Analysis of Variation Characteristics and Driving Factors of Precipitation Isotopes in the Monsoon Region of Offshore China—A Case Study of Hong Kong

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Abstract: To explore the isotopic composition of precipitation in the monsoon region of offshore China, this paper takes Hong Kong, China as the study area. Based on the Global Network of Isotope in Precipitation (GNIP), the data about hydrogen and oxygen stable isotopes in the precipitation of Hong Kong from 1961 to 2022 were collected, from which its time variation trend was obtained via linear regression. Further, the distribution characteristics and influencing factors of hydrogen and oxygen stable isotopes in the precipitation of Hong Kong were analyzed. According to the results, the precipitation isotopes and d-excess in Hong Kong have no significant inter-annual variability. The seasonal variation of precipitation isotope and d-excess is monthly apparent, both of which are lower in the rainy season and higher in the dry season. In addition, the seasonal periodicity of isotope and d-excess proves that the main source of precipitation is marine water vapor, and the source of water vapor controlling precipitation in Hong Kong remains stable as a whole. The global meteoric water line in Hong Kong is δD=8.17δ18O+11.82, which is very close to the global one. Meanwhile, δ18O in precipitation is negatively correlated with the temperature, precipitation, and water vapor pressure. As the main driving force to control its isotope variation, precipitation conceals the effect of temperature. Taking Hong Kong as an example, the above research reveals some characteristics of monsoon regions in offshore China, which is of positive significance for further investigating the influencing factors of the hydrologic cycle and isotope change at regional and local scales in the future.

Keywords: Atmospheric Precipitation; Hydrogen and Oxygen Stable Isotope; Hong Kong; Local Meteoric Water Line; d-excess

1. Introduction

Water resources are related to all aspects of human activities with a crucial impact on the economy and environment. However, with the growth of the world population and the advancement of industrialization and urbanization, problems about global hydrology and water resources are exacerbating. For example, shortage of water resources, destruction of water ecology, and waste of water resources all over the world have brought serious loss on human production and life, posing great challenges to the sustainable development of human society in the future (Mishra, 2023). As for problems with water resources in China, there is uneven spatio-temporal distribution of water resources, limited per capita possession, serious water pollution and waste, etc. With the continuous development of China, the adverse effects triggered by them have become increasingly prominent, leading to more frequent and serious extreme meteorological events such as drought, flood, and sea level rise in some areas. At the same time, greater challenges have been imposed on the management and protection of local water resources (Zhang et al., 2023, Ju et al., 2023). Nowadays, with more attention paid to climate change and water resources management, it is particularly imperative to foster an in-depth understanding of the hydrologic cycle mechanism.

As the input of the water cycle, precipitation as a vital part is the initial source of land water resources. Considering climate and environmental changes will affect the abundance and ratio of hydrogen and oxygen isotopes in precipitation, observation of this change enables people to perceive the geochemical and hydrologic cycle (Dansgaard, 1964). H-O stable isotopes are the inherent composition of water molecules, which will be fractionated in different degrees due to humidity, temperature, and evaporation in the water vapor circulation. Because of the mass variation, H-O stable isotopes will show diverse enrichment rates in the phase transition. In other words, water molecules containing light isotopes such as ^{1}H and ^{16}O preferentially enter the gas phase, while water molecules containing ^{2}H and ^{18}O tend to enrich in the liquid phase due to their heavier mass (Clark I D, 1997). For this reason, H-O stable isotopes of precipitation in nature are intertwined with temperature, precipitation, elevation, continent, latitude, and other factors (Dansgaard, 1964). Abundant meteorological and hydrologic information can be obtained through H-O stable isotopes of precipitation (Gu, 2011), such as retrieving atmospheric circulation process (Dansgaard, 1953), tracing water vapor sources (Araguás-Araguas et al., 1998), judging regional weather and climate characteristics (Zhang and Yao, 1994), etc.

In 1958, the Global Network of Isotope in Precipitation (GNIP) was initiated by the International Atomic Energy Agency (IAEA) and the World Meteorological Organization (WMO), which launched operations in 1961. It continuously monitors and tracks the stable isotope composition of precipitation and records the changes in meteorological indicators synchronously, which provides a data basis for the study of stable isotopes in precipitation and the water cycle. Craig (1961) analyzed the δD and$\delta^{18}O$ data from lakes, rivers, and atmospheric precipitation, which found that their linear relationship exists. In 1961, he put forward the Global Meteoric Water Line (GMWL): $\delta D = 8\delta^{18}O+10$. Chinese research on stable isotopes in atmospheric precipitation is relatively late, which began with the scientific investigation of Mount Everest in 1966 (Zhang et al., 1973). At present, many scholars have studied the stable isotopes of precipitation and the sources of water vapor in various regions of China, with copious achievements made in the Loess Hilly and Gully Region (Zhang et al., 2019), Haihe River Basin (Wang, 2014), northwest arid region (Huang et al., 2015, He et al., 2018, Chang et al., 2019), Yangtze River Basin (Chen et al., 2011, Wang et al., 2019), and eastern monsoon regions (Wang, 2012).

