The Variability of Stable Isotopes and Water Origin of Precipitation over the Maritime Continent

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Abstract

The seasonal water cycle features over the maritime continent were determined using water sources from seven regions produced by global Rayleigh-type circulation model. The model output was validated statistically to reproduce stable isotopes by the observed $\delta^{18}O$ and $\deltaD$ content of precipitation at eight stations. The model explains the Asian-Australian monsoon circulation well and demonstrates the seasonal changes of the water origin on the basis of three climatic patterns as a signature of rainy and dry season: (1) the semi-annual pattern, seasonal changes are indicated by the raise of water vapor from Indian Ocean for rainy season and southern maritime continent for dry season (2) the anti-monsoonal pattern, represented by the alternating raise and retreat of water vapor from the southwest Pacific Ocean, southern and tropical maritime continent seas, and (3) the monsoonal pattern, characterize-izd by the raise water vapor from the Indian Ocean and northern maritime continent sea for rainy season and southern maritime continent seas for dry season.


1. Introduction

The Indonesian maritime continent consists of many islands in a warm pool of sea water and is located between two great oceans—the Pacific Ocean and Indian Ocean, and two major continents—the Asian and Australian continents. There have been believed the thermal difference between sea and continent is the main cause of monsoon (Halley 1686; Ramage 1968; Wang et al. 2003). This tropical region is also influenced by Inter-tropical Convergence Zone (ITCZ) which causes high spatial and temporal rainfall variability. These factors may produce unique variability of isotopic precipitation.

Since Dansgaard (1953), the isotopic content ($\delta^{18}O$ and $\deltaD$) in precipitation have been known to have important role for reconstructing the atmospheric circulation, hydrological cycle, and paleoclimate. Recently, the simulated isotopes in precipitation has been developed into Atmospheric General Circulation Model to observed global precipitation isotopes distribution. For the instance, Yoshimura et al. (2003, 2004) developed a Rayleigh-type one layer isotope circulation model (ICM) and Colored moisture analysis (CMA) having a good reproduction in precipitation isotopes variation and describing water circulation trajectory. The ICM/CMA has been used and confirmed good reproduction in isotopic precipitation over Asian monsoon region (e.g. Ichiyanagi et al. 2005; Fudeyasu et al. 2011).

There are few studies in isotopic precipitation and its relation to climatology over maritime continent (e.g. Kurita et al. 2009). However, the dynamical water vapor processes from particular region to maritime continent has not fully understood. Studying the dynamical water sources over maritime continent will aid to understand hydrological processes related to the Asian-Australian monsoon and their association with isotopic variability. Furthermore, the discussion of isotopic signal in precipitation might be useful for paleoclimate study. Thus, the aim of this study is to examine how the water vapor transported from the upstream, mixed with other water masses, and distillated over maritime continent.

Since ICM/CMA have well performance in Asian monsoon region to estimating water origin, those integrated model are used in this study.

2. Dataset and method

Data of precipitation and stable isotopes contents ($\delta^{18}O$ and $\deltaD$) over the maritime continent were gathered from the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) and the International Atomic Energy Agency/Global Network of Isotopes in Precipitation (IAEA/GNIP) (Fig. 1). Most JAMSTEC samples were collected between 2001 and 2006 (Kurita et al. 2009), and only two of those stations continued to collect data until May 2007: Kototabang (100.19°E, 0.12°S, 865 masl, GAW) and Peleliu (134.15°E, 7.02°N, 11 masl, PLL). The other stations are Jambi (103.37°E, 1.36°S, 26 masl JMB), Manado (124.55°E, 1.32°N, 95 masl, MND), Makassar (119.32°E, 5.03°S, 43 masl, MKS), and Denpasar (115.10°E, 8.45°S, 3 masl, DPS). $\delta^{18}O$ was measured by a MAT 252 mass spectrometer with 0.1‰ analytical precision, and $\deltaD$ by a continuous-flow isotope ratio mass spectrometry with 2.0‰ analytical precision (Large-Scale Hydrological Cycle Research Group, IORGC, JAMSTEC, 2008). Two GNIP stations were Jakarta (106.83°E, 6.18°S, 8 masl, JAK) and Darwin (12.43°S, 130.87°E, 26 masl, DAR) (IAEA/WMO 2006).

