainwater samples for determining stable isotope values for more than 30 years at two stations, namely, Jakarta (JAK) and Jayapura (JYP). However, the last data collection at these stations occurred in 1998 and 1991, respectively. Other GNIP stations in Indonesia at which data were collected for shorter periods were Batan (BTN) in 1997–2003, and Tongkol (TKL) in 1997–1999. The limited number of observation stations, the monthly observational timescale, and the fact that the observational data were not up to date made it difficult to perform comprehensive research on the stable isotopes in precipitation specifically in the IMC.

The Japan Agency for Marine-Earth Science and Technology (JAMSTEC) was launched the observational networks of stable isotopes in precipitation, in order to understand the hydrological cycle from the perspective of water resources in the Asian monsoon region in 2001.
Observational Research on Stable Isotopes in Precipitation over Indonesian Maritime Continent

Some of the objectives of this program were to fill in the gaps among the data collected at the GNIP's observational stations and to undertake short-term sampling to determine temporal and spatial variations in the Asian regions affected by monsoons. In this program, daily precipitation data were collected and water sampling was performed to determine the value of stable isotopes ($\delta^{18}O$ and $\delta^D$) at observational stations across the IMC, namely, Kototabang (GAW), Jambi (JMB), Denpasar (DPS), Makasar (MKS), Manado (MND), and Peleliu (PLL) (Large-Scale Hydrological Cycle Research Group, IORGC, 2008). Most JAMSTEC samples were collected between 2001 and 2007; for DPS, MKS and MND, samples were collected until 2010.

Fig. 1 shows the locations of the GNIP and JAMSTEC observational stations in the IMC. The observational periods and locations of JAMSTEC and GNIP stations are shown in detail in Table 1.

Besides GNIP and JAMSTEC, another observational dataset was available from an independent research group. That is, Moerman et al. (2013) collected precipitation data and performed rainwater sampling to determine the levels of stable isotopes daily for five years (2006–2011) in Gunung Mulu National Park, located in the northwest of Borneo.

III. Short-Term Isotopic Variability in Precipitation Events in the IMC

Short-term analysis of stable isotopic content in precipitation was needed to explore the influence of local meteorological factors on isotopic content variability in one particular place and/or in a short timescale (one precipitation event or several days). Very little observational research has been performed at this timescale, meaning that there is little information on the factors that control the isotopic composition in precipitation in the short term, especially related to the amount effect in the IMC at this timescale. Recently, some important findings were obtained by Muller et al. (2015), using the combination of high-frequency sampling of the isotopes within precipitation during 16 precipitation events and an analysis of the vertical structure of precipitation performed by vertically orienting a micro-rain radar. They found

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Table 1  Locations of observational station and observational periods for stable isotope samples.

| No. | Station          | Latitude | Longitude | Altitude (masl) | Period     |
|-----|------------------|----------|-----------|-----------------|------------|
| JAMSTEC                                      |
| 1   | Kototabang (GAW) | 0.12°S   | 100.19°E  | 865             | Jan 2001–Mar 2010 |
| 2   | Jambi (JMB)      | 1.36°S   | 103.37°E  | 26              | Apr 2001–Dec 2005 |
| 3   | Denpasar (DPS)   | 8.45°S   | 115.10°E  | 3               | Nov 2002–Mar 2010 |
| 4   | Makasar (MKS)    | 5.03°S   | 119.32°E  | 43              | Nov 2002–Feb 2010 |
| 5   | Manado (MND)     | 1.32°N   | 124.55°E  | 95              | Nov 2002–Feb 2010 |
| 6   | Peleliu (PLL)    | 7.02°N   | 134.15°E  | 11              | Dec 2001–May 2007 |
| GNIP                                        |
| 7   | Jakarta (JAK)    | 6.18°S   | 106.83°E  | 8               | Jan 1962–Dec 1998 |
| 8   | Jayapura (JYP)   | 2.53°S   | 140.72°E  | 3               | Feb 1961–Dec 1991 |
| 9   | Batan-CRDIRT (BTN)| 6.28°S  | 106.67°E  | 45              | Jan 1997–Dec 2003 |
| 10  | Tongkol (TKL)    | 6.15°S   | 106.8°E   | 10              | Jan 1997–Dec 1999 |
that, even when their air masses are derived from similar locations, different precipitation events can have very different isotopic content variability; in addition, they showed that a very local amount effect was controlled by the intensity of precipitation (rain rate), the altitude at which precipitation was produced, microphysical processes within and near clouds, and also the type of precipitating cloud (convective or stratiform), for observations at different timescales. Little research focusing specifically on the IMC has been performed at this timescale. Fudeyasu et al. (2011) performed an intensive observational study of isotopic content in six hourly precipitation samples to determine the effect of a mesoscale process on the isotopic composition in a precipitation event. In addition, Moerman et al. (2013) investigated the relationship between $\delta^{18}O$ and local climate controls by high-frequency sampling of $\delta^{18}O$ within one precipitation event in northern Borneo.