The monsoon region in offshore China is one of the most representative monsoon-affected regions in Asia, whose precipitation changes have a critical impact on agriculture, water resources, and the ecological environment in China and its neighboring countries. In offshore China, water shortages, especially during the dry season, result from an already limited supply that is unable to meet the increasing demand for domestic, agricultural, and industrial water because of urbanization and rapid population growth. Rising temperatures and changes in precipitation patterns as well as sea-level rise further deteriorate water shortages, increase the risk of coastal flooding, and endanger the sustainability of water resources. Although there have been some studies on the variation of precipitation in the monsoon region of offshore China, the understanding of its isotopic characteristics and driving factors is still insufficient. In this region, isotope study can provide us with significant clues about precipitation water source, precipitation formation mechanism, and atmospheric movement. Taking Hong Kong located in the monsoon region of offshore China at the GNIP as an example, this paper aims to profoundly analyze the variation characteristics and driving factors of precipitation isotopes in the monsoon region of offshore China, so as to deepen the understanding of regional water cycle, provide reference for the application of stable isotopes to trace water vapor sources in monsoon climate region, and lays theoretical basis for the optimal development of water resources and water risk management in the future.

2. General Situation of the Study Area

Hong Kong (22°09'-22°38'N，113°50'-114°31'E) is a special administrative region on the eastern coast of the Pearl River Delta of China, facing Macao across the sea in the west, Shenzhen in the north, and Wanshan Islands in Zhuhai in the south. With an important geographical location as shown in Figure 1, it is a vital hub for the connection between mainland China and overseas. Hong Kong consists of Hong Kong Island, Kowloon Peninsula, and New Territories Islands, with a total area of 1106km^2. With many kinds of rocks in Hong Kong, there are great ups and downs and complex terrain, including mountains, hills, plains, and coasts, among which mountains and hills occupy most of the land as seen in Figure 1. In addition, Hong Kong has numerous islands, bays, and ports, constituting a unique coastline.

Located at the junction of tropical and subtropical regions, Hong Kong has a typical monsoon climate that features a hot and humid summer and a relatively cool winter with abundant rainfall. Its average annual precipitation is about 2000mm, mainly concentrated in summer. As for its temperature, the average temperature for many years is about 23℃, the average temperature in summer is about 30℃, and the average temperature in winter is about 15℃. Under the influence of monsoon, the climate of Hong Kong can be divided into obvious dry and rainy seasons. The rainy season is usually from May to October, during which Hong Kong is affected by the warm and humid southeast monsoon, and the airflow with abundant water vapor rises from the ocean. When encountering terrain barriers such as mountains and hills, it is easy to form a large-scale convective cloud cluster, which leads to continuous precipitation. The dry season generally lasts from November to April of the following year, during which Hong Kong is affected by the northern monsoon, the airflow is relatively dry, and the precipitation is remarkably reduced. Meanwhile, Hong Kong is influenced by typhoons all year round with May to September as its typhoon season every year, which is prone to extreme weather such as severe storms.

Hong Kong is a highly developed city with a large population which is about 7.43 million, according to the pertinent data in 2021. As an international financial, commercial, and shipping center, Hong Kong is advanced in economic development, whose pillar industries include financial services, trade, tourism, and shipping. Due to the high degree of urbanization, Hong Kong also faces some environmental problems, such as air pollution, garbage disposal, and land use (Ma et al., 2023).

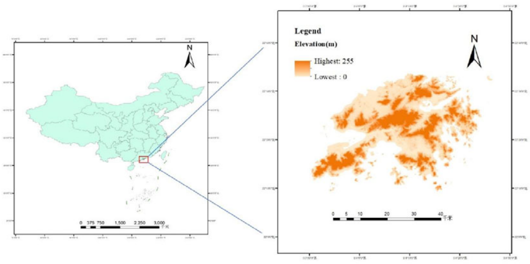

Figure. 1 Geographical Location and Elevation Distribution Characteristics of Hong Kong

3. Data Sources and Research Methods

3.1 Data Sources

In this study, Hong Kong, China was selected as the study area and its isotope data from 1961 to 2022 were obtained by the GNIP (https://www.iaea.org/services/networks/GNIP). Some meteorological data including precipitation, temperature, and water vapor pressure were accessed by GNIP, the other by NASA. Besides, topographic data and land cover data were obtained by the Resource and Environment Science and Data Center of the Chinese Academy of Sciences. GNIP was established in 1960 by IAEA in cooperation with WMO, which is a global network monitoring the hydrogen and oxygen isotope in precipitation. The network uses appropriate standards and precautions to ensure reliable isotope data and standardizes methods to prevent evaporation, taking into account the representative nature of samples when establishing stations. Stable isotope measurement is usually implemented by isotope ratio mass spectrometry and laser absorption spectrometry. Sampling equipment such as rainwater collectors, burial samplers, sample bottles, and basic laboratory equipment also follow specific error control methods, which can guarantee data accuracy to a great extent. The analysis accuracy of $\delta^{18}O$ and δD in the monitoring network of GNIP is $\pm 0.1‰$ and $\pm 1‰$.

