Diurnal variation of stable isotopes in rainfall observed at Bengkulu for the YMC-Sumatra 2017

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Abstract. Diurnal variability of stable isotopes in precipitation and its controlling factors are poorly understood, especially in the tropics. This study investigated the diurnal variability of stable isotopes in rainfall observed at Bengkulu in southern Sumatra, Indonesia. Rainfall samples were collected at 6-h intervals from 1 December 2017 to 15 January 2018 for the Year of the Maritime Continent (YMC-Sumatra 2017). The oxygen and hydrogen isotopic compositions (δ¹⁸O and δ²H) of the rainwater varied from −15.1‰ to −1.8‰ and from −108.9‰ to −1.3‰, respectively, and the d-excess varied from 1.9‰ to 17.1‰. The observations at Bengkulu revealed that diurnal variation in rainfall amount was not significant for the entire period; however, the δ¹⁸O was lighter in both the early morning and the afternoon and heavier before noon and overnight. The δ¹⁸O became gradually depleted in the periods of continuous rain that occurred during 1–4 and 21–24 December. The amount of morning rain was much greater than evening rain in these periods, whereas the amount of evening rain was greater than morning rain in other periods. Based on satellite-derived CMORPH data, it is assumed that morning rain and evening rain corresponded to weak rainfall over surrounding sea region and strong rainfall over inland regions of Sumatra, respectively. The differences in moisture source and ratio of stratiform/convective rain rate between morning and evening might affect the isotopic composition of rainfall in the tropics.

Keywords : isotopes, CMORPH, stratiform, convective.

1. Introduction
Many previous studies that have discussed precipitation isotope changes in the tropics on timescales longer than a day have suggested that long-term isotopic changes might be controlled by large-scale moisture transport [1, 2, 3]. In palaeoclimatic reconstructions, the relationships between large-scale climate variability, rainwater, and cave drip water δ¹⁸O have been investigated in northern Borneo on daily–interannual timescales [4, 5]. Moreover, relationships between precipitation isotopes and
precipitation amount have been determined based on daily rainfall isotopes in Papua [6]. The seasonal and intra-annual variations of rainfall isotopes have been investigated using daily rainfall isotope datasets acquired at six sites across the Indonesian Maritime Continent (IMC) [7,8]. However, the spatial and temporal resolutions of the observed rainfall isotopes were inadequate to elucidate the factors controlling the isotopic variations.

A later study investigated the high-resolution spatiotemporal characteristics of rainfall isotopes using data acquired weekly at 33 meteorological stations across the IMC [9]. The findings of these earlier studies on timescales longer than a day suggested that rainfall isotopes are affected by the Madden–Julian Oscillation, Asian and Australian monsoons, and El Niño–Southern Oscillation. However, the relationships between the rainfall isotopes and meteorological parameters remain poorly understood, especially in the tropics where rainfall variation is predominantly diurnal. A few observational studies have conducted investigations on rainfall isotope changes on timescales shorter than a day during rain events in Sumatra [10]. Therefore, this study focused on the diurnal variation of stable isotopes in rainfall observed in the tropics and investigated the differences in the rainfall isotopes between morning and evening rain.

2. Data and Methods
Rainfall samples were collected at 6-h intervals at BMKG (Agency for Meteorology, Climatology, and Geophysics) Bengkulu meteorological station (3.87°S, 102.33°E) in southern Sumatra (Indonesia) from 1 December 2017 to 15 January 2018 during the Year of the Maritime Continent (YMC-Sumatra 2017). Overall, 63 rainwater samples were collected and the stable isotope ratios of the rainwater were measured using a cavity ring-down spectroscopy isotopic water analyser (L2120-i, Picarro Inc., Sunnyvale, CA, USA) at the Isotope Hydrology Laboratory of Kumamoto University, Japan. The stable isotopes of oxygen and hydrogen (δ18O and δD) of the rainwater were expressed by convention as a deviation in parts per thousand (‰) from the Vienna Standard Mean Ocean Water (V-SMOW). The analytical errors for δ18O and δD were 0.2‰ and 0.6‰, respectively. The deuterium excess (d-excess), defined as δD − 8 × δ18O, is a second-order isotope parameter that is sensitive to ambient conditions during the evaporation of water from the ocean surface.