ICM, maintaining atmospheric-balance equation to calculate atmospheric water transport (Oki et al. 1995), was used to simulate the stable isotopic content in precipitation. The CMA was applied to track the dynamic water vapor movement from the upstream to deposition site. The tagged-water source regions were divided into seven sections: Inland consisting of Asia, Africa, and Australia Continent (LN), Indian Ocean (IO), northern maritime continent sea (NM), tropical maritime continent sea (TM), southern maritime continent sea (SM), northwest Pacific Ocean (NP), and southwest Pacific Ocean (SP) (Fig. 1). The model was applied to the Japanese 25-year Reanalysis project (JRA-25) and the Japan Meteorological Agency Climate Data Assimilation System (JCDAS) with a spatial resolution of 1.125° × 1.125° from 1979 to 2007 (Onogi et al. 2007). Precipitation and vapor flux data of JRA-25/JCDAS are also used.

Observed isotope data were used to clarify the validation of simulated isotope in ICM (Table 1). The correlation coefficients
been caused by the uncertainty in evaporation isotopic ratios and local-scale processes which are not accommodated in the model (Yoshimura et al. 2003).

3. Results and discussion

There have been several studies in annual climatological circulation over maritime continent (e.g. Hamada et al. 2002; Aldrian and Susanto 2003; Chang et al. 2005). Generally, precipitation can be divided into three major types: semi-annual, anti-monsoonal, and monsoonal. The semi-annual precipitation can be characterized by two peaks of the rainy season in March to May and October to December with small variance. The anti-monsoonal is characterized by one peak of rainy in March to August. The Monsoonal region is characterized by one peak of rainy season in November to March. The discussion of water sources in each station will be grouped based on these annual cycle types.

Figure 2 shows the seasonal variation of the observed precipitation, observed and simulated $\delta^{18}O$, d-excess, and the simulated precipitable water on the basis of the seven regions. The d-excess, defined as $d = \delta D - 8 \times \delta^{18}O$ (Dansgaard 1964), depends on temperature, humidity, and wind speed around the water source (Merlivat and Jouzel 1979). Figure 3 shows the precipitation and water flux anomaly and several water sources spatial distribution. The figure reveals a diverse monsoonal circulation that is responsible for water vapor transport to maritime continent. Here, the contributions of each vapor mass to the precipitation and its association to monsoonal circulation are discussed in next sub-section.

Rayleigh’s distillation ratio describing condensation during vapor transport from source region is also discussed (figure is not shown). The ratio is defined as:

$$ f = \left( \frac{\delta_v}{\delta_{vo}} + 1000 \right)^{\alpha-1} $$

where $\delta_v$, $\delta_{vo}$, and $\alpha$ are isotopic water sources just before precipitation, initial isotopic water sources from source region (−9.4 on sea and −10 on land), and fractionation factor (1.0094) (Yoshimura et al. 2003).

Table 1. Coefficient correlation of observed and ICM simulated $\delta D$ and $\delta^{18}O$ composition in precipitation. The italic font indicates the correlation coefficient is significant at 95%.

<table>
<thead>
<tr>
<th>No</th>
<th>Station</th>
<th>Corr. $\delta^{18}O$</th>
<th>RMSE $\delta^{18}O$</th>
<th>n</th>
<th>Corr. $\delta D$</th>
<th>RMSE $\delta D$</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>JAMSTEC</td>
<td>0.39</td>
<td>3.95</td>
<td>55</td>
<td>0.44</td>
<td>34.09</td>
<td>55</td>
</tr>
<tr>
<td>2</td>
<td>JMB</td>
<td>0.75</td>
<td>3.52</td>
<td>52</td>
<td>0.78</td>
<td>29.18</td>
<td>52</td>
</tr>
<tr>
<td>3</td>
<td>MND</td>
<td>0.57</td>
<td>6.53</td>
<td>43</td>
<td>0.56</td>
<td>54.30</td>
<td>43</td>
</tr>
<tr>
<td>4</td>
<td>MKS</td>
<td>0.63</td>
<td>7.21</td>
<td>38</td>
<td>0.66</td>
<td>42.66</td>
<td>37</td>
</tr>
<tr>
<td>5</td>
<td>PLL</td>
<td>0.62</td>
<td>7.43</td>
<td>51</td>
<td>0.63</td>
<td>59.81</td>
<td>51</td>
</tr>
<tr>
<td>6</td>
<td>DPS</td>
<td>0.75</td>
<td>5.11</td>
<td>35</td>
<td>0.78</td>
<td>45.87</td>
<td>35</td>
</tr>
</tbody>
</table>

Fig. 1. Distribution of Japan Agency for Marine-Earth Science and Technology (JAMSTEC; circles) and Global Network of Isotopes in Precipitation (GNIP; triangles) rainwater-isotope sampling stations and the seven regions of tagged-water origin. The sign of cross (X), plus (+), and minus (−) indicate semi-annual, anti-monsoonal, and monsoonal precipitation type respectively.