3.2 Research Methods

Since the content of ^{18}O and D in nature is tiny, the relative value (δ) is used to express the content of ^{18}O and D. δ is the deviation in thousandths of the concentration of heavy isotopes (^{18}O and D) in water samples relative to the Vienna Standard Mean Ocean Water (V-SMOW):

$$\delta_{sample} = [\frac{R_{sample}-R_{VSMOW}}{R_{VSMOW}}] \times 1000(‰) \quad (1)$$

Rsample and R_{VSMOW} are the ratios of D/H or ^{18}O /^{16}O in the sampled water and V-SMOW respectively. When δ in the meteoric water sample is negative, the isotope ^{18}O or D of the water sample is depleted relative to the standard. On the contrary, when δ is positive, the isotope ^{18}O or D of the water sample is enriched relative to the standard.

The calculation of the monthly (annual) weighted average value of isotopes is to use a statistical method, with monthly (annual) precipitation taken as the weight item to carry out weighted average treatment on stable isotope data in precipitation. The calculation method is as follows:

$$\overline{\delta} = \frac{\sum P_i \delta_i}{\sum P_i} (‰) \quad (2)$$

δ_i is δ of the precipitation sample with the i-th precipitation P_i, and the precipitation P_i is the weight. If δ is the monthly average eigenvalue, the denominator is the monthly precipitation. If δ is the annual average eigenvalue, the denominator is the annual precipitation.

As for the stable isotope $\delta^{18}O$ and δD in precipitation, the scatter points ($\delta^{18}O$ and δD) plotted on the coordinate system are used for linear regression, and the least square method (LSR) is used for analysis and calculation, so as to obtain the linear correlation between $\delta^{18}O$ and δD in local precipitation. Besides, its equation is the local meteoric water line (LMWL).

To determine the environmental factors affecting the stable isotope variation in atmospheric precipitation, the correlation between precipitation isotope and environmental factors was established based on analyzing its seasonal and inter-annual variation characteristics. Premised on the least square method, the regression analysis of the relationship between precipitation isotope composition and environmental factors such as precipitation, temperature, and water vapor pressure is implemented by Origin 2022. Meanwhile, the significance test is used to judge whether there is a positive or negative correlation with a confidence level above 95%.

4. Results and Discussion

4.1 Temporal Variation of Hydrogen and Oxygen Stable Isotopes in Precipitation

4.1.1 Inter-annual Variation Characteristics of Isotopes

Based on the isotope data obtained by GNIP, the change of $\delta^{18}O$ annual weighted average of atmospheric precipitation in Hong Kong from 1961 to 2022 is shown in Figure 2. The range of $\delta^{18}O$ varied from -9.58‰ to -4.39‰ and the multi-year average value was -6.60 ‰. Moreover, the maximum and minimum appeared in 1987 and 1999 respectively, the standard deviation was 1.02‰, and the coefficient of variation (CV) was -15.46%. The annual weighted average value of δ D in atmospheric precipitation is shown in Figure 3, which ranges from -66.3 ‰ to -27‰ with -42.45‰ as the multi-year average value. The maximum and the minimum appeared in 1987 and 1999 respectively, the standard deviation is 8.31‰, and the CV is -19.58%. The CV of the weighted mean values of $\delta^{18}O$ and δD is small, which reflects that the source of water vapor in Hong Kong is relatively stable, resulting in a small fluctuation of values. By analyzing the data of $\delta^{18}O$ and δD, it is found that the arithmetic average values of $\delta^{18}O$ and δD from 1961 to 2022 were -4.93‰ and -28.49‰ respectively. There is a big difference between this value and its weighted average for many years, which indicates the significant influence of rainfall effect in Hong Kong. The heavy isotope depletion of the events with heavy rainfall and its high weight in the calculation of the weighted average make the weighted average far less than the arithmetic average. The stable isotope δD of global precipitation ranges from -350‰ to 50‰, and $\delta^{18}O$ ranges from -50‰ to 10‰, with their arithmetic average values of -22‰ and -4‰ respectively. The contents of δD in atmospheric precipitation monitored by stations in China range from -210‰ to 2.0‰, and that of $\delta^{18}O$ range from -24‰ to 2.0‰, with their arithmetic average values of -50‰ and -8‰ respectively. The values of hydrogen and oxygen isotopes in atmospheric precipitation measured by the Hong Kong monitoring station are within the fluctuation range of precipitation isotopes in the whole world and China. In addition, the arithmetic mean values of $\delta^{18}O$ and δD for many years are obviously higher than the national average values, which is related to the geographical feature that the station is close to the ocean.

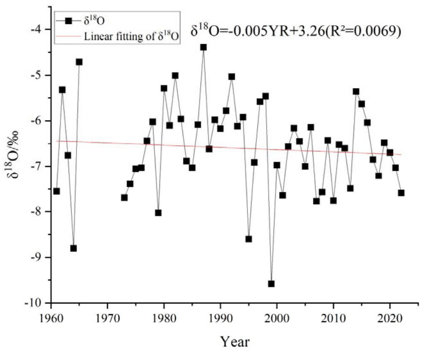

Figure. 2 Variation Trend of Annual Weighted Average Value of $\delta^{18}O$ in Precipitation at Hong Kong Station From 1961 to 2022

