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Re-evaluation of the effects of precipitation amount and temperature on precipitation $\delta^{18}O$ at the monthly and interannual timescales

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ABSTRACT

Proxy records of the oxygen isotope ratio of $^{18}O/^{16}O$ of past precipitation ($\delta^{18}O_p$) have played an important role in revealing past hydroclimatic changes, on the basis of global observed relationships between monthly precipitation $\delta^{18}O_p$ and both precipitation amount and temperature only of a few years as reported by Dansgaard in 1964. It is therefore crucial to systematically re-evaluate the relationships using modern instrumental data. We analysed monthly and annual mean correlations from 108 global stations over the past about 60 years. Consistent with previously reported results, monthly $\delta^{18}O_p$ values in the high latitudes (≥60°) show a significant positive correlation with temperature (referred to as 'temperature effect') and a negative trend with precipitation amount in the low latitudes (≤20°) ('amount effect'). However, these correlations do not hold true for yearly mean data for more than three-quarters of the stations evaluated. This indicates that the relationships between the different temporal resolutions could be more complicated than previously thought. For the related natural archives, such as ice cores, sediments, and carbonates, further careful evaluation is required to establish the robustness of their paleoclimatic implications.

Key words: GNIP stations, paleo-$\delta^{18}O_p$ records, precipitation amount effect, precipitation $\delta^{18}O$, temperature effect

HIGHLIGHTS

- 108 GNIP stations were collected to re-analyse the relationships between $\delta^{18}O_p$ and climate variables on monthly and interannual timescales.
- The relationships between $\delta^{18}O_p$ and climate variables varied on monthly and interannual timescales.
- The results implied that the change of precipitation isotopic values may not be dominated by local climate change, but more likely a response to global atmospheric circulation.

1. INTRODUCTION

Natural archives enhance the study of prehistoric climate change. The paleoprecipitation data, in particular, inferred from proxy records of the oxygen and hydrogen isotope ratio of $^{18}O/^{16}O$ ($\delta^{18}O$, Craig 1961), provide important clues for deciphering global hydroclimatic and oceanic circulations over both short-term and orbital timescales. Lines of evidence can be retrieved from various materials, such as the high-latitude and high-altitude ice cores (North Greenland Ice Core Project (NGRIP) Members 2004; EPICA Community Members 2006), the carbonates (Wang *et al.* 2001, 2005; Yuan *et al.* 2004; Cruz *et al.* 2005; Cheng *et al.* 2016), the tree-rings (McCarroll & Loader 2004; Treydte *et al.* 2006; Allen *et al.* 2022), and the sediment cores of lake or peat land (Zhang *et al.* 2011; Rao *et al.* 2020). The reliability of these proxies essentially depends on an understanding of modern spatio-temporal precipitation $\delta^{18}O$ ($\delta^{18}O_p$) variability and its relation to regional and global hydroclimatic processes (Dansgaard 1964; Bowen 2008).

The observed monthly $\delta^{18}O_p$ ($\delta^{18}O_{mp}$) data has been reported ever since the initial operation of the Global Network of Isotopes in Precipitation (GNIP) in 1961. The analysis of a 2-year (1961–1962 CE) dataset by Dansgaard in 1964 showed a generally negative correlation between $\delta^{18}O_{mp}$ values and the monthly precipitation amount (P_m) ('amount effect') in the low latitudes. A clearly positive correlation was expressed between $\delta^{18}O_{mp}$ values and monthly mean temperature (T_m) ('temperature effect') in the high latitudes (Dansgaard 1964). These relationships have been widely used as a fundamental benchmark in paleoclimatic interpretations over the past several decades. The ice-core $\delta^{18}O$ data from Antarctica (EPICA

Community Members 2006) and Greenland (NGRIP Members 2004), for example, have been taken as an indicator of the past temperature. In the low-latitude regions, paleoprecipitation $\delta^{18}O_p$ records have been interpreted as a proxy of the monsoonal intensity, and the local or regional precipitation amount (Fleitmann *et al.* 2003; Tierney *et al.* 2008).

Subsequently, with the increase of GNIP stations, the spatial distribution of $\delta^{18}O_p$ and its relationship with climate-related parameters (including the precipitation amount and temperature) on the monthly timescale from 154 stations over the world were re-analysed in 1993 (Rozanski *et al.* 1993), using a similar approach to Dansgaard (1964). And the results also presented a strong inverse relationship between the mean monthly or annual $\delta^{18}O_p$ and the amount of monthly precipitation in the tropical marine stations located between 20°S and 20°N. While the correlation of $\delta^{18}O_p$ and the surface temperature for the stations situated in the northern hemisphere (40°N to 60°N) was different and lower (0.31‰ per °C) than that (0.69‰ per °C) calculated by Dansgaard (1964), and this relationship on the monthly timescale was even non-linear and varied in different stations (Rozanski *et al.* 1993). In fact, many studies focused on the $\delta^{18}O_p$–T relationship in the high latitudes have been conducted, such as Shuman *et al.* (2001) who presented a temporal $\delta^{18}O_p$–T slope by a snow pit approach which is different from the spatial slope of Greenland (Dansgaard 1964); Vinther *et al.* (2010) provided information on the seasonal aspects of the climate signal in Greenland ice cores, and Sjolte *et al.* (2011) discussed the $\delta^{18}O_p$–T for various timescales in context with the modelling of $\delta^{18}O_p$ in Greenland. And for the low-latitude areas, based on the observed and model data, Kurita *et al.* (2009) found the $\delta^{18}O_p$–P_m relationship varied substantially from place to place. In short, current research results (Gourcy *et al.* 2005; Zhang & Wang 2016; Allen *et al.* 2018; Cai *et al.* 2018; Yang *et al.* 2018; Balagizi & Liotta 2019; Falster *et al.* 2021) all challenged the application of early findings (i.e. 'temperature effect' or 'amount effect') of Dansgaard (1964) to the interpretation of the paleoclimate records associated with $\delta^{18}O_p$.