Rainfall amount and air temperature data observed at 6-h intervals were acquired from the BMKG Bengkulu meteorological station. The spatial distribution of precipitation over Indonesia was produced using the Climate Prediction Center morphing method (CMORPH) rain rate (real-time version) for the YMC Domain (15°S–15°N, 80°–160°E) [11], for which the spatial and temporal resolutions were 8 km at the equator and 30 min, respectively.

3. Results and Discussions
3.1. Temporal variation
Temporal variations in δ18O, d-excess, and rainfall amount observed at 6-h intervals at Bengkulu throughout the entire observation period are shown in figure 1. The δ18O and δD (not shown in the figure) of rainfall varied from −15.1‰ to −1.8‰ and from −108.9‰ to −1.3‰, respectively, and the d-excess varied from 1.9‰ to 17.1‰. Figure 1 shows reasonably continuous rain persisted from 1 to 4 December 2017 and from 21 to 24 December 2017. During these periods, δ18O became gradually depleted from approximately −3‰ to −9‰ (hereafter, the δ18O depleting periods). Sudden depletion of δ18O that corresponded to periods of heavy rain occurred on 13, 14, and 27 December 2017 and on 10 January 2018. Except during the above periods, δ18O showed only small variation. With reference to the temporal characteristics of δ18O variation, the observation period was divided into four stages: 1–4 December (P1), 5–20 December (P2), 21–24 December (P3), and 25 December to 15 January (P4).

The local meteoric water line (LMWL) throughout the entire observation period was δD = 8.03 × δ18O + 11.6. However, during periods P1–P4 its value was δD = 8.81 × δ18O + 15.7, δD = 7.50 × δ18O + 14.4, δD = 8.38 × δ18O + 16.9, and δD = 8.00 × δ18O + 11.9, respectively. All correlation coefficients were >0.98 with statistical significance. Both the slope and the intercept of the LMWL for periods P1 and P3 were relatively higher in comparison with periods P2 and P4. The differences in
LMWL could be attributable to processes such as evaporation in the source region, precipitation within the cloud, and evaporation of raindrops. Generally, a “rainfall amount effect” whereby δ¹⁸O values become depleted with increasing rainfall amount is found in the tropics [8]. In figure 1, however, the temporal characteristics of rainfall amount and δ¹⁸O do not appear to match. Relationships between δ¹⁸O and rainfall amount or air temperature observed at Bengkulu for the entire period are shown in figure 2. The correlation coefficients of these relationships were 0.02 and 0.18 for rainfall amount and air temperature, respectively; however, neither relationship was found significant.

**Figure 1.** Temporal variations of δ¹⁸O, d-excess, and rainfall amount observed at 6-h intervals at Bengkulu from 1 December 2017 to 15 January 2018. Closed circles with solid line, open circles with dashed line, and bars indicate δ¹⁸O, d-excess, and rainfall amount, respectively.

**Figure 2.** Scatter diagrams between δ¹⁸O and (a) rainfall amount and (b) air temperature observed at Bengkulu throughout the entire observation period.