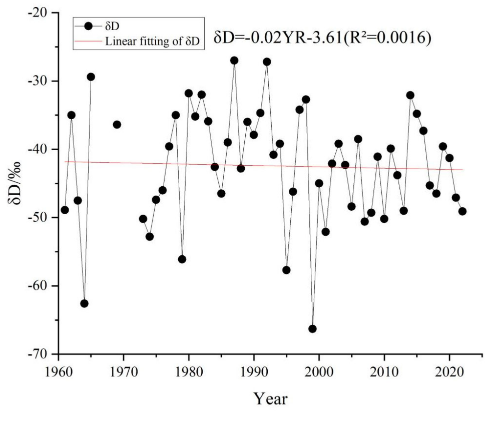

Figure. 3 Variation Trend of Annual Weighted Average Value of δD in Precipitation at Hong Kong Station From 1961 to 2022

Combined with Figure 2 and Figure 3, it can be seen that the inter-annual variation trends of $\delta^{18}O$ and δD in Hong Kong are consistent, which proves that the fluctuations of two isotopes are generally affected by the same environmental factors and the change range from 2000 to 2022 is small. Linear fitting of $\delta^{18}O$ and δD as seen in Figure 2 and Figure 3 shows that the linear equation of $\delta^{18}O$ is $\delta^{18}O=-0.005YR+3.26$ ($R^2=0.0069$), and that of δD is $\delta D=-0.02YR-3.61$ ($R^2=0.0016$). Based on the significance test of these two isotopes over time, it is found that their p are both above 0.05. The results manifest that the variations of the two isotopes are not significant at a 95% confidence level inter-annually.

According to Figure 4 which reflects the inter-annual variation of precipitation and temperature, the trend of precipitation has no obvious change, but the temperature has an increasing trend year by year. The linear equation obtained by linear fitting of temperature is $T=0.01YR+1.84$ ($R^2=0.17$). Comparing the linear equations of $\delta^{18}O$ and δD, it can be found that their slope signs are opposite. The time variation trend of temperature-year was tested, and the p was found to be lower than 0.05. Results prove that there was a significant upward trend of air temperature during the observation period. At the same time, combined with the variation trends of $\delta^{18}O$ and δD, it could be seen that the increase in temperature did not directly lead to the enrichment trend of isotopes at the annual scale. It was speculated that the reason for this result might be that the station was greatly affected by the precipitation effect.

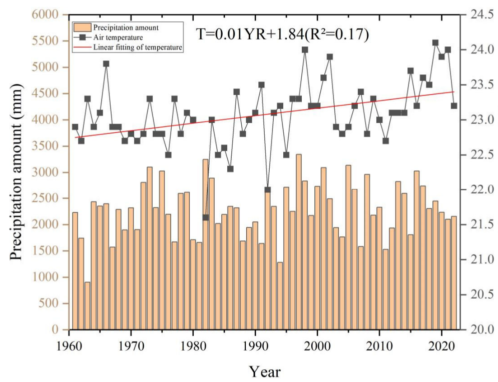

Figure 4 Variation Trend of Average Annual Temperature and Annual Precipitation at Hong Kong Station From 1961 to 2022

4.1.2 Seasonal Variation Characteristics of Isotopes

The monthly average variation characteristics of δD and $\delta^{18}O$ in Hong Kong from 1961 to 2022 are shown in Figure 5. The stable isotope δD of atmospheric precipitation in each month varies from -52.5‰ to -5.4‰, with an average value of -27.46‰ and a CV of -64.48%. The value of $\delta^{18}O$ ranged from -7.74‰ to 2.47‰, the average value was -4.815‰, and the CV was -43.05%. The CV of δD and $\delta^{18}O$ can be found to be larger on the monthly scale, which indicates that the seasonal variation of water vapor sources in Hong Kong is large due to the influence of multiple monsoons in a year.

Figure 5 shows that the variation patterns of δD and $\delta^{18}O$ on the monthly scale also have high synchronization, with the maximum of δD and $\delta^{18}O$ in February and the minimum in August. On the whole, the contents of the two isotopes were depleted in the rainy season (the mean values of δD and $\delta^{18}O$ were -42.87‰ and -6.63‰ respectively) and enriched in the dry season (the mean values of δD and $\delta^{18}O$ were -12.05‰ and -3‰ respectively). The contents of δD and $\delta^{18}O$ increased

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slightly from January to February, decreased rapidly from March to August, and rose rapidly from August to December. Combined with their larger CV, this phenomenon further reflected the obvious seasonal variation of δD and $\delta^{18}O$.

The obvious seasonal difference of the monthly annual mean values of δD and $\delta^{18}O$ in Hong Kong may be related to the water vapor cycle. In the rainy season, Hong Kong is dominated by the southeast monsoon and affected by the southwest monsoon. During this period, precipitation is mainly controlled by ocean water vapor, while the values of δD and $\delta^{18}O$ in ocean water vapor are slightly depleted (Zhang, 2020), which leads to the low values of δD and $\delta^{18}O$ in this period. The dry season in Hong Kong is dominated by the northern inland monsoon, and the isotopes of the inland air mass are often richer than those of the marine air mass, providing higher δD and $\delta^{18}O$ in this period. May and October are the transition periods of the two types of monsoons, during which the isotope values of δD and $\delta^{18}O$ are in the middle position throughout the year.

In addition, the period from May to September is the typhoon season in Hong Kong every year, and typhoons passing through the ocean will carry a large amount of water vapor. At the same time, the low-pressure area will make the water vapor in the air liquefy more easily, thus forming a wide range of rainfall in the local area. As a result, δD and $\delta^{18}O$ decreased continuously from May to August, and the significant increase of δD and $\delta^{18}O$ in October may be related to the gradual weakening of the typhoon influence on Hong Kong.

