Precipitation Stable Isotope Variability in Tropical Monsoon Climatic Zone of Asia

Xia Chengcheng, Liu Guodong*, Hu Yue, Meng Yuchuan

State Key Laboratory of Hydraulics and Mountain River Engineering, College of Water Resource and Hydropower, Sichuan University, Chengdu, China

The corresponding author’s e-mail address: liugd988@163.com

Abstract. The temporal and spatial variability of precipitation stable isotopes in tropical climatic zone of Asia are analyzed based on the data provided by GNIP during the study period, which is from January 2015 to December 2016. Results indicate that the monsoon activities are the major parameters that control the characteristics of precipitation stable isotopes on both temporal and spatial scale. On the annual scale, the extreme values, average values and the variation ranges of $\delta^{18}O$ and d-excess vary considerably among stations, showing differences of the controlling air masses. The monthly variation of $\delta^{18}O$ and d-excess have significant regularities, which are strongly correlated to the distance of water transport and the location of moisture sources respectively. The spatial distribution of stable isotopes in months of different seasons is generally consistent with the tropical monsoon circulation during the four seasons, as values decrease along the path of monsoon flow in summer and winter, and show features of transition periods in spring and autumn as a result of barometric movement. It can serve as a useful tool to contribute valuable information for the research of regional monsoon and water circulation.

1. Introduction

As an important part in the process of vapor transport, precipitation is closely related to oceans, rivers, lakes and glaciers, and plays an important role in the global water circulation. Hydrogen and oxygen stable isotopes are distinctive attributes of water bodies and are sensitive to the environmental change. Therefore, the hydrogen and oxygen stable isotopes have great advantages in reconstructing the historical records of climate and predicting the trends of the climatic and environmental changes, as a unique tracer and indicator for environmental conditions[1]. The studies of stable isotopes in precipitation began in the 1950s, and the technology of hydrogen and oxygen stable isotopes has been widely applied in the research of hydrology, meteorology, ecology and other fields over the past 60 years, which provide important information for the study of the atmospheric circulation model and the mechanism of water cycle[2-6].

South Asia, Southeast Asia and South China are located in the tropical climatic zone, where the directions of prevailing wind vary with seasons, under the influence of seasonal thermal differences between the Pacific, the Indian Ocean and the Asian continent, and the relative position of the planets. The mainlands and islands in these regions are affected by multiple monsoons, and the temporal and spatial variation of moisture sources is very complex. Moisture from the Indian Ocean, the Arabian Sea, the Bengal Bay, the South China Sea and the western Pacific is transported to these regions via different paths. In these regions with complex moisture sources, changes in oceans and atmospheric circulation (e.g., the changes in the movement or SST gradient of the Western Pacific subtropical high)
will lead to the variation of the transport path of moisture and the ratio of moisture from different sources, which result in the changes of composition in precipitation isotopes.

Based on the isotopic monitoring data of 15 GNIP stations set on South China, South Asia and Southeast Asia, this paper assesses the variability of precipitation isotopes with regard to space and time. In addition, the seasonal variation of d-excess and its indicative effect on moisture sources are also analyzed. This may be helpful in revealing the relationship between the characteristics of stable isotopic variation in precipitation and monsoon activities, and providing isotopic evidences for the study of regional water cycle and monsoon circulation.

2. Method and data
Since 1961, the Water Resources Program of the International Atomic Energy Agency (IAEA) and the World Meteorological Organization (WMO) have set up more than 800 precipitation monitoring stations in more than 100 countries around the world, and established the Global Atmospheric precipitation Isotope Network (GNIP). Hydrogen and oxygen stable isotopes and tritium in monthly precipitation at monitoring stations, the recorded corresponding geographic information (longitude, latitude, altitude) and meteorological data (including temperature, humidity, vapor pressure) are measured by GNIP. The collection and transportation of samples comply with strict procedures and standards established by the IAEA, and the analytical work is carried out in the laboratories of the research institutions of the member States. The error of analysis is well controlled. In the past 50 years, GNIP has become an important tool for the study of hydrological and climatic processes at the global and regional scales, especially for the study of the relationship between climate factors and precipitation isotopes[7-8].