### 3.2 Diurnal variation

To elucidate the characteristics of the diurnal variation in rainfall isotopes, rainfall amount, air temperature, δ¹⁸O weighted by the rainfall amount, and d-excess were averaged over specific 6-h intervals (i.e., 01, 07, 13, and 19 local time (LT)) for the entire period. Because the temporal characteristics of δ¹⁸O were similar in the δ¹⁸O depleting periods (P1 and P3) and in the other periods (P2 and P4), the meteorological and isotopic values were also averaged for these periods. Diurnal variations of rainfall amount, air temperature, δ¹⁸O, and d-excess are shown in figure 3. Figure 3a shows that diurnal variation in rainfall amount was not evident for the entire period; however, a large difference was found between the δ¹⁸O depleting periods and the other periods. The
amount of morning rain (02–07 LT and 08–13 LT) was much greater than evening rain (14–19 LT and 20–01 LT) for the δ¹⁸O depleting periods. Conversely, the amount of evening rain was much greater than morning rain for the other periods. Figure 3b shows clear diurnal variation in air temperature for all periods, i.e., higher during daytime (08–13 LT and 14–19 LT) and lower during night-time (20–01 LT and 02–07 LT). Remarkably, the air temperature before noon (08–13 LT) for the δ¹⁸O depleting periods was much lower than that of the same time in the other periods. Heavy rainfall and low temperature before noon (08–13 LT) were assumed to prevent evaporation from the land around Bengkulu for the δ¹⁸O depleting periods. From Figure 3c, clear diurnal variation in δ¹⁸O is evident for all periods, i.e., light values in the early morning (02–07 LT) and afternoon (14–19 LT) and heavy values before noon (08–13 LT) and overnight (20–01 LT). The δ¹⁸O values before noon (08–13 LT) for both the entire period and the δ¹⁸O depleting periods were found much lighter than for the other periods. Figure 3d shows that d-excess values throughout the day for the δ¹⁸O depleting periods were higher than for the other periods, especially in the early morning (02–07 LT). The large difference in d-excess values indicates that the moisture source (evaporation process) and/or precipitation process within the cloud (condensation process) must have been different between these periods.

The diurnal cycle of rainfall and its regional variation over Sumatra have been investigated in earlier research [12], which revealed that convective rainfall with a broad peak between 15–20 LT predominates over the land area, whereas rainfall in the early morning, comprising almost equally of stratiform and convective types, is predominant over the surrounding sea region. To consider the diurnal cycle of rainfall and moisture source, the spatial distribution of rainfall over the IMC was investigated using satellite-derived CMORPH data.

Diurnal variations of rainfall patterns averaged over the specific 6-h intervals for the entire period are shown in figure 4. Heavy rainfall extends over the inland region of Sumatra in the afternoon (14–19 LT) and overnight (20-01 LT), while weak rainfall extends over the surrounding sea region in the early morning (02–07 LT) and before noon (08–13 LT). It is assumed that the morning rain for the δ¹⁸O depleting periods and evening rain for the other periods correspond to the surrounding sea region and the inland area of Sumatra, respectively. Thus, the moisture source and the ratio of stratiform/convective rain rates between these periods might be different. These differences might affect the isotopic compositions of the rainfall.

Figure 3. Diurnal variations of (a) rainfall amount, (b) temperature, (c) δ¹⁸O, and (d) d-excess observed at Bengkulu and averaged for each specific period. Dates 12/1–1/15 correspond to the entire period, and 12/1–4, 12/5–20, 12/21–24, and 12/25–1/15 correspond to periods P1–P4, respectively.
Figure 4. Diurnal variations of precipitation patterns averaged over specific 6-h intervals from 1 December 2017 to 15 January 2018. Black dot indicates the location of the Bengkulu meteorological station.