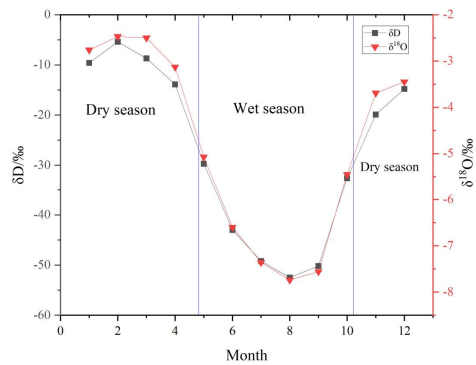

Figure. 5 Variation Trend of Monthly Average Value of δD and δ18O of Hong Kong Station From 1961 to 2022

4.2 Temporal Variation Characteristics of d-excess at Hong Kong Station

4.2.1 Inter-annual Trend of d-excess

d-excess, expressed as $d=\delta D-8\delta^{18}O$ (Dansgaard, 1964), is a derivative index used to reflect the deviation degree of the ratio of D and 18O isotopes from the relative equilibrium state in water, which can describe the source and circulation of water. The value of d is positively correlated with the temperature of the water vapor source and negatively correlated with the relative humidity, which is affected by the precipitation formed by the local water vapor cycle (Yang, 2010) and the degree of secondary evaporation under the cloud (humidity condition) (Aragoás-Aragoás et al., 1998). The global average precipitation d value is about 10‰.

The inter-annual variation trend of d-excess at Hong Kong station from 1961 to 2022 is shown in Figure 6. The weighted average value of d-excess varied from 6.3‰ to 14.8‰, and the multi-year average value was 10.41‰. Besides, the maximum and the minimum appeared in 1965 and 1974 respectively, with a standard deviation of 1.71 ‰ and a CV of 16.41%. The observed data show that the CV of d-excess is small, which indicates that the meteorological conditions of water vapor source and evaporation characteristics of precipitation place in Hong Kong are relatively stable on an annual scale. In addition, Hong Kong's multi-year arithmetic average of 10.93‰ is slightly higher than the global average of rainwater d. The arithmetic mean of d-excesses for many years in Hong Kong also proves that the precipitation due to ocean water vapor is dominant in all precipitation because the d-excesses of precipitation due to ocean water vapor are close to 10‰ (Craig, 1961, Dansgaard, 1964).

Linear fitting is implemented on the change of the annual weighted mean value of d-excess over time as shown in Figure 6, and the linear relationship equation between d-excess and year is d-excess=0.017YR-23.69 (R^2=0.029). The variation of d-excess over the years is tested and the result is $p>0.05$, which also reflects that the meteorological conditions of water vapor sources failed to change significantly from 1961 to 2022, that is, the water vapor sources controlling precipitation in Hong Kong remained stable as a whole.

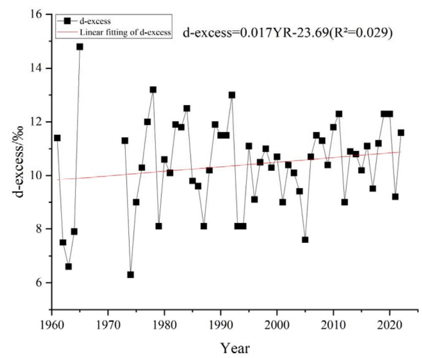

Figure. 6 Inter-annual Variation Trend of d-excess in Hong Kong Station From 1961 to 2022

4.2.2 Seasonal Periodic Characteristics of d-excess

Based on Figure 7 showing the variation characteristics of the monthly average value of d-excess in Hong Kong from 1961 to 2022, the variation range of d-excess value is 9.2‰~14.3‰, with the maximum in February and the minimum in November. The variation range is small with 11.03‰ as its average value, close to the average d in global precipitation of 10‰. According to Figure 7, the average d value in Hong Kong varies with time, which increases from January to February, gradually decreases from March to July, and increases from August to December with fluctuation.

The average value of d in the rainy season in Hong Kong is 10.08‰. The dry season lasts from November to April of the following year, during which the average d is 11.98‰. Compared with the dry season, the humidity of the water vapor source in Hong Kong in the rainy season is higher with lower temperature slower evaporation process, which leads to a lower d-excess of water vapor.

The average values of d in spring from March to May, summer, autumn, and winter are 11.3‰, 9.63‰, 10‰, and 13.2‰ respectively. The average values of d in spring are slightly higher and the lowest in summer, while it is equal to those in global precipitation in autumn and the highest in winter. Comparing the data, the seasonal variation characteristics of d are obvious.

The characteristics of the monsoon climate in Hong Kong can be seen from the change in d value: the d value in spring is slightly higher, which reflects that part of precipitation water vapor comes from continental water vapor. The d value is the lowest in summer, which indicates that the precipitation water vapor mainly originates from the warm and humid air mass produced by the low latitude ocean, and also reveals a certain secondary evaporation under the cloud in Hong Kong in summer, leading to the low d value. The d value in autumn shows that marine water vapor is dominant in precipitation water vapor. The highest d value in winter indicates that the influence of secondary evaporation on precipitation isotopes in Hong Kong is very weak and the main source of winter precipitation is continental water vapor.