However, several points could be made regarding the foregoing studies regarding modern relationship between $\delta^{18}O_p$ and climate parameters (the temperature and precipitation amount). (1) The 2-year spatio-temporal relationships between $\delta^{18}O_{mp}$ and T_m or P_m ('temperature effect' or 'amount effect') is insufficient to decipher the information reserved in the natural archives, like the $\delta^{18}O$ (or δD) of ice core, speleothem, sediment of lake, and tree-ring cellulose. (2) This is because the isotopic compositions in these natural archives are not directly inherited from precipitation. For example, the $\delta^{18}O$ of speleothem and tree-ring cellulose is indirectly related to $\delta^{18}O_p$ (Lachniet 2009). Water in the soil and vadose zone could buffer the monthly/seasonal $\delta^{18}O_p$ variation (Genty *et al.* 2014; Duan *et al.* 2016; Sun *et al.* 2018; Baker *et al.* 2019; Li *et al.* 2019). (3) Furthermore, numerous paleo-$\delta^{18}O_p$ records have been created with resolutions, rather than the monthly to seasonal resolutions (NGRIP Members 2004; Cruz *et al.* 2005; EPICA Community Members 2006; Cheng *et al.* 2016). (4) Those subsequent works about $\delta^{18}O_p$–T (P) were mostly based on the models or a specific site, which did not have adequately spatially representative. (5) Last but not least, the GNIP data are being updated, which provides an opportunity for re-examining the relationship between $\delta^{18}O_p$ and local climate-related parameters on the longer timescales or larger data volumes. All of the foregoing factors emphasize the need for re-examination of the relationships between $\delta^{18}O_p$ and temperature/precipitation on the long-term timescale to better interpret these paleo-$\delta^{18}O$ records.

Here, based on the updated data provided by the GNIP, the relationships between $\delta^{18}O_p$ and temperature in the high-latitude regions and that between $\delta^{18}O_p$ and precipitation in the low-latitude regions on the monthly and interannual timescales were re-analysed. The objective is to verify whether the 'temperature effect' and 'amount effect' of monthly scale exist globally with an updated and expanded data size, and whether these relationships hold true for the longer timescale (interannual scale). And it is expected to provide a further understanding of the significance of the paleoprecipitation isotopic records.

2. DATA AND METHODS

All original data used in this paper, including the monthly mean $\delta^{18}O_p$ ($\delta^{18}O_{mp}$), monthly mean temperature (T_m), monthly precipitation amount (P_m), annual weighted mean $\delta^{18}O$ ($\delta^{18}O_{wa}$), annual precipitation total (P_a), and annual average temperature (T_a), were downloaded from the GNIP website (http://www-naweb.iaea.org/napc/ih/IHS_resources_gnip.html) in December 2020 (Supplementary Table S1). The selection of GNIP stations in this study is mainly based on: (1) *The regional selection*: considering the main purpose of this study is to determine the 'temperature effect' and 'amount effect' in the high latitudes and low latitudes, respectively, we therefore choose the typical high-latitude areas with the latitude more than 60° in both the hemispheres and the equatorial zone with 20°S–20°N (Rozanski *et al.* 1993). (2) *The number of data*: only the stations whose number of monthly raw data is more than 50 were selected. Finally, a total of 108 sites were selected (Supplementary Table S1; Figure 1). Twenty-eight stations are located in the northern high latitudes (>60°N) and three in the southern high latitudes (>60°S). The remaining 77 stations are located in the low latitudes between 20°N and 20°S.

For the analysis method, we used the same method of linear correlation analysis as that of Dansgaard (1964). And we used the MATLAB software to batch process the data to obtain the corresponding slopes, intercepts, correlation coefficients, and significance level values (p), and generate detailed regression graphs. The corresponding maps are generated by the ArcGIS software. All statistical criteria are based on the p values. Significance levels for linear correlations are classified as: significant ($p < 0.05$), moderately significant ($0.05 < p < 0.1$), less significant ($0.1 < p < 0.2$), and non-significant ($p > 0.2$). Considering the length and readability of this paper, the corresponding slopes, intercepts, correlation coefficients, and significance level values are presented in Supplementary Table S1.

3. RESULTS AND DISCUSSION

3.1. Relationships between $\delta^{18}O_p$ and temperature at high-latitude regions

On the monthly timescale, $\delta^{18}O_{mp}$ values in 31 stations at the high-latitude regions (28 stations in the Northern Hemisphere (NH) and 3 stations in the Southern Hemisphere (SH)) all show a significant positive correlation with T_m (Figures 1, 2(a) and 3(a)). This result is similar to the results of earlier research (Dansgaard 1964). It is implied that $\delta^{18}O_p$ at the high latitudes could be mainly controlled by the change of temperature on the monthly timescale. However, the slopes of $\delta^{18}O_p/T$ varied from station to station in the NH, with a range of 0.09–0.49‰/°C (Supplementary Table S1; Figures 2(a) and 3(a)), which is less than the spatial slope (0.67‰/°C) of $\delta^{18}O_p/T$ proposed by Dansgaard. And this feature is consistent with the results reviewed by Jouzel (Jouzel *et al.* 1997), that the temporal slope of $\delta^{18}O_p/T$ in a given site or region is lower than the present-day spatial slope in this region.