To study the spatial and temporal distribution of isotopes in tropical Asia under the influence of monsoon, 15 stations in different countries from GNIP database are selected with the study period from January 2015 to December 2016. Geographic information and numbers of samples (expressed as N) during the study period for each site are shown in Table 1. According to the locations of the selected stations, our study area is divided into five parts: South China (SC), Indochina Peninsula (IP), Malay Archipelago (MA), the north of South Asia (NSA) and the south of South Asia (SSA).

The composition of the hydrogen and oxygen stable isotopes is expressed by relative contrast to the 1000 difference of Vienna standard mean ocean water’s (VSMOW) as the following form:

$$\delta^{18}O (‰) = \left( \frac{R_s}{R_{std}} - 1 \right) \times 1000$$

Where Rs represents the ratio of 18O/16O in precipitation and Rstd represents the ratio of 18O/16O in VSMOW.

The isotopic value of precipitation provided by GNIP is the weighted average of monthly precipitation, and the formula is as follows:

$$\delta_{(w)} = \frac{\sum P_i \delta_i}{\sum P_i}$$

Where $\delta_{(w)}$ represents the precipitation weighted average of $\delta^{18}$O (or $\delta^2$H), $P_i$ represents the precipitation amount of the i-th precipitation event and $\delta_i$ represents the $\delta$ value of the i-th precipitation event.
Table 1. Geographic Information and numbers of samples for each GNIP station during the study period.

| Site                          | Country | Latitude | Longitude | Altitude | Location          | N  |
|-------------------------------|---------|----------|-----------|----------|-------------------|----|
| Dhaka (Savar)                 | BD      | 23.95    | 90.28     | 14       | South Asia        | 21 |
| Barisal                       | BD      | 22.70    | 90.36     | 10       | South Asia        | 22 |
| Hong Kong (King's Park)       | CN      | 114.17   |           |          | South China       | 24 |
| Hanoi (IGS)                   | VN      | 21.03    | 105.84    | 15       | Indochina Peninsula | 20 |
| Dong Hoi                      | VN      | 17.46    | 106.62    | 1        | Indochina Peninsula | 20 |
| Diliman Quezon City           | PH      | 14.64    | 121.04    | 42       | Malay Archipelago | 12 |
| Bangkok                       | TH      | 13.73    | 100.50    | 2        | Indochina Peninsula | 9  |
| Katugastota                   | LK      | 7.33     | 80.62     | 477      | South Asia        | 14 |
| Wellampitiya                  | LK      | 6.95     | 79.87     | 5        | South Asia        | 24 |
| Alor Star                     | MY      | 6.20     | 100.40    | 5        | Malay Archipelago | 22 |
| Kota Bahru                    | MY      | 6.17     | 102.28    | 7        | Malay Archipelago | 22 |
| Kota Kinabalulu               | MY      | 5.93     | 116.06    | 9        | Malay Archipelago | 22 |
| Kuala Terengganu              | MY      | 5.38     | 103.10    | 10       | Malay Archipelago | 21 |
| Kuantan                       | MY      | 3.78     | 103.33    | 1        | Malay Archipelago | 21 |
| Johor Bahru                   | MY      | 1.60     | 103.67    | 35       | Malay Archipelago | 23 |

3. Results and analysis

3.1. Temporal variability of stable isotopes in precipitation

3.1.1. Variability on the annual timescale. For the linear relationship exists between $\delta^{18}O$ and $\delta^2H$, only the variability of $\delta^{18}O$ is focused on in the following discussion. To determine the moisture sources on different time scales, the variation of d-excess (expressed as $d = \delta^2H - 8\delta^{18}O$), which is mainly determined by the surface temperature and humidity of moisture source, is also discussed. The variation ranges and the arithmetic average of $\delta^{18}O$ and d-excess for all the stations are presented in Figure 1. Among stations in the five regions, the maximum $\delta^{18}O$ value is 1.97, which appears in Dhaka, and the minimum $\delta^{18}O$ value is -12.42, which appears in Barisal. The largest variation range of $\delta^{18}O$ appears in Barisal, which is from -12.42 to 0.19, with a difference of 12.61, showing a complex proportion of moisture from different sources on the annual timescale. The smallest range of $\delta^{18}O$ appears in Diliman Quezon City, which is from -7.7 to -1.26, with a difference of 6.44, which indicates the proportion of moisture from different moisture sources is relatively stable.