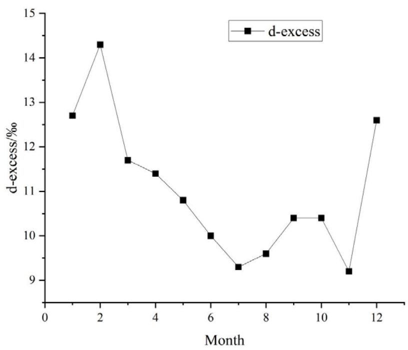

Figure 7 Change Trend of Monthly Average Value of d-excess in Hong Kong Station From 1961 to 2022

4.3 Characteristics of Local Meteoric Water Line at Hong Kong Station

The meteoric water line refers to the correlation line between stable isotope δD and $\delta^{18}O$ composition in meteoric water. Its slope reflects the difference in fractionation rate between D and ^{18}O, while the intercept reflects the deviation of D from the equilibrium state (Peng et al., 2010). Therefore, the precipitation line can be used to trace the precipitation source, judge the response of the hydrologic process to the climate system, and determine the characteristics and variation laws of the water cycle in the study area.

Based on the isotope data from GNIP, a linear regression method was used to establish water lines for all isotope sites during the Hong Kong observation period as shown in Figure 8(a). Their linear regression equation them $\delta D=8.17\delta^{18}O+11.82$ ($R^2=0.97$). The higher determination coefficient R2 indicates that the correlation between δD and $\delta^{18}O$ is better. The global meteoric water line proposed by Craig (1961) is $\delta D=8\delta^{18}O+10$. It can be seen from Figure 8(a) that the meteoric water line in Hong Kong is very close to it, indicating that the rainfall in Hong Kong is controlled by ocean water vapor as a whole, and isotopes in raindrops are mainly equilibrium fractionated when the annual-scale falling water is formed. As reported in previous studies, the slope and intercept of the local meteoric water line in southern China are too large. For example, the meteoric water line equation in Xiamen is $\delta D=8.16\delta^{18}O+10.68$ (Wu et al., 2012), and that in Nanjing is $\delta D=8.47\delta^{18}O+17.52$ (Wang et al., 2013). The slope and intercept of local meteoric water lines in northwest and northeast China are relatively small. Some scholars have proposed that the meteoric water line equation in the northwest arid area is $\delta D=7.24\delta^{18}O+1.96$ (Li et al., 2012a) and that in the northeastern area is $\delta D=7.20\delta^{18}O-2.39$ (Li et al., 2012b). By observing the above atmospheric precipitation line equation, it can be found that the slope and intercept of meteoric water line in Hong Kong are closer to those in southern China, which reflects that Hong Kong has the climatic characteristics in southern China to a certain extent, affected by similar climate system, water vapor transport path, and precipitation process. Compared with the meteoric water line equations in northwest and northeast China, it is found that the slope and intercept of the meteoric water line in Hong Kong are higher, which is because Hong Kong is located in the coastal area, closer to the source area of water vapor, which has a short migration distance along the way without strong leaching (Gao et al., 2017). Furthermore, it is also because the secondary evaporation under clouds experienced during the precipitation falling in Hong Kong is relatively weak. In addition, the slopes and intercepts of LMWL in a 17-year time scale drawn by Zhang Lin (2009a) based on isotope data of Hong Kong precipitation from 1986 to 2002 in the GNIP data set are 8.13 and 11.39 respectively. Meanwhile, Yang et al. (2022) obtained LMWL slopes and intercepts of 8.26 and 12.65 respectively in a 21-year time scale based on GNIP precipitation data from 1996 to 2016, which are in proximity to the slopes and intercepts of Hong Kong meteoric water line from 61-year data in this study. This result indicates that the water vapor source of Hong Kong precipitation is relatively stable in a longer time scale from another perspective.

According to Figure 8(b), the meteoric water line equations for dry and rainy seasons in Hong Kong are $\delta D=7.69\delta^{18}O+11.07$ and $\delta D=8.00\delta^{18}O+10.08$ respectively. The slope of meteoric precipitation in the dry season in Hong Kong is smaller than that in the rainy season. This is because the dry season is mainly affected by the northern inland monsoon, with less precipitation and low humidity, which puts the atmospheric water vapor content in an unsaturated state. The non-equilibrium fractionation caused by the strong secondary evaporation effect under clouds will reduce the slope of LMWL. The intercept of the dry season in Hong Kong is higher than that of the rainy season, which indicates that relative to the rainy season, the humidity in the formation of water vapor mass in the dry season in Hong Kong is lower, the dynamic fractionation is stronger, and the contribution of local recycled water vapor in precipitation air mass is greater. Comparing the meteoric water lines in dry and rainy seasons in Hong Kong with the global meteoric lines, it is found that the slope in dry season is low, and the slope in rainy season is almost consistent with the global one, which indicates that the precipitation in dry season comes from sources with different stable isotope ratios, while the precipitation in rainy season mainly comes from marine water vapor.