On further analysis of these stations in the NH, the smaller slopes occurred in some sites where the behaviour of precipitation and temperature are not synchronized (Figures 4(a) and 5(a)). For example, the smallest value of slope (0.09‰/°C) is presented in the NY ALESUND station from Norway (NH_{33} in Figure 2(a)), where the precipitation decreased from January to June, and increased from July to December, but the behaviour of temperature was contrast (NH_{33} in Figure 4(a)). Likewise, the slopes of $\delta^{18}O_p/T$ from the stations with relatively less precipitation in the warm season were generally small, e.g. NH_{24}, NH_{25}, NH_{31}, and NH_{32} stations in Figures 2(a) and 4(a). Furthermore, two stations from the SH, SH_{12}, and SH_{13} in Figure 3(a), respectively, which are closed to each other, had different slopes (Supplementary Table S1; Figure 3(a)). Similar

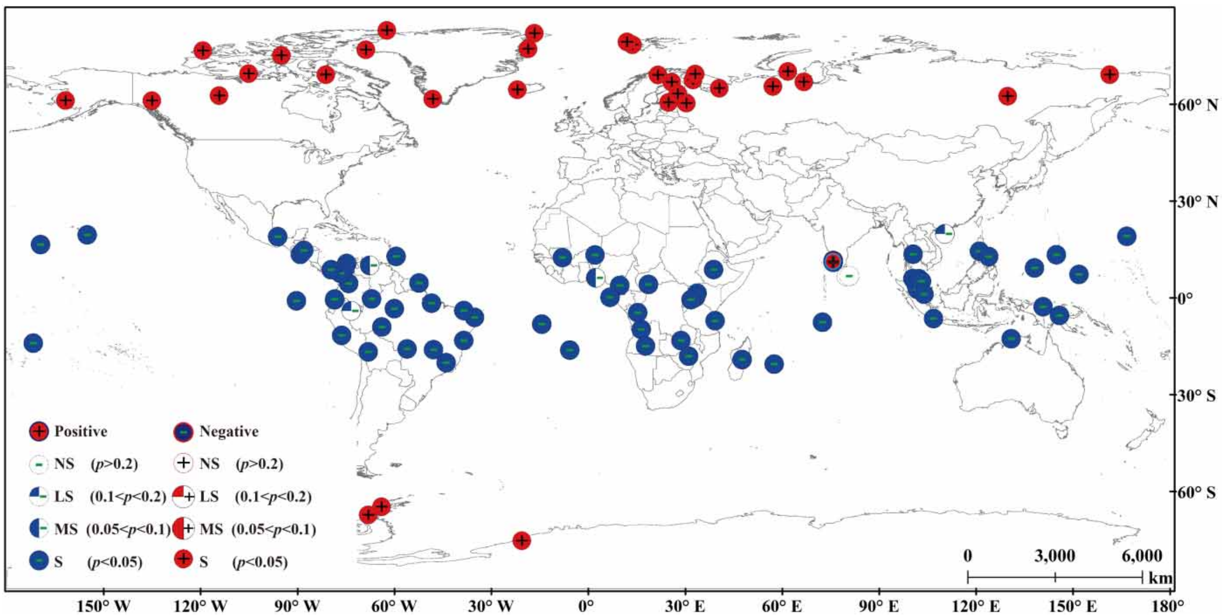

Figure 1 | The correlations between $\delta^{18}O_{mp}$ and T_m in the high latitudes and between $\delta^{18}O_{mp}$ and P_m in the low latitudes. The red circles represent positive correlations between $\delta^{18}O_{mp}$ and T_m. The blue circles represent negative correlations between $\delta^{18}O_{mp}$ and P_m. The significance levels of the correlations are classified based on p values and represented by different symbols. Detailed information of 108 stations and correlations are given in Supplementary Table S1. Please refer to the online version of this paper to see this figure in colour: https://dx.doi.org/10.2166/wcc.2023.446.