The values of d-excess also exhibit great seasonal variation in each station. The maximum d value appears in Dong Hoi, which is 21.10, and the minimum d value appears in Alor Star, which is -0.3. The largest range of d appears in Dong Hoi, which is from 1.92 to 21.10, with a difference of 19.18. The smallest range of d appears in Johor Bahru, which is from 6.62 to 12.70, with a difference of 6.08. It can be found that the majority of stations in SSA and MA have smaller variation range than those in other regions. The reason for this feature is due to the locations of stations, those island stations which are surrounded by one ocean and far away from another are strongly affected by the near-source moisture during every season of the year. When the remote-source air mass dominate the region in a given season, the moisture contributed by the near ocean is also considerable because of the surface evaporation along the transport paths, thus the fluctuations are weakened. The arithmetic average of monthly precipitation weighted d values for each station is plotted in Figure 1 by the square symbol. Differences among stations are obvious. The average d values of most stations in NSA, SSA, SC and
IP are slightly higher than 10, which is regarded as the global average level, and the majority of the average values are between 10.5 and 12.5, showing that the moisture from the Indian Ocean and Bengal Bay whose d values are greater than 10 contributes to the precipitation for the most part on the annual timescale. However, the average d values of most stations in MA are below or similar with the global average, which indicates the moisture contribution of the western Pacific Ocean and South China Sea which is characterized by the slightly lower d value than the global average for the annual precipitation is predominant.

Figure 1. Box-plots of δ18O and d-excess in different regions of tropical monsoon climatic zone of Asia. Boxes represent the 25th and 75th percentiles, the median is represented by the line through the box. Whiskers represent the max and min value. The squares in the middle refers to average values of the two years.

3.1.2. Variability on the monthly timescale. The variation of δ18O and d-excess on the monthly timescale are presented in Figure 2. The variation of δ18O in all five regions shows a similar trend in winter and spring of the northern hemisphere. The values begin to increase in November or December, reach the peak in February or March, and then begin to decrease until the valley value occur, indicating that moisture from a same source controls the tropical climatic zone during these two seasons. It can be seen that the peaks of stations in NSA occur before other stations and the peak values of the stations is higher, which demonstrates that NSA is the closest region to the moisture source. The difference between stations in the five regions lies in the variation trend in summer and autumn, when δ18O values of stations in NSA, IP and SC stabilize in the trough, but those of stations in SSA and MA increase and reach a local peak. Based on the different variation regularities, the characteristics of δ18O among stations can be divided into two groups, one includes stations in NSA, IP and SC, and another includes stations in SSA and MA. The result indicates that different moisture sources control the two groups respectively in these two seasons. It is obvious that the value of δ18O in SSA is much higher than that in MA, which is close to 0 and reach beyond 0 at a certain month. The result suggests that SSA is located closer to the moisture source than MA, despite the values of the two stations increase and decrease synchronously. According to the analysis above, it can be identified that moisture from the northern Indian Ocean and the Bengal Bay dominates the tropical climatic zone of Asia during winter and spring, and that from the equatorial area of Indian dominates and the western Pacific Ocean dominates the two groups respectively during summer and Autumn.
The variation of monthly precipitation amount weighted average of d-excess between stations is distinct. In NSA, the d values of stations is relatively low in winter which is usually below 10 and the valley values occur in January or February. For most months in Spring and Autumn, the values are above 10. There exists local valleys in July, August and September, when it is summer in the northern hemisphere. In SSA, the d values in most months plotted above 10, indicating that the region is dominated by the moisture from the Indian Ocean. Lower values which are below 10 only occur in August and September, which could be explained by the influence of moisture from the Pacific and the South China Sea, whose surface humidity above the sea is relatively low. In MA, the monthly average values of d-excess change with a small amplitude, which increase from winter to summer and decrease from summer to winter gradually. The peak values which occur in summer are higher than 10, showing that moisture from the Indian Ocean dominates the region during that season. Similar trends of d values are discovered between stations in IP and SC, where the latitude range is from 13 to 23°. The variation amplitude in the two regions is higher compared with that of other regions, for the sake that moisture from different sources dominate these regions by turns, and the contribution rate of moisture from each source varies from month to month. The values decrease from winter to summer and increase from summer to winter, which is identical with the variation in MA. However, the maximum values of the two regions are much larger than that of MA. The contribution of moisture from local evaporation of surface water with high value of d-excess accounts for this phenomenon when the air mass travels towards the continental area from the sea. It is interesting to find that most points of SC are higher than that of IP when the curve is on the upward trend from March to August, but inverse relationship occurs when the curve is on the downward trend from September to February, which indicates that stations in SC are closer to the moisture source from March to August, and stations in IP are closer during the other months.