Cloud type and composition were found to be factors that control isotopic variability along the west coast of Sumatra (Fudeyasu et al., 2011). The level of stable isotopes in convective-type precipitation was shown initially to decrease in the early stage of precipitation and then increased in the later stage (Fudeyasu et al., 2011; Moerman et al., 2013). In contrast, stable isotopes in precipitation value from more organized clouds was relatively stable during a precipitation event. Another factor that was shown to control the short-term variability of stable isotopes in precipitation is the post-condensation process (Moerman et al., 2013).

**IV. Intraseasonal Variability of Stable Isotopes in Precipitation in the IMC**

Intraseasonal variability of the level of stable isotopes in precipitation in the Maritime Continent was explored by focusing on the correlation between $\delta^{18}O$ in precipitation at JAMSTEC stations and the MJO. The MJO is an intraseasonal fluctuation that occurs in the tropics, characterized by a large-scale atmospheric circulation anomaly that originates over the western Indian Ocean and propagates eastwards into the Pacific Ocean; this phenomenon lasts about 30–60 days (Madden and Julian, 1971, 1972; Zhang, 2005). The MJO affects different kinds of weather and climate phenomena (Zhang, 2013). The active MJO phase was shown to affect the IMC region in many ways, from increasing the level of precipitation (Hidayat and Kizu, 2010) to causing serious flooding (Wu et al., 2013). An MJO event was divided into eight phases according to the location of the convective area in tropical regions (Wheeler and Hendon, 2004). Phase 1 of MJO is when the center of the convective area is located in the western Indian Ocean, and successive phases occur when the center of the convective area moves eastwards through the tropics until reaching phase 8, when it reaches the Pacific Ocean.

With regard to the relationship between the pentad weighted average of $\delta^{18}O$ in precipitation and the pentad MJO index, it was shown that the correlation was stronger for stations on Sumatra (GAW and JMB) than for other stations. Water was mainly derived from the Indian Ocean at GAW and JMB, when MJO was in the active phase (June, August and October), but this was not in the case at the other stations. Water was mainly derived from the South China Sea at the other stations when MJO was in the inactive phase (Ichiyanagi, 2009). Fig. 2 shows the pentad weighted average of $\delta^{18}O$ in precipitation
Observational Research on Stable Isotopes in Precipitation over Indonesian Maritime Continent

(\delta^{18}O_p) and the pentad MJO index (downloaded from http://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_mjo_index/pentad.html) from January to June 2004 (Fig. 2a–c) and January to June 2005 (Fig. 2d–f). The stations on Sumatra (Fig. 2a and 2d) showed a better correlation of \delta^{18}O_p and MJO index than those in the center (Fig. 2b and 2e) and east of the IMC (Fig. 2c and 2f). Moerman et al. (2013) made additional findings about MJO and \delta^{18}O in precipitation in the IMC by analyzing \delta^{18}O depletion when an MJO event occurred in Borneo. MJO, which involves the large-scale movement of convective cloud from the Indian Ocean to the Pacific Ocean, along with large-scale moisture transport, is known as one of the factors influencing stable isotope variability in the IMC (Fudeyasu et al., 2011).