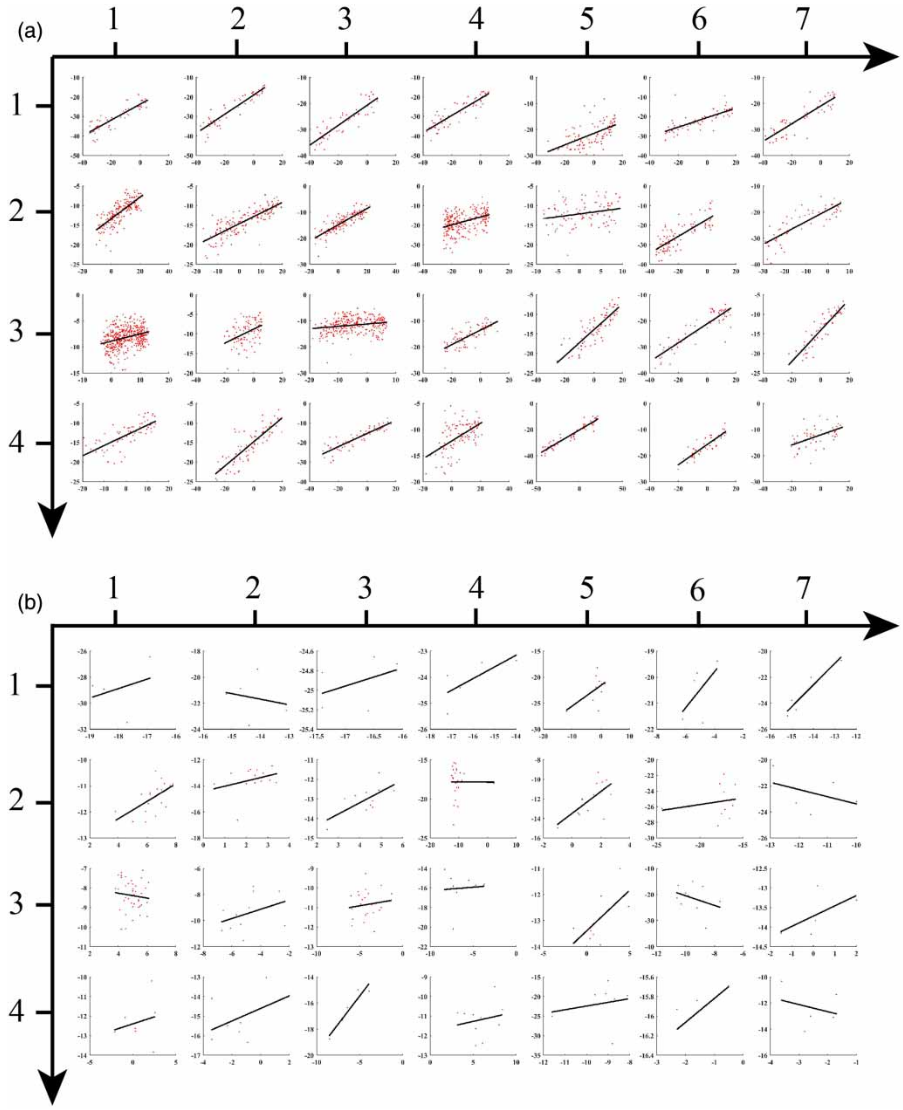

Figure 2 | Linear correlations between $\delta^{18}O_p$ and T for 28 NH latitudinal stations on the monthly timescale (a) and on the interannual timescale (b). The naming order follows the matrix naming method, i.e. NH_{ij}, *i* represents the number of row, *j* indicates the column. And the corresponding ID of stations is also displayed in Supplementary Table S1.

to the feature of NH, the slope of the SH_{12} station with relatively less precipitation in the warm season were smaller (0.30‰/°C) than that in SH_{13} station (0.44‰/°C, Figures 3(a) and 5(a)), although their seasonal variation of monthly temperature, $\delta^{18}O_{mp}$ and *d*-excess were all broadly consistent (Figure 5(a) and 5(b)). Besides, some stations with synchronized behaviour of precipitation and temperature, but with asynchronized pattern of *d*-excess, also presented small slope values, e.g. NH_{15}, NH_{16}, NH_{34}, NH_{41}, NH_{44}, and NH_{47} stations in Figures 2(a) and 4(b). Notably, *d*-excess is an important parameter that may relate to the climatic condition in the moisture source area, the distance on the moisture route from the source area to the precipitation location, and the possible condensation and re-evaporation process during the transportation of moisture (Merlivat & Jouzel 1979; Johnsen *et al.* 1989; Pfahl & Wernli 2008; Pfahl & Sodemann 2014), and it has been widely used in the ice core and other paleoclimatic studies to reflect the information of climatic variables (relative humidity and temperature) in the moisture source (Stenni *et al.* 2001; Masson-Delmotte *et al.* 2005a, 2005b; Jouzel *et al.* 2007; Steffensen *et al.* 2008). In short, these results demonstrate the seasonal distribution of precipitation and moisture source may also affect the variation of $\delta^{18}O_{mp}$ at stations from the high-latitude regions, in addition to the dominance of temperature.

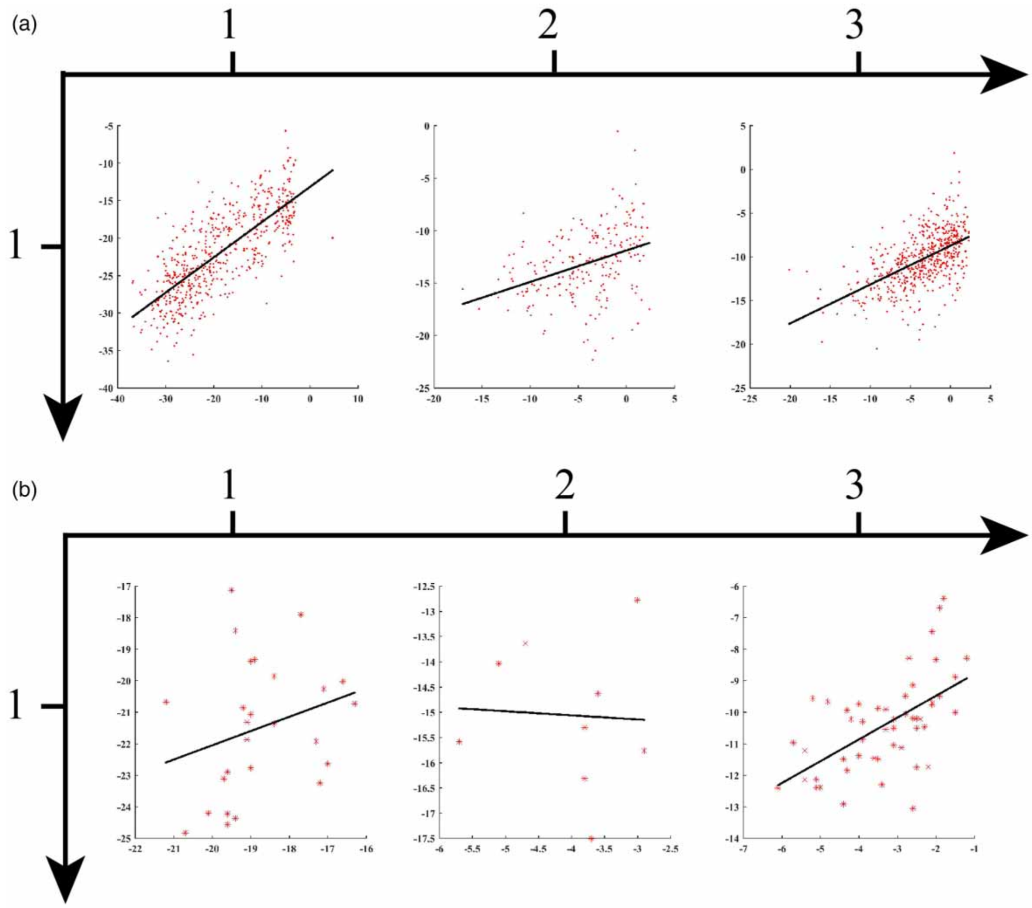

Figure 3 | Linear correlations between $\delta^{18}O_p$ and T for 3 SH latitudinal stations on the monthly timescale (a) and on the interannual timescale (b). The information about the ID name is the same in Figure 2, but the abbreviation is SH_{ij}.