Fig. 2. Long-term monthly mean of precipitation (clear bars), observed $\delta^{18}O$ (black circles), simulated $\delta^{18}O$ (black square), precipitable water (colored bars), and d-excess (white circles).
et al. 2003). The ratio has a range between 0 and 1 describing there is no condensation during transport if c closes to 1 and vice versa.

3.1 Semi-annual type

The semi-annual precipitation pattern can be observed at GAW and JMB station (Figs. 2a–2b). This pattern is characterized by two peaks of precipitation in every year. Although the precipitation variability over GAW and JMB are low, the first peak can be seen in March (JMB) and April (GAW), while another peak occurs in December. These two peaks are associated with southward and northward ITCZ movement through the tropical area twice a year. The ITCZ movement have been described and simulated by David son et al. (1984) and Chao (2000). The amount effect appeared in these stations indicated by significant correlation between observed precipitation and δ 18O. The δ 18O is defined as 

\[ \delta^{18}O = \frac{R_{obs} - R_{SM}}{R_{SM}} \times 1000 \]

where \( R_{obs} \) is the observed δ 18O and \( R_{SM} \) is the SM δ 18O. The δ 18O from each water source was calculated using the isotopic precipitation and precipitable water from seven water sources region over JAMSTEC and SM has a peak in JJAS (GAW = 0.48 and JMB = 0.70) indicating water vapor more resist to condensate during transport than other months. The positive correlation by SM and SM has a peak in JJAS (GAW = 0.48 and JMB = 0.70) indicating water vapor more resist to condensate during transport than other months. The positive correlation by SM and poor condensation is related to the raise of Australian monsoon indicating dry season and producing enrichment in δ 18O during JJA (Fig. 3b). The significant correlations indicate that in stations affected by the semi-annual pattern, seasonal changes can be characterized by the raise of IO for rainy season and the SM presence for dry season.

Over the western part of the maritime continent, water originating from IO appeared over GAW to the north of Sumatra Island throughout the year (Fig. 2a). Nevertheless, small amounts of water from IO reached JMB during JJAS (GAW = 0.48 and JMB = 0.70) indicating water vapor more resist to condensate during transport than other months. The positive correlation by SM and poor condensation is related to the raise of Australian monsoon indicating dry season and producing enrichment in δ 18O during JJA (Fig. 3b). The significant correlations indicate that in stations affected by the semi-annual pattern, seasonal changes can be characterized by the raise of IO for rainy season and the SM presence for dry season.

Table 2 shows the relationship between observed δ 18O from eight stations and precipitable water amount from seven regions (see Fig. 1) contributing over 10% at least one month per years. This explains Asian and Australian monsoon influence the variability of δ 18O. The IO water source tends to contribute negative correlation corresponding to the Asian monsoon which is responsible for the water vapor transport from Indian Ocean and amount effect process especially during DJF (Fig. 3a). The distillation ratio shows IO condensate during transport with ratio varies about less than 0.5 meaning the water vapor experience condensation during transport and producing low δ 18O. The distillation ratio of SM has a peak in JJAS (GAW = 0.48 and JMB = 0.70) indicating water vapor more resist to condensate during transport than other months. The positive correlation by SM and poor condensation is related to the raise of Australian monsoon indicating dry season and producing enrichment in δ 18O during JJA (Fig. 3b). The significant correlations indicate that in stations affected by the semi-annual pattern, seasonal changes can be characterized by the raise of IO for rainy season and the SM presence for dry season.

3.2 Anti-monsoonal type

The anti-monsoonal pattern can be observed at the PLL station, indicated by a precipitation peak in May (Fig. 2c). There was significant correlation between observed precipitation and δ 18O (\( R_{corr} = -0.46 \)). Table 2 demonstrates that water sources from the south (TM, SM, and SP) have significant correlation with observed δ 18O negatively. In contrast, water source NM contributes positive correlation to isotopic precipitation. The depletion of δ 18O begins in May, accompanied by an increase in vapor originating from south. The heavy rainfall from the south occurs until October and the decreasing in precipitation was accompanied by increasing

Table 2. Correlation coefficient of observed δ 18O of precipitation and precipitable water from seven water sources region over JAMSTEC and GNIP stations.