3.2. Spatial variability of stable isotopes in precipitation
As the largest continent in the world, the Eurasia has the most typical monsoon feature in the world, under the role of land-sea thermal difference. The spatial distribution of precipitation stable isotopes in different seasons are not similar as a result of monsoon activities, which leads to variational regional circulation characteristics among seasons. Spatial interpolation analysis of δ¹⁸O are taken to further reveal the distribution characteristics of precipitation stable isotopes among different seasons(January, April, July and October in 2015 are selected to stand for the four seasons) using the Kriging Method. The result is shown in Figure 3.

In January, a low value center occurs in the Indian Ocean, with a latitude of about 7.5° and a longitude of about 81°. A high value center occurs in the South China Sea, with a latitude of about 22° and a longitude of about 115°. In general, the δ¹⁸O value is high in high-latitude area and low in low-latitude area, which is contrary to the well-known “latitude effect” caused by the temperature and
precipitation amount decreasing as the latitudes going up. The reason for this is due to the air masses from diverse sources possess different isotopic signals, by which the temperature effect and amount effect are masked. As shown in Figure 2, heavy isotopes deplete gradually along three paths, the first one is from the South China Sea to the southern islands and sea area of the Pacific Ocean, the second one is from the South China Sea to the south Bengal Bay, and the last one is from the northern inland area to the south Bengal Bay. Values are relative depleted in the coast and sea area of the Indian Ocean and the South Bengal Bay than those of the Pacific Ocean at similar latitudes. The main reason is that the former is mainly influenced by winter monsoon blew from inland area which is depleted in heavy isotopes and the latter is influenced by the northeast trade wind from the Pacific Ocean which is relative enriched with heavy isotopes. In July, the $\delta^{18}$O value is high in the equatorial area, and it depletes gradually when it passes over the Pacific Ocean and the Indian Ocean via different paths long southwest-northeast direction. This distinct discrepancy can be explained by the isotopic fractionation accompanied by rainout, when the moist air masses move from the high-latitude area to the low-latitude area forced by southwesterly monsoon. Months of April and October show features of transition periods between summer months and winter months. In April, there exists a high value center in the western Pacific, which in shape extends in a northwest-southeast ward direction and the $\delta^{18}$O values deplete from the high value center towards the northeast and southwest directions. It could be explained by the northward moving of subtropical high in spring. In October, the high value center moves southward and depletes from western Pacific to the high latitude area along northeast direction. The southward movement of atmospheric pressure belt and the prevailing of continental monsoon could may be the causes of this phenomenon. According to the discussion above, the spatial distribution of stable isotopes are generally consistent with the movement of monsoon in each season and can be used as a useful tool to reflect the characteristics of monsoon flow field in this area.

Figure 3. The spatial distribution of precipitation weighted mean values of $\delta^{18}$O in tropical monsoon climatic zone in different months: (a) January(standing for winter season), (b) April(standing for spring season), (c) July(standing for summer season) and (d) October(standing for autumn season).
4. Conclusion
In this paper, temporal and spatial variability of precipitation stable isotopes in 15 stations of tropical monsoon climatic zone are discussed. Based on the geographic position, the study area is divided into five regions. On the annual timescale, the variation of δ\(^{18}\)O and d-excess in one region are similar as a whole but differences between regions are distinct, which reflect complexity of the distance of air masses transport and moisture sources. The characteristics of δ\(^{18}\)O on the monthly timescale are divided into two groups according to the variation regularities. The difference between the two groups lies in summer months, when the curves of stations in the two groups show reverse trends, which can be explained by the influence of different moisture sources. When the trends are similar, size differences between regions are a result of diverse distance from the moisture source, which is directly correlated with the rainout histories of air masses before reaching a given region. The values and variation amplitude of d-excess are due to the dominate air masses. The spatial distribution of precipitation stable isotopes in different seasons has great correlation with monsoon activities, which always decreases on the moving direction of monsoon owing to the fractionation caused by precipitation along the paths.

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