4. Concluding remarks
To elucidate the diurnal variation of stable isotopes in rainfall, rainfall samples were collected at Bengkulu from 1 December 2017 to 15 January 2018. The diurnal variation in rainfall amount was not significant for the entire period; however, the $\delta^{18}O$ was lighter in both the early morning and the afternoon and heavier before noon and overnight. Because of the temporal characteristics of $\delta^{18}O$, the meteorological and isotopic values were averaged for the $\delta^{18}O$ depleting periods (P1 and P3) and in the other periods (P2 and P4). As a result, the amount of morning rain was much greater than evening rain for the $\delta^{18}O$ depleting periods, whereas the amount of evening rain was much greater than morning rain for the other periods. The d-excess values for the $\delta^{18}O$ depleting periods were higher than for the other periods, especially in the early morning. From the average of the satellite-derived CMORPH data for the entire period, the morning rain for the $\delta^{18}O$ depleting periods and the evening rain for the other periods might have corresponded to weak rainfall over the surrounding sea region and strong rainfall over inland regions of Sumatra, respectively. The isotopic compositions of moisture and rainfall should be different depending on the moisture source and ratio of stratiform/convective rain rates. Therefore, diurnal variation of rainfall might affect the determination of the isotopic compositions of rainfall in the tropics. Further research will be needed to improve the understanding of the precipitation process using in situ observations such as rawinsondes and meteorological radar.

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## Appendix Table A1

Summary of precipitation isotope observations at Bengkulu meteorological station.

| No. | Date          | Time (LT) | Time (UTC) | Rain (mm/6h) | Temp. (℃) | δ18O (%) | δ2H (%) | d-excess (‰) |
|-----|---------------|-----------|------------|--------------|-----------|---------|---------|--------------|
| 1   | 2017/12/1     | 00:00     | 10:00      | -            | -         | -       | -       | -            |
| 1   | 2017/12/2     | 00:00     | 10:00      | -            | -         | -       | -       | -            |
| 1   | 2017/12/3     | 00:00     | 10:00      | -            | -         | -       | -       | -            |
| 1   | 2017/12/4     | 00:00     | 10:00      | -            | -         | -       | -       | -            |
| 1   | 2017/12/5     | 00:00     | 10:00      | -            | -         | -       | -       | -            |
| 1   | 2017/12/6     | 00:00     | 10:00      | -            | -         | -       | -       | -            |
| 1   | 2017/12/7     | 00:00     | 10:00      | -            | -         | -       | -       | -            |
| 1   | 2017/12/8     | 00:00     | 10:00      | -            | -         | -       | -       | -            |
| 1   | 2017/12/9     | 00:00     | 10:00      | -            | -         | -       | -       | -            |
| 1   | 2017/12/10    | 00:00     | 10:00      | -            | -         | -       | -       | -            |
| 1   | 2017/12/11    | 00:00     | 10:00      | -            | -         | -       | -       | -            |
| 1   | 2017/12/12    | 00:00     | 10:00      | -            | -         | -       | -       | -            |
| 1   | 2017/12/13    | 00:00     | 10:00      | -            | -         | -       | -       | -            |
| 1   | 2017/12/14    | 00:00     | 10:00      | -            | -         | -       | -       | -            |
| 1   | 2017/12/15    | 00:00     | 10:00      | -            | -         | -       | -       | -            |
| 1   | 2017/12/16    | 00:00     | 10:00      | -            | -         | -       | -       | -            |
| 1   | 2017/12/17    | 00:00     | 10:00      | -            | -         | -       | -       | -            |
| 1   | 2017/12/18    | 00:00     | 10:00      | -            | -         | -       | -       | -            |
| 1   | 2017/12/19    | 00:00     | 10:00      | -            | -         | -       | -       | -            |
| 1   | 2017/12/20    | 00:00     | 10:00      | -            | -         | -       | -       | -            |
| 1   | 2017/12/21    | 00:00     | 10:00      | -            | -         | -       | -       | -            |
| 1   | 2017/12/22    | 00:00     | 10:00      | -            | -         | -       | -       | -            |
| 1   | 2017/12/23    | 00:00     | 10:00      | -            | -         | -       | -       | -            |
| 1   | 2017/12/24    | 00:00     | 10:00      | -            | -         | -       | -       | -            |
| 1   | 2017/12/25    | 00:00     | 10:00      | -            | -         | -       | -       | -            |

*Remark: No th mean there is rain but so little that unmeasurable*
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