By an analysis of the effect of MJO on isotopic variability in the IMC, using data on the isotopes in precipitation from ground observations, isotopic content in vapor derived from ground observations, satellite measurements and simulation/model data, it was shown that high isotopic content (\delta D in vapor) occurred during the period before MJO onset, which then gradually decreased in water in the midtroposphere during the MJO (Kurita et al.,...
2009); in addition, the changes over time in the source of moisture during MJO events were reported (Berkelhammer et al., 2012). Tuinenburg et al. (2015) also showed that there were differences in MJO sequences (specific humidity/δD phase) in the IMC compared with those in the Indian Ocean; specifically, in the IMC, there were fewer large-scale precipitation events, possibly due to the presence of islands and/or a larger spatial scale of diurnal cycle.

Investigating the isotopic response to a mesoscale convective system as part of intraseasonal variability, Kurita (2013) stated that the amount effect of isotopic variability in the tropics is not directly controlled by the amount of rainfall, but is instead influenced by large-scale convective activity involving several mesoscale convective systems.

V. Annual and Seasonal Variability of Stable Isotopes in Precipitation in the IMC

In previous research on annual and seasonal precipitation variability, the IMC was divided into three regions: annual, semiannual and local types (Aldrian and Susanto, 2003). In addition, using the isotopic content of precipitation, Suwarman et al. (2013a) analyzed seasonal and annual variability of the levels of precipitation and δ18O at JAMSTEC stations (GAW, JMB, DPS, MKS, MND and PLL) from 2001 to 2007 and GNIP stations (JAK and Darwin) from 1962 to 1998. In this research, several regions and characteristics regarding the source of water vapor during dry and wet seasons were distinguished, and different regions were also classified based on the annual variability of isotopic content. The current review article adds supplemental data from DPS, MKS and MND stations for the years 2008–2010 to this earlier work. The results show that, in the IMC, variability in the amount of precipitation can be divided into three types, namely, semiannual, monsoonal and anti-monsoonal. The time-series data of the monthly precipitation rate and δ18O for all stations are shown in Fig. 3. At all stations, the average precipitation rates in the dry (March to August) and wet seasons (September to February) were less than 150 mm/month and more than 450 mm/month, respectively. The δ18O value in the observation period ranged from −13‰ to 0‰. Fig. 4 shows the seasonal variations of the precipitation rate, deuterium excess (d-excess), δ18O and δD (δ2H). GAW (Fig. 4a) and JMB (Fig. 4b) stations represent the semiannual type, with two peaks in precipitation at GAW, from January to April and September to December. Although the precipitation variability at JMB was actually relatively small in this dataset, Hamada et al. (2002) stated that JMB station represents the semiannual precipitation type, with maximum precipitation in September to February.

With regard to variability in the stable isotopes value at GAW station, it ranged from −8.8‰ to −5.8‰ for annual δ18O and −57‰ to −36‰ for annual δD. GAW station is located in the mountains on Sumatra, and the altitude effect led to significantly lower isotopic values than at other stations in the IMC. A comprehensive analysis of the altitude effect in the IMC was performed by Permana (2011) in Papua. Using data on isotopic content from precipitation and ice-core analysis, altitude and temperature were found to be the dominant factors controlling isotopic variability in Papua in the short-term period (daily variability), with isotope lapse rates of 0.23‰/100 m and 1.80‰/100 m for δ18O and δD, respectively, in June 2010 (dry season) (Permana, 2011). Other stud-
Observational Research on Stable Isotopes in Precipitation over Indonesian Maritime Continent

Fig. 3. Time-series data of monthly precipitation rate (bar graph) and $\delta^{18}O$ (line graph) at JAMSTEC (a–f) and GNIP (g and h) stations.
Fig. 4. Long-term monthly means of δ¹⁸O (solid line, bottom panel), δD (dashed line, bottom panel), precipitation (bar graph, middle panel) and D-excess (solid line, top panel) for JAMSTEC and GNIP stations.
ies in tropical regions, namely, in Cameroon and Bolivia, identified the altitude effect; the δ¹⁸O lapse rate for the rainy/wet season (0.23% –0.26‰/100 m) was larger than for the dry season (0.11%–0.16‰/100 m) (Gonfiantini, 2001). Furthermore, Poage and Chamberlain (2001) reported a linear relationship between the isotopic content of precipitation and the altitude of approximately 0.28‰/100 m globally, apart from in the Himalayas and regions at extreme latitudes.