On the interannual timescale, the relationship between $\delta^{18}O_{wa}$ and T_a in the high latitudes on the interannual timescale is different from that on the monthly timescale (Figures 2, 3, 6). Specifically, the relationships of $\delta^{18}O_p$/T in five stations (NH_{17}, NH_{21}, NH_{23}, NH_{25}, and NH_{43} stations in Figure 2(b)) showed a significant positive, but with a large range of $\delta^{18}O_p$/T gradient (0.33–1.66‰/°C). And two stations (NH_{15} and NH_{35}) show a moderately significant positive, one station (NH_{14}) shows less significant positive, and 14 stations (NH_{11}, NH_{13}, NH_{16}, NH_{22}, NH_{26}, NH_{32}, NH_{33}, NH_{34}, NH_{37}, NH_{41}, NH_{42}, NH_{44}, NH_{45}, and NH_{46}) are non-significant. Nonetheless, the $\delta^{18}O_{wa}$ values for the remaining six stations (NH_{12}, NH_{24}, NH_{27}, NH_{31}, NH_{36}, and NH_{47} in Figure 2(b); Supplementary Table S1) display negative correlations with T_a. In the southern high latitudes (three stations total), $\delta^{18}O_{wa}$ data in SH_{13} station show a significant positive correlation with T_a, and SH_{11} station is less positive, but the remaining SH_{12} station displays a negative correlation with T_a (Figures 3(b) and 6; Supplementary Table S1).

Furthermore, among the six stations (five in NH, one in SH) with a significant positive relationship of $\delta^{18}O_p$/T, two stations (NH_{17} and NH_{43}) only had 5 years data (Figure 2(b)), which may influence their results' reliability due to the limitation of the data size. Consequently, there are only four stations from the high latitudes that showed a robust significant positive relationship of $\delta^{18}O_p$/T on the interannual timescale. Interestingly, these four stations all present a larger $\delta^{18}O_p$/T gradients on the interannual timescale than that on the monthly timescale (Supplementary Table S1). For instance, the slope of $\delta^{18}O_p$/T in NH_{25} station was 0.15‰/°C at the monthly timescale, but 1.12‰/°C at the interannual timescale. Besides, the SH_{12} station close to the SH_{13} station (Figures 1 and 6), but their $\delta^{18}O_p$/T relationships on the interannual timescale displayed a marked difference. Specifically, the SH_{13} station showed a significant positive $\delta^{18}O_p$/T relationship, with a gradient of 0.69‰/°C. The SH_{12} station, however, presented a negative $\delta^{18}O_p$/T relationship (−0.08‰/°C), although it did not pass the significance test at 5% confidence (Figure 3(b)).