<table>
<thead>
<tr>
<th></th>
<th>LN</th>
<th>IO</th>
<th>NM</th>
<th>TM</th>
<th>SM</th>
<th>NP</th>
<th>SP</th>
</tr>
</thead>
<tbody>
<tr>
<td>GAW</td>
<td>0.22</td>
<td>-0.27*</td>
<td>-0.09</td>
<td>0.33*</td>
<td>0.23**</td>
<td></td>
<td></td>
</tr>
<tr>
<td>JMB</td>
<td>-0.43*</td>
<td>-0.41*</td>
<td>-0.04</td>
<td>0.13</td>
<td>0.23**</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PLL</td>
<td>0.26**</td>
<td>-0.36*</td>
<td>-0.33*</td>
<td>0.15</td>
<td>-0.37*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MND</td>
<td>0.27**</td>
<td>-0.21</td>
<td>-0.14</td>
<td>0.07</td>
<td>-0.28**</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MKS</td>
<td>-0.68*</td>
<td>-0.54*</td>
<td>-0.60*</td>
<td>0.51*</td>
<td>0.62*</td>
<td>0.67*</td>
<td></td>
</tr>
<tr>
<td>JAK</td>
<td>-0.35*</td>
<td>-0.20*</td>
<td>-0.31*</td>
<td>0.16**</td>
<td>0.35*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DPS</td>
<td>-0.60*</td>
<td>-0.52*</td>
<td>-0.61*</td>
<td>-0.03</td>
<td>0.34*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DAR</td>
<td>-0.37*</td>
<td>-0.47*</td>
<td>-0.53*</td>
<td>-0.62*</td>
<td>0.05</td>
<td>0.11</td>
<td></td>
</tr>
</tbody>
</table>

Note: empty column indicates the water origins contribute fewer than 10% throughout years that is not calculated their correlation. The bold font indicates the correlation coefficient value is significant at 95% (*) and 90% (**) .

![Fig. 3. Spatial distribution of water sources from IO, NP, SP, NM, SM, precipitation and vapor flux anomaly of JRA-25/JCDAS during DJF (a) and JJA (b). The water sources contour interval is 10 mm day\(^{-1}\) and contour color corresponds to the region shown in Fig. 1. Shaded areas (dotted contour) indicate region having precipitation anomaly > 2 mm day\(^{-1}\) (< −2 mm day\(^{-1}\) ). Scale of vapor flux vector is shown in lower right. Stations are shown by their precipitation patterns: semi-annual (circle), anti-monsoonal (triangle), and monsoonal precipitation cycle (square).](image-url)
in $\delta^{18}O$ gradually with distillation ratio varies less than 0.5. This suggests the water vapor experiences condensation from the south through the sea at eastern Sulawesi before arriving in PLL (see vapor flux in Fig. 3b) causing enrichment in $\delta^{18}O$. During November to April, water vapors from the south were absent, resulting in light precipitation and enrichment of $\delta^{18}O$. Water vapor from NM appeared in all months with distillation ratio varies 0.44 to 0.73. The lowest value occurs in May and higher occurs in DJFMA with high ratio correspond to enrichment in isotope. This suggests the characteristics of seasonal changes can be identified by the alternating raise and retreat of water originating from SP, SM, and TM around the anti-monsoonal region as signatures of rainy and dry season. However, the low variability of d-excess in this station is not easily explained by these water origins scheme.

Over the northeast part of maritime continent, water vapor from NP reaches northern Kalimantan Island during DJF (Fig. 3a). The water sources movement coincides with the Indonesian throughflow sea-surface current, which carries cool water from the Pacific Ocean to the sea toward the eastern Sulawesi via northern Irian Jaya (Godfrey 1996). This cool water current sustains the formation of convection (Aldrian and Susanto 2003). This condition is plausible causes of enrichment in $\delta^{18}O$ over PLL. In JJA, the moisture from SP flows toward northern Irian Jaya (Fig. 3b). The raise of SP is also coincided with the small part of the Indonesian throughflow (Gordon and Fine 1996; Aldrian and Susanto 2003). This water vapor is accompanied by a warm surface-sea current generating convective precipitation and produce depletion in $\delta^{18}O$.

### 3.3 Monsoonal type

The monsoonal pattern under strong influence of the Asian and Australian monsoons is observed in MND, MKS, JAK, DPS, and DAR stations (Figs. 2d, e, f, g, h). This region has one peak (trough) during June-July-August (JJA). It has been noted by previous study (e.g. Ramage 1968; Yasunari 1981), this monsoonal pattern covers majority in south equatorial around maritime continent as shown in Fig. 3.