The annual δ¹⁸O value at JMB station was observed to range from −8.9‰ to −4.1‰ and annual δD ranged from −60‰ to −25‰. Lightest value of isotopic content at JMB was observed twice: in March to June and also in November.

The anti-monsoonal type was observed at PLL, indicated by a precipitation peak in April to July (Fig. 4f). The annual δ¹⁸O value at the PLL station ranged from −6.2‰ to −2‰ and annual δD ranged from −41‰ to −8‰. The d-excess is a second-order isotope parameter proposed by Dansgaard (1964) based on the relationship between δ¹⁸O and δD (D=δD−8δ¹⁸O), which is specifically sensitive to the conditions during the evaporation of water from the surface and closely correlated with the source of moisture and relative humidity (Phafl and Sodemann, 2014). Annual d-excess variability observed in PLL ranged from 8‰ to 10‰, which was smaller than at the other stations and almost constant for the whole year. Rusmawan et al. (2013) explained that the low variability of d-excess at PLL was related to a shift of the source of water there from the north and south Pacific Ocean for wet season (DJF) and dry season (JJA) respectively, which coincided with the Indonesian throughflow sea-surface current, generating convective precipitation and depleting δ¹⁸O. Lightest value of isotopic content (δ¹⁸O and δD) at PLL was observed in May.

The monsoonal precipitation pattern was observed at DPS, MKS, MND, JAK and JYP. At DPS (Fig. 4c), the annual δ¹⁸O value ranged from −6.2‰ to −2‰ and annual δD ranged from −41‰ to −8‰. Lightest value of isotopic content (δ¹⁸O and δD) at DPS was observed in December to February. MKS station (Fig. 4d) had an annual δ¹⁸O value ranging from −8‰ to −1.5‰, and annual δD ranged from −52‰ to −7‰; at this station, the average weight of the isotopes was highest when the amount of precipitation was lowest in July to September. At JAK (Fig. 4g), the annual δ¹⁸O value ranged from −6.2‰ to −4‰ and annual δD ranged from −40‰ to −19‰. Lightest value of isotopic content (δ¹⁸O and δD) at JAK was observed in the period that also had the highest precipitation in December to February. The annual δ¹⁸O value in JYP (Fig. 4h) ranged from −6.5‰ to −3.9‰ and the annual δD ranged from −44‰ to −26‰. The same as at the other monsoonal-type stations, lightest value of isotopic content in JYP occurred in the same period as when there was the highest precipitation in January to April. At MND station (Fig. 4e), the annual δ¹⁸O value ranged from −8‰ to −5‰ and the annual δD ranged from −51.7‰ to −29.3‰. The d-excess values at MND, JAK and JYP also tended to be constant or showed low variability throughout the year.

The annual and seasonal variability patterns or seasonal change of the value of stable isotopes in precipitation in the IMC are closely related to the Asian–Australian monsoon circulation. Seasonal change in the semiannual pattern in Sumatra (GAW and JMB) was characterized by the rising of water vapor from the
Indian Ocean in the wet season and from the southern oceanic part of the Maritime Continent in the dry season. Seasonal change in the monsoonal pattern (JAK, DPS, MKS, MND and JYP) can be identified by the rising of water vapor from the Indian Ocean and the northern oceanic part of the Maritime Continent in the wet season and its southern part in the dry season. Lastly, seasonal change in the antimonsoonal pattern (PLL) can be identified by irregular rising and retreating of water vapor that came from the southwest Pacific Ocean, and the southern and tropical parts of the ocean in the IMC (Suwarman et al., 2013a).