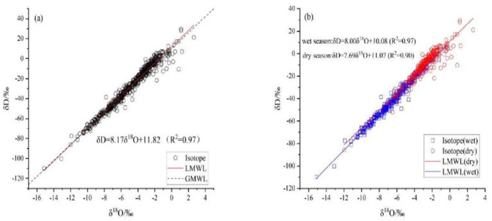

Figure. 8 Characteristics of Local Meteoric Water Line at Hong Kong Station. (a) Annual Local Meteoric Water Line; (b) Local Meteoric Water Line in Rainy and Dry Seasons

4.4 Analysis of Influencing Factors of Isotope Variation at Hong Kong Station

4.4.1 Precipitation Effect

The composition of stable isotopes in precipitation is intertwined with precipitation, and the negative correlation between stable isotopes and precipitation is called the precipitation effect. Its essence is a "leaching", that is, due to the difference in fractionation rates between light and heavy isotopes, the heavy isotope content in the remaining water vapor of the air mass will continue to decrease after multiple precipitation processes (Li et al., 2010). Some studies have shown that the exchange between raindrops and environmental water vapor and the evaporation effect will have a certain impact on the formation of rainfall effect (Dansgaard, 1964).

The data of $\delta^{18}O$ and precipitation in Hong Kong during the selected period are divided into three groups according to time, namely 1961-1981, 1982-2002, and 2003-2022. The correlation between the two groups is shown in Figure 9. It can be found that $\delta^{18}O$ and precipitation in Hong Kong in different periods are negatively correlated. The linear equations of atmospheric precipitation $\delta^{18}O$ and P in three periods in Hong Kong are obtained by linear fitting respectively: $\delta^{18}O=-0.01P-2.75$ ($R^2=0.51$), $\delta^{18}O=-0.007P-3.41$ ($R^2=0.31$), $\delta^{18}O=-0.008P-3.41$ ($R^2=0.42$)。

Comparing the above linear equations of atmospheric precipitation $\delta^{18}O$ with precipitation P, it can be found that the slope and R^2 are not much different. According to this result, the climate model in Hong Kong is relatively stable, and the influence of ocean temperature and atmospheric circulation is relatively constant on the one hand. On the other hand, the meteorological system or seasonal meteorological model in the surrounding areas has not changed significantly in various years. The significance test of the above three data groups shows that P values are all less than 0.01, indicating that the precipitation effect is significant.

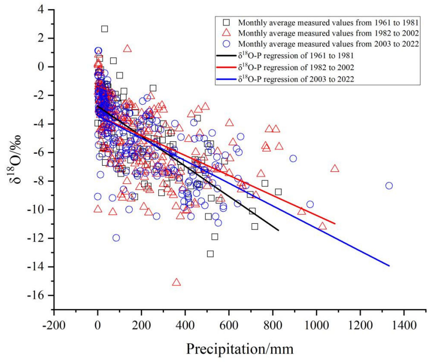

Figure. 9 Relationship Between $\delta^{18}O$ and Precipitation in Different Periods

4.4.2 Temperature Effect

Studies have shown that temperature is more closely related to precipitation isotopes than precipitation, altitude, and latitude, which affect the isotopic composition of rainwater (Yapp, 1982). The fractionation coefficient α in the Rayleigh fractionation equation will be affected by temperature. The higher the temperature, the greater the α, and the higher the content of heavy isotopes in precipitation. That is to say, there is a positive correlation between temperature and isotope composition of precipitation, which is called the temperature effect (Dansgaard, 1964).

The correlation between monthly mean $\delta^{18}O$ of atmospheric precipitation and monthly mean temperature in Hong Kong from 1961 to 2022 is shown in Figure 10. It can be found that $\delta^{18}O$ decreases with the increase of temperature. Linear fitting between atmospheric precipitation $\delta^{18}O$ and air temperature in Hong Kong indicates that the linear equation is δ18O=-0.37T+3.86 ($R^2=0.44$). The results show that there is a negative correlation between $\delta^{18}O$ and air temperature, that is, the temperature effect does not exist in this study area, and even an "anti-temperature effect" appears. The reason lies in the change of water vapor source caused by monsoon switching, and the seasonal periodicity of isotopes in initial water vapor makes the isotope composition low in summer and high in winter. In addition, due to the influence of monsoon activity, the seasonal variation characteristics of precipitation and temperature are consistent, while the correlation between the two parameters and isotopic composition is opposite. In low latitudes, the "precipitation effect" is the more important controlling factor for isotopes, which may mask the influence of temperature.

Studies have shown that $\delta^{18}O$ values in precipitation are negatively correlated with temperature in many areas affected by the monsoon in China, which is contrary to the temperature effect (Liu et al., 1997). Zhang Xinping pointed out that the temperature effect in China mainly occurs in the middle and high latitudes, especially in inland areas (Zhang et al., 2009b). According to the above research, the "anti-temperature effect" observed in Hong Kong is consistent with the laws obtained by previous studies based on China's national and regional scales.