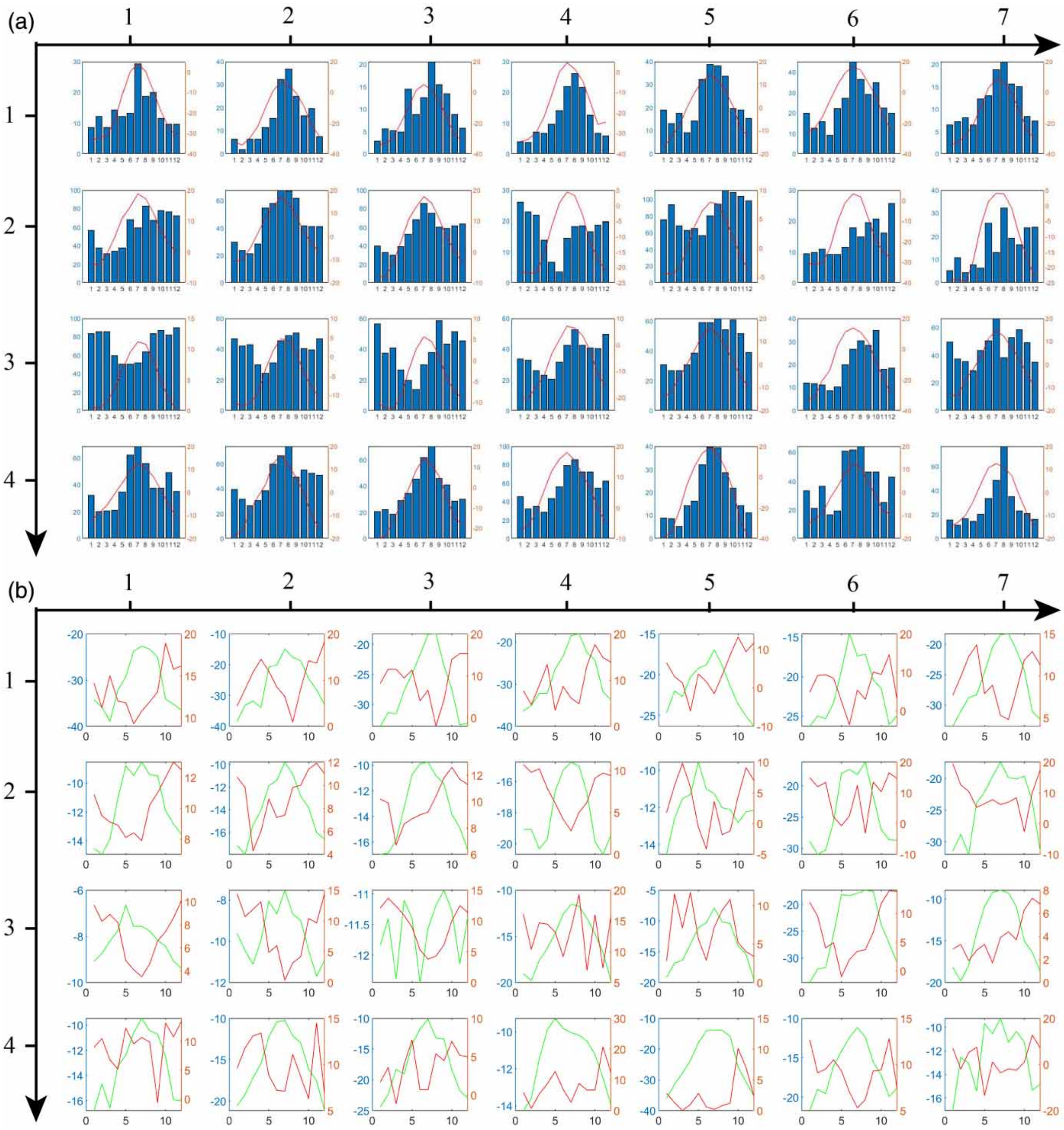

Figure 4 | (a) P_m (blue bar, unit is mm) versus T_m (red curve, unit is °C) for 28 NH latitudinal stations; (b) $\delta^{18}O_{mm}$ (green curve, ‰, VSMOW) versus *d*-excess (red curve, ‰, VSMOW) for 28 NH latitudinal stations. The information about the ID name is the same in Figure 2. Please refer to the online version of this paper to see this figure in colour: https://dx.doi.org/10.2166/wcc.2023.446.

Obviously, the relationship between $\delta^{18}O_p$ and T_a in the high latitudes was more complicated on the interannual timescale. In practice, there is increasing evidence that the $T/\delta^{18}O_p$ relationships in polar region vary at multiple timescales and do show spatial heterogeneity (Jouzel *et al.* 1997; and references therein). For instance, it has been found that there are significant differences between the temperature records from the east coast and the west coast in Greenland (Dansgaard *et al.* 1975). However, the behaviour of isotopic records from the interior of Greenland did not follow consistently the changes of temperature reserved at either the east or west coast stations (Robin 1983). Furthermore, based on the GCM model simulations, it was demonstrated that the estimated temporal slopes varied over specific regions (Jouzel *et al.* 1994), which is also presented in this study. And this phenomenon may be attributed to the fact that the variation of $\delta^{18}O_p$ could be controlled by other

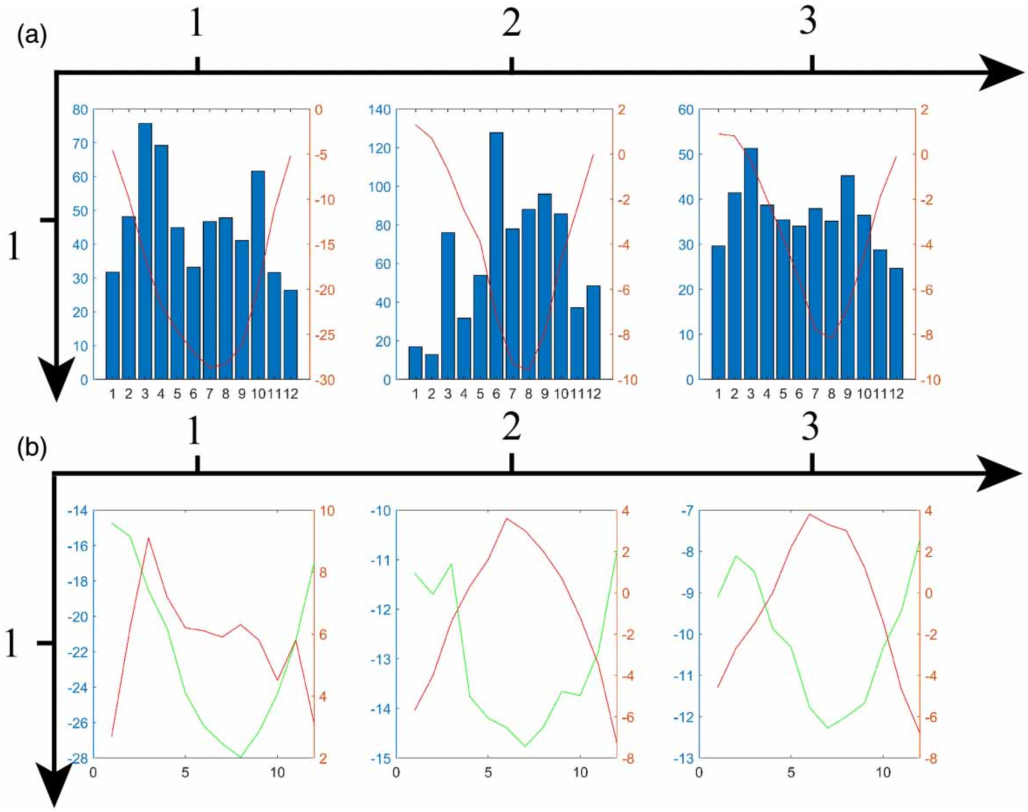

Figure 5 | (a) P_m (blue bar, unit is mm) versus T_m (red curve, unit is °C) for 3 SH latitudinal stations; (b) $\delta^{18}O_{mm}$ (green curve, ‰, VSMOW) versus *d*-excess (red curve, ‰, VSMOW) for 3 SH latitudinal stations. The information about the ID name is the same in Figure 2, but the abbreviation is SH_{ij}. Please refer to the online version of this paper to see this figure in colour: https://dx.doi.org/10.2166/wcc.2023.446.

factors (Allen *et al.* 2018; Balagizi & Liotta 2019; Falster *et al.* 2021), in addition to the local temperature. Interestingly, some studies suggested that the behaviour of $\delta^{18}O_p/T$ slopes may be associated with the alternating modes of the North Atlantic Oscillation, which is associated with temperature anomalies of opposite sign to the east and west of the crest (Barlow *et al.* 1993). Besides, some results based on GCM demonstrated the shift of moisture source (e.g. North Atlantic vs. North Pacific) for a Greenland site could generate a local $\delta^{18}O_p$ anomaly of ~7‰, under a local climate condition without significant change (Charles *et al.* 1994).