In tropical regions, the precipitation level and isotopic content (δ^{18}O & δD) have a unique relationship called the amount effect (Dansgaard, 1964), as mentioned in section I. The amount effect could only be identified at IMC observation stations to give monthly averaged data, rather than weekly or daily data. Table 2 presents the amount effect conditions at all stations and also their isotopic local meteoric water line (LMWL), which reflects the relationship between δD and δ^{18}O. Statistically significant amount effects were observed at DPS (r=−0.85), MKS (r=−0.73), JAK (r=−0.73) and JYP (r=−0.70). At GAW and JMB stations, there was a negative correlation between precipitation rate and δ^{18}O, but this was not statistically significant. The amount effect was not observed at MND station (r=0.15). Fig. 5 shows the long-term relationship between the monthly mean values of precipitation rate and δ^{18}O derived from the monthly averages for the different observational periods shown in Table 1 for all stations. It is difficult to determining which factors control the amount effect owing to the complexity of convection or rain formation; however, some processes are known to influence the negative correlation between precipitation amount and isotopic content, such as the fractionation process of heavy isotopes during condensation/initial rain and the post-condensation process, including the evaporation of falling raindrops at low relative humidity (in arid regions) and diffusive exchange between falling drops and surrounding vapor (Dansgaard, 1964; Stewart, 1975; Lee and Fung, 2008; Risi et al., 2008). In the IMC, the post-condensation process was one factor that influenced the amount effect on
Observational Research on Stable Isotopes in Precipitation over Indonesian Maritime Continent

![Graph](image)

**Fig. 5.** Relationship between precipitation rate and $\delta^{18}O$ at all observational stations. Black (gray) solid line is the regression line for MKS (DPS), which represents the amount effect. Black dashed line is the regression line for MND, which shows that the amount effect was not observed at this station.

![Graph](image)

**Fig. 6.** Linear relationship of monthly $\delta^{18}O$ and $\delta D$ at eight stations. Local meteoric water line and global meteoric water line are indicated by the solid and dashed lines, respectively.

A very short timescale, such as for a single rain event (Moerman et al., 2013). For longer periods, such as when using the long-term monthly mean, the amount effect was associated with large-scale atmospheric conditions like the movement of the Intertropical Convergence Zone (Kurita et al., 2009), and also the MJO and ENSO phenomena (Cobb, 2007; Moerman et al., 2013).

The global relationship between monthly $\delta^{18}O$ and $\delta D$ in natural waters was recognized by Craig (1961) and named the global meteoric water line (GMWL). In contrast, the relationship between $\delta^{18}O$ and $\delta D$ in a particular local region is defined as the LMWL. The LMWL of monthly isotopes in precipitation collected at all observational stations and the equation for the best fit line through the sample points for both isotopes are summarized in Table 2 and Fig. 6. $\delta^{18}O$ and $\delta D$ are well correlated at each station ($R>0.9$), indicating that these two isotopes are closely associated in the fractionation process. The slope of each LMWL among the stations can be divided into two groups: the first group, which has a slope near 8, is dominated by continental stations (GAW, MND, JAK, BTN and TKL) and corresponds to the theoretical results under isotopic equilibrium conditions. The other group includes stations with a slope near 7 (JMB, DPS, MKS, PLL and JYP); these stations are mainly located near the coast and in a small island. Previous comparisons of the relationship between $\delta^{18}O$ and $\delta D$ for marine and continental stations showed that the slope was usually less steep at marine stations (Rozanski et al., 1993; Clark and Fritz, 1997). However, the relationship between $\delta^{18}O$ and $\delta D$ can be complicated by different sources of water vapor, different air mass trajectories and different isotope exchange processes below the cloud base.

**VI.** Interannual Variability of Stable Isotopes in Precipitation in the IMC

Interannual variability of stable isotopes in precipitation over the Maritime Continent was explored by investigating the correlation between $\delta^{18}O$ in precipitation and the ENSO index, which represents El Niño or La Niña conditions. ENSO involves the interaction between the atmosphere and the ocean in the tropical
Pacific, which can influence precipitation variability for a few years (interannual). Strong El Niño conditions have caused serious problems in the IMC, such as drought and forest fires (Siegert et al., 2001), as well as increased lightning activity (Hamid et al., 2001).