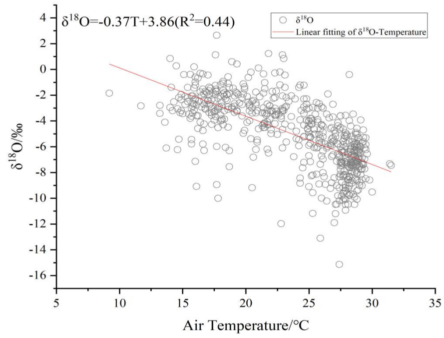

Figure. 10 Relationship Between $\delta^{18}O$ and Temperature in Precipitation

4.4.3 Correlation with Water Vapor Pressure

As an exponential standard used to measure the dryness and wetness of the atmosphere, water vapor pressure is positively correlated with relative humidity. In an unsaturated atmosphere, due to evaporation during raindrop falling, isotopes are more likely to undergo dynamic fractionation, which leads to the enrichment of heavy isotopes. The lower the water vapor pressure, the lower the atmospheric saturation, the stronger the secondary evaporation effect under the cloud, and the richer the isotope composition.

According to Figure 11 showing the relationship between $\delta^{18}O$ and water vapor pressure in precipitation in Hong Kong, $\delta^{18}O$ decreases with the increasing water vapor pressure. The linear equation is $\delta^{18}O=-0.23E+1.31(R^2=0.44)$. The results indicate that $\delta^{18}O$ is negatively correlated with water vapor pressure in Hong Kong. Such a relationship proves that the climate characteristics in Hong Kong are similar to those in the middle and low latitudes. Namely, due to the small temperature difference throughout the year, the main reason for the secondary evaporation of precipitation is the change in atmospheric humidity. In the rainy season, Hong Kong has heavy precipitation, high air humidity, and high water vapor pressure, which leads to high atmospheric saturation, weak secondary evaporation effect under clouds, and negative isotope composition. Meanwhile, low precipitation, low air humidity, and low water vapor pressure in the dry season bring low atmospheric saturation, a strong secondary evaporation effect under clouds, and positive isotope composition.

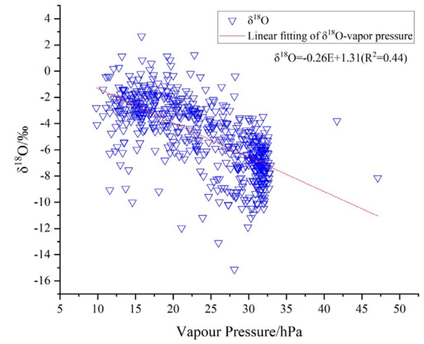

Figure. 11 Relationship Between $\delta^{18}O$ and Water Vapor Pressure in Precipitation in Hong Kong

5. Conclusion and Prospect

Based on the precipitation isotope and meteorological data from GNIP, this study investigates the variation of precipitation isotope time series from 1961 to 2022 at the Hong Kong station located in the coastal monsoon region of southern China. The variation laws of isotope and d-excess are analyzed on the inter-annual and seasonal scales. Besides, the local meteoric water line equation is established and the influencing factors of precipitation isotope variation are discussed. Finally, the following conclusions are drawn:

The values of $\delta^{18}O$ and δD in Hong Kong are affected by the same environmental factors, and the seasonal variation of $\delta^{18}O$ and δD is obvious on the monthly scale, which is low in summer and high in winter, depleted in the rainy season, and enriched in the dry season. Precipitation formed by marine water vapor is dominant in all precipitation in Hong Kong, and the water vapor source controlling precipitation in Hong Kong remains stable as a whole.

The d-excess of Hong Kong has obvious seasonal periodicity, which is higher in winter and lower in summer, indicating that Hong Kong has monsoon climate characteristics. In addition, the difference between dry and rainy seasons of d-excess indicates that the source of water vapor in Hong Kong in the rainy season is higher in humidity and lower in temperature than that in the dry season, and the evaporation process is slower.

The equation of the water line in Hong Kong is established: $\delta D=8.17\delta^{18}O+11.82$ ($R^2=0.97$), which reflects that Hong Kong is controlled by equilibrium fractionation as a whole during the formation of annual scale precipitation. Through the similar slope and intercept with other periods of Hong Kong water line equation in previous studies, it is confirmed from another perspective that the water vapor source of Hong Kong precipitation is relatively stable in a longer time scale. In addition, by comparing the water lines in the dry and rainy seasons in Hong Kong with the global ones, it is found that the precipitation in the dry season in Hong Kong comes from sources with different stable isotope ratios, while the precipitation in the rainy season is mainly from marine water vapor.

The temporal variations of isotopes in Hong Kong are controlled by the seasonal variations of precipitation and atmospheric circulation model, but the temperature effect is not significant. At the same time, the precipitation effect is significant and the degree of non-equilibrium fractionation related to water vapor pressure is also affected. The correlation between $\delta^{18}O$ in precipitation and precipitation data in Hong Kong has a similar slope and determination coefficient in three different periods, which reflects that the climate model in Hong Kong is relatively stable.

The results of this study provide valuable insights into the behavior of isotopes in precipitation and their application in isotope hydrology. Meanwhile, this study emphasizes the importance of continuous isotope monitoring in hydrologic cycle research, especially in areas with complex climatic and environmental conditions. However, there are still some problems in this study, such as insufficient accuracy of isotope observation, insufficient observation of meteorological elements, and insufficient quantitative evaluation of the atmospheric circulation model. To improve the study reliability, we should not only strengthen the time accuracy and coverage of isotope data collection, further explore the influence mechanism of different factors on precipitation isotope changes, but also analyze the correlation between regional and local atmospheric circulation indicators and precipitation isotopes in the southern monsoon region.

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