3.2. Relationships between $\delta^{18}O_p$ and precipitation amount in low latitudes

In the low latitudes, the $\delta^{18}O_{mp}$ values in 70 of the 77 stations showed a significant negative correlation with the P_m, although six stations do not show a significant negative correlation, and even one station (KOZHIKODE) at the south of Indian peninsula shows a significant positive correlation (Figures 1 and 7(a); Supplementary Table S1). As can be seen from Figure 1, these abnormal stations are all located in the coastal areas of the mainland, which may be affected by the tropical cyclones (typhoons and hurricanes) in the surrounding seas. The source of typhoon generation, different paths, the location of the typhoon where the precipitation is located and the frequency of typhoons, will all affect the regional $\delta^{18}O_p$ variability (Lawrence & Gedzelman 1996; Ohsawa & Yusa 2000; Lawrence *et al.* 2004; Fudeyasu *et al.* 2008; Xu *et al.* 2019; Sun *et al.* 2022). Moreover, the coasts of the continent will also be affected by the marine environment, such as the ocean currents. On the whole, mostly stations $\delta^{18}O_{mp}$ in the low latitudes present a negative correlation with the P_m. This indicates the $\delta^{18}O_{mp}$ values are mainly governed by an 'amount effect' in the low latitudes on the monthly timescale, supporting the previous conclusions with 2-year observations reported in 1964 (Dansgaard 1964).

The correlations between $\delta^{18}O_{wa}$ and P_a are complicated for all 77 stations located in the low latitudes (Figures 6 and 7(b)). Eighteen stations display a significant negative correlation, 7 stations a moderately significant correlation, 4 stations a less significant correlation, and 33 stations a non-significant correlation. For the remaining 16 stations, the $\delta^{18}O_{wa}$

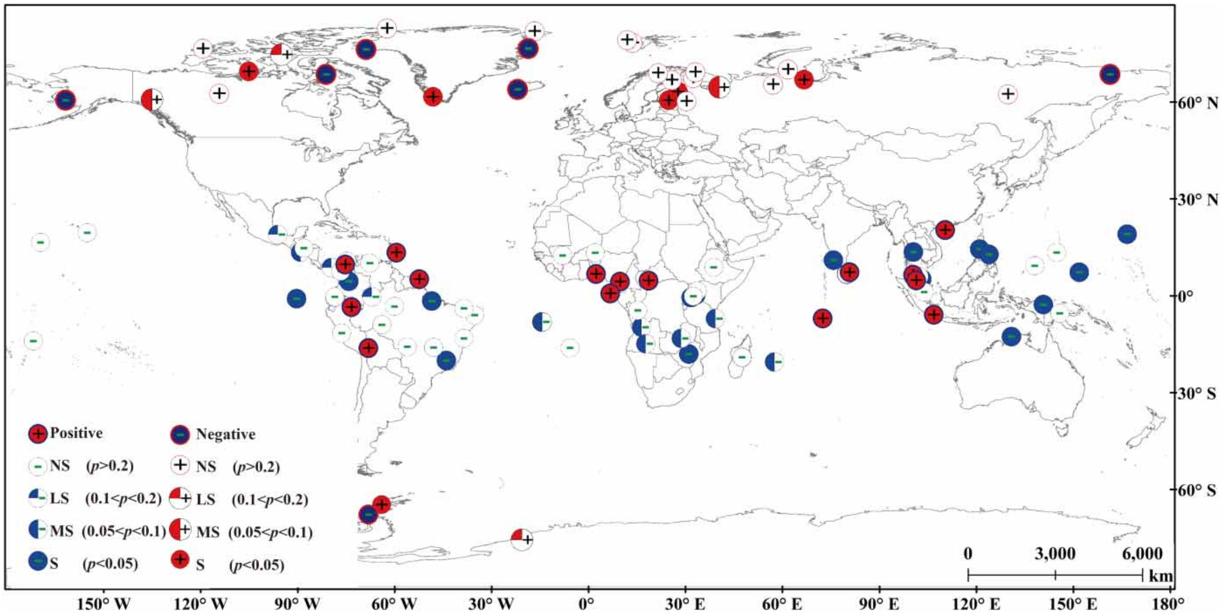

Figure 6 | The correlations between $\delta^{18}O_{wa}$ and T_a in the high latitudes and between $\delta^{18}O_{wa}$ and P_a in the low latitudes. The interpretation is the same in Figure 1, but on the interannual timescale. Detailed results of 108 stations and the correlations are given in Supplementary Table S1 and Figures S4–S6.

values show positive correlations with the P_a (Figures 6 and 7(b)). Obviously, the relationship between $\delta^{18}O_{wa}$ and P_a in the low latitudes on the interannual timescale is not like the monthly relationship with spatial consistency and significant positively correlated.

Furthermore, in the database provided by GNIP, the monthly raw data is sometimes not available. Then, to avoid the possible bias on annual weighted mean data by missing some monthly $\delta^{18}O_p$ values and ensure the validity of the results, some stations dataset with: (1) the number of $\delta^{18}O_{mp}$ row data is more than 100, (2) the total of months precipitation which $\delta^{18}O_{mp}$ row data is used as weight to calculate the $\delta^{18}O_{wa}$ value must account for more than 80% of the annual precipitation, (3) the number of covering years should be more than 9, selected for further analysis and comparison (Supplementary Table S2). Finally, 5 northern high-latitude stations, 2 southern high-latitude stations, and 36 low-latitude stations were considered. The results are also not as spatially uniform as the monthly timescale, confirming the relationship between $\delta^{18}O_{wa}$ and climatic variables (precipitation amount and temperature) on the interannual timescale is not as strong as on the monthly timescale (Figure 8).