Using simulated data (Yoshimura et al., 2008) from 1982 to 2011 for all seasons, as presented by Suwarman (2013b) showed there were no correlation between δ¹⁸O in precipitation and the ENSO index for central Sumatra, eastern Java and Borneo. However, positive correlations were observed in northern Sumatra, western Java and the eastern part of the IMC. Meanwhile, in Bangkok, ENSO was shown to be closely correlated with δ¹⁸O in precipitation only in May and October (Ichiyanagi and Yamanaka, 2005b). Fig. 7 shows the 13-month running average of δ¹⁸O and ENSO index (retrieved from http://www.cpc.ncep.noaa.gov/data/indices/sstoi.indices) for the Mt. Mulu/Borneo station (Fig. 7a) (precipitation isotope data were retrieved from Moerman, 2013), the JMB station (Fig. 7b) and the JYP station (Fig. 7c). On Borneo, isotopes in precipitation were significantly correlated with the ENSO index (r=0.94) for the whole observation period (2006–2011); however, at the remaining stations in the IMC, isotopes in precipitation and the ENSO index did not show a good correlation throughout the observation period. A good correlation between isotopes in precipitation and the ENSO index was only identified for specific events; for example, at JMB (Fig. 7b), such a correlation was observed in the years 2003 and 2004, when there was an El Niño event (r=0.73). The same phenomenon was observed at JYP (Fig. 7c), where isotopes
in precipitation showed a good correlation with the ENSO index in the years 1981–1983, in which El Niño also occurred; this finding was also made by Permana (2011) using ice-core analysis in Papua. In addition, for some regions in the IMC, the ENSO phenomenon can be traced using the levels of isotopes in precipitation within a specific period of time. For example, on Borneo, \( \delta^{18}O \) in precipitation was found to be a better tracer of ENSO indices than precipitation data (Moerman, 2013). In another study, \( \delta D \) in vapor in Indonesia simulated by the ECHAM model was also shown to be a better indicator of drought and flooding than ENSO indices (Sutanto et al., 2013).

Suwarman (2013b), using the isotopes value in water vapor and precipitation, analyzed the movement of moisture in ENSO conditions in the IMC. In accordance with the amount effect, both depletion and enrichment of stable isotopes corresponded to the appearance of areas of convergence or divergence of air masses over the IMC when La Niña and El Niño conditions prevailed, respectively. In La Niña years, newly evaporated water came from the Indian Ocean, the Pacific Ocean, and also from the north and south of the Maritime Continent, resulting in higher than average precipitation in the IMC. These circumstances resulted in greater depletion of stable isotopes in water vapor over the IMC. The opposite occurred during El Niño, namely, the IMC became an area where air mass diverged, and wind in the IMC was directed to both the Pacific Ocean and the Indian Ocean. This prevented water vapor from the Pacific Ocean reaching the IMC and also prevented Indian Ocean water vapor from reaching Sumatra and other parts of the IMC. Thus, the isotope content increased above the average.

Observational research on the interannual variability of stable isotopes in precipitation in the IMC has been impeded by the limited availability of data across both spatial and temporal ranges. Therefore, little research linking the levels of stable isotopes in precipitation with the ENSO phenomenon in the IMC has been reported. However, several studies confirmed that interannual variability of precipitation in the IMC was closely correlated with ENSO, mainly in the dry season (Aldrian and Susanto, 2003; Hamada et al., 2002, 2012; Hendon, 2003; Ropelewski and Halpert, 1987). In addition, a study using the levels of stable isotopes in stalagmite dripwater on Borneo showed that the effect of a large ENSO on the variability in local precipitation isotopes can be preserved in dripwater, enabling the reconstruction of past ENSO variability (Moerman et al., 2014).