Although MND precipitation is classified as a monsoonal type, $\delta^{18}O$ cannot be easily explained in relation to the amount of precipitation (Fig. 2d). The correlation between observed precipitation and $\delta^{18}O$ was insignificant ($R_{\text{MND}} = -0.24$). This indicates the monsoonal pattern in MND cannot produce an inverse variation of $\delta^{18}O$. The seasonal water origin and $\delta^{18}O$ variation was similar with PLL, especially during May to October. However, the correlation of isotopic precipitation in MND with CMAP (spatial resolution 2.5°) precipitation shows the amount effect can be found more significant in northern to northeastern MND (figure is not shown). Table 2 also shows that significant negative (positive) correlation with SP (NM) which is similar to PLL. This suggests the variability of $\delta^{18}O$ was due to large-scale processes related to the water origin and distillation process identical with PLL. However, low variability of d-excess in MND may not be explained by water origin model.

The correlation between precipitation and $\delta^{18}O$ in the other stations was significant ($R_{\text{MKS}} = -0.64$, $R_{\text{JAK}} = -0.28$, $R_{\text{DPS}} = -0.65$, and $R_{\text{DAR}} = -0.54$), meaning that the amount effect appeared in those stations (Figs. 2e, f, g, h). The water sources from IO and northern part of each station also tend to contribute negative correlation, while water source from southern contribute positive correlation (Table 2). Similar reason with the semi-annual types, this evidence is strongly related to the Asian-Australian monsoon circulation.

The appearance of moisture from NM and IO during DJF indicates a rainy season over the monsoonal stations in the south equator. The northeastern and western wind drives vapor masses from NM and IO to the Java, Bali, Sulawesi Island, and DAR (Fig. 3a). The distillation ratio of IO and NM varies less than 0.4 and appeared in NDJFMA. This evidence shows the condensation during transport corresponds to depletion in $\delta^{18}O$. In JJA, the raise of SM over the southern parts of Indonesia indicates the dry season (Fig. 3b). High distillation ratio from SM (above 0.70) occurs during this month meaning the water vapor is difficult to condensate and corresponds to enrichment in isotope. Most seasonal changes can be characterized by the alternating raise of water vapor from IO + NM (and TM for DAR) for rainy season and SM (except for DAR) for dry season in the monsoonal region, except for MND. The seasonal change of water origin plausibly corresponds to the d-excess variability in MKS. The raise (retreat) of SM coincided with the low (high) values of d-excess. In the dry season, low values of d-excess can occur because of re-evaporation processes during rainout (Datta et al. 1991; Liu et al. 2008).

### 4. Summary

ICM/CMA was applied to JRA-25/JCDAIS and reproduced the simulated stable isotope and water origin. This simulated data was validated by observation data and can be used to clarify the signature of seasonal changes on the basis of the water sources and distillation quantities during transport from surrounding region. However, the simulated isotope values are underestimated and water source model is still difficult to explain d-excess variation in several stations satisfactorily. This unexplained phenomenon may caused by local scale processes such as the re-evaporation of raindrops during rainfall which cannot be accommodated in CMA. However, we are conscious this possibility is still immature and should be examined by more observation.

As documented in the previous study (e.g. Aldrian and Susanto 2003), the majority of maritime continent is affected by Asian-Australian monsoon circulation or ITCZ and there are exception in particular area (anti-monsoonal region). The monsoonal circulation and its influence to isotopic variability can be explained by water origin analytic method in CMA. Generally, the rainout process can explain the isotopic signal. High (low) distillation ratio occurs during Australian (Asian) monsoon and corresponds to high (low) isotopic values in major part maritime continent. As results, the seasonal changes of water origin on three types of annual precipitation were determined.

The semi-annual type stations, represented by GAW and JMB, are influenced by water source from the Indian Ocean for most months of the year. The seasonal changes can be characterized by the raise of water vapor from Indian Ocean in rainy season and from southern maritime continent sea in dry season. The anti-monsoonal pattern located around PLL, northeast maritime continent, obtains moisture mainly from the northern maritime continent sea. The seasonal change of the water source was marked by the alternating raise (retreat) of the water vapor from the Southwest Pacific Ocean, southern and tropical maritime continent sea for rainy (dry) season. The monsoonal precipitation pattern is represented by MND, MKS, JAK, DPS, and DAR. The monsoonal pattern in MND does not result in a typical monsoonal pattern in $\delta^{18}O$ due to large rainout process which is similar to PLL. The other monsoonal stations are located mostly in the south maritime continent. The seasonal changes can be featured by the alternating raise of water sources from Indian Ocean and northern maritime continent sea for rainy season and southern maritime continent sea for dry season in the monsoonal region.

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