**VII. Future Study**

The stable isotopes in precipitation (\( \delta^{18}O \) and \( \delta D \)) value indicate the source and previous transport of the water because water with high and low levels of isotopes experiences different fractionation processes during the change of water phase (Gat, 2005). Because of the unique composition and characteristics of stable isotopes in precipitation, they have been used to explore climate variability. Ichiyanagi et al. (2002) explained the close relationship between stable isotopes in precipitation in the Antarctic and ENSO, and Aggarwal et al. (2004) discovered that stable isotopes in precipitation in the Indian subcontinent were correlated with the source of the moisture and the route through which it had been transported, but not the level of precipitation. Other studies used d-excess and precipitation isotopes to trace atmospheric circulation (Araguás-Araguás et al., 1998; Bur-
nett et al., 2004; Datta et al., 1991; Leguy et al., 1983; Sengupta and Sarkar, 2006).

Rozanski et al. (1992) stated that, although the correlation between the isotopic composition of precipitation and weather/climate at a high altitude is relatively well known, little is known about this issue in tropical areas. However, owing to recent studies using observational data, as discussed in section II, the link between the isotope signature of precipitation and weather/climate in the IMC is now being explored. Unfortunately, with the lack of observational data, our knowledge of the isotopic signature of precipitation in the IMC, especially in association with hydrological cycle processes, has remained limited. There is a need to explore the associations of meteorological factors and phenomena such as the effect of the diurnal cycle of precipitation, IOD (Indian Ocean Dipole) explained by Saji et al., (1999) and cross-equatorial northerly surge/cold surge (Hattori et al., 2011) with the isotopic composition in precipitation in the IMC, as well as to improve our understanding of the correlation between ENSO and stable isotopes in precipitation. In order to achieve this, observational data from the IMC with much better spatial and temporal resolution are needed.

VIII. Summary

The Indonesian Maritime Continent is a unique location in the tropics that consists of many land masses and seas. The thermal difference between the sea and the land is the main cause of monsoons in this region. The levels of stable isotopes (δ¹⁸O and δD) in precipitation can be used to understand weather and climate processes in this region.

There are several types of seasonal variation in stable isotopes in the IMC. Interannual variability of stable isotopes in the IMC was shown to be mainly due to ENSO activity (El Niño and La Niña). However, intraseasonal variability is closely related to the MJO phenomenon. Cloud type and the post-condensation processes are the factors controlling stable isotope variability in the short term.

The amount effect, namely, the negative correlation between precipitation amount and stable isotope levels, was observed in the IMC monthly using monthly averaged data obtained at DPS, MKS, PLL, JAK and JYP.

The collection of observational data and the sampling of stable isotopes in precipitation in the IMC are very important due to the enormous area of the IMC. Further investigations using data collected at a greater number of observational stations in the IMC are needed to obtain a more comprehensive understanding of the stable isotopes throughout this region.

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この論文に対する「討論」を2016年9月30日まで受け付けます。
インドネシア海大陸における降水の安定同位体の観察研究

Halda A. BELGAMAN・一柳鉄平・田上雅浩・Rusmawan SUWARMAN

インドネシア海大陸（IMC）は熱帯地方にあって、多数の島と海から構成されている。この多数の島と海の配置は、独特の気候や気候特徴を形成している。IMCでは、降水の安定同位体の変動を調べる様々な水文気象学的な研究が行われている。降水の安定同位体比（δ¹⁸O, δD）は、大気過程（例えば、降水量、気温、水循環）に関する情報を得るために使われる。国際原子力機構による全球降水同位体観測網は、1961年より世界的に月単位の降水同位体の観測を行っており、海洋研究開発機構ではIMCの降水同位体の変動をさらに理解するために、2001年より観測を開始した。降水の安定同位体の季節変動には、降水量と気温の関係が見られ、降水の安定同位体の経年変動ではエルニーニョ南方振動による影響、季節内変動ではマッデン・ジュリアン振動による影響が認められた。また、短期変動には雲タイプや凝結後のプロセスによる影響が認められた。

キーワード：安定同位体、降水、インドネシア海大陸、エルニーニョ南方振動、マッデン・ジュリアン振動