Interestingly, the correlation between $\delta^{18}O_{mp}$ and P_m of KOZHIKODE station in south India shows a significant positive correlation (Figure 1). Contrary to the results on the monthly timescale, the $\delta^{18}O_{wa}$ is a significant negative correlation with the P_a on the interannual timescale. Similarly, WELLAMPITIYA at Sri Lanka, which is near KOZHIKODE, is also non-significantly negative on the monthly timescale, but significant in the recheck results on the interannual timescale (Figure 8), although the interannual results of raw data (Figure 6) show an insignificant negative correlation, which may be caused by some years in the statistical raw data missing some months data. In fact, the correlation between $\delta^{18}O_p$ and P at other sites in the Indian subcontinent affected by the Indian monsoon is also more significantly negative on the interannual scale than on the monthly timescale (Li *et al.* 2015). It may be a regional feature of the Indian subcontinent and requires further exploration for the underlying mechanism.

In summary, in the high latitudes, the relationship between $\delta^{18}O_p$ and T is more spatially consistent and significantly positively correlated on the monthly timescale, but it does not show such consistency and significantly positive correlation on the interannual timescale. Similarly, in the low latitudes, the relationship between $\delta^{18}O_p$ and P on the monthly timescale is more significant than that on the interannual timescale. So, it would not be fully appropriate to use the $\delta^{18}O_p$ records as indicators of paleotemperature in the high latitudes and paleorainfall amount in the low latitudes, at least on the interannual timescale.

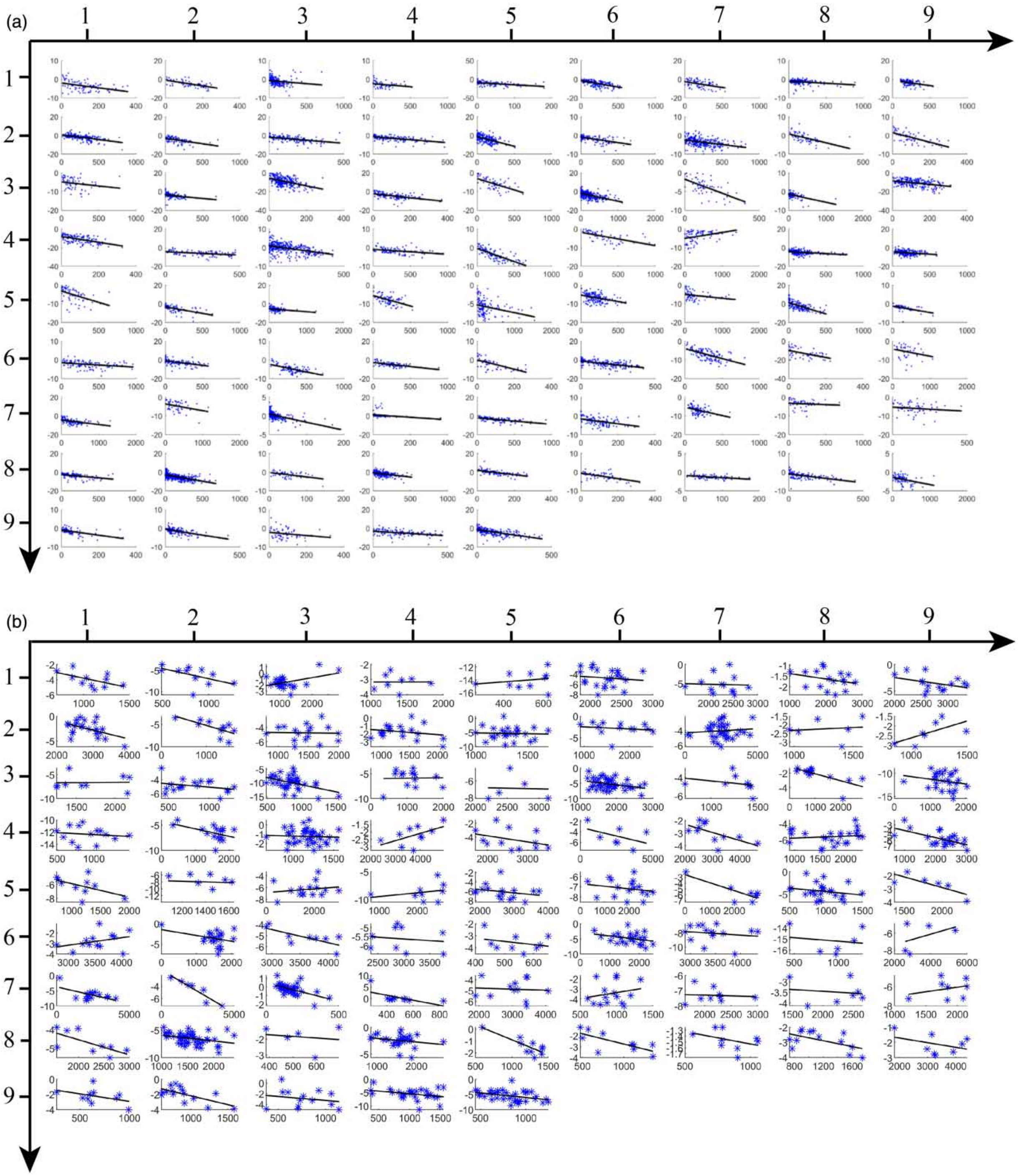

Figure 7 | Linear correlations between $\delta^{18}O_p$ and P for 77 low latitudinal stations on the monthly timescale (a) and on the interannual timescale (b). The information about the ID name is the same in Figure 2, but the abbreviation is L_{ij}.

3.3. Perspective from the paleo-$\delta^{18}O_p$ records

Over the past decades, the $\delta^{18}O$ records of high-latitude ice cores have been used as a paleotemperature indicator (NGRIP Members 2004; EPICA Community Members 2006). However, this has been widely challenged. Modern observations (Johnsen *et al.* 1989), model simulations (Charles *et al.* 1994), and deuterium excess evidence (Masson-Delmotte *et al.* 2005a, 2005b) have highlighted the influence of the moisture sources and atmospheric circulation on ice core $\delta^{18}O$ data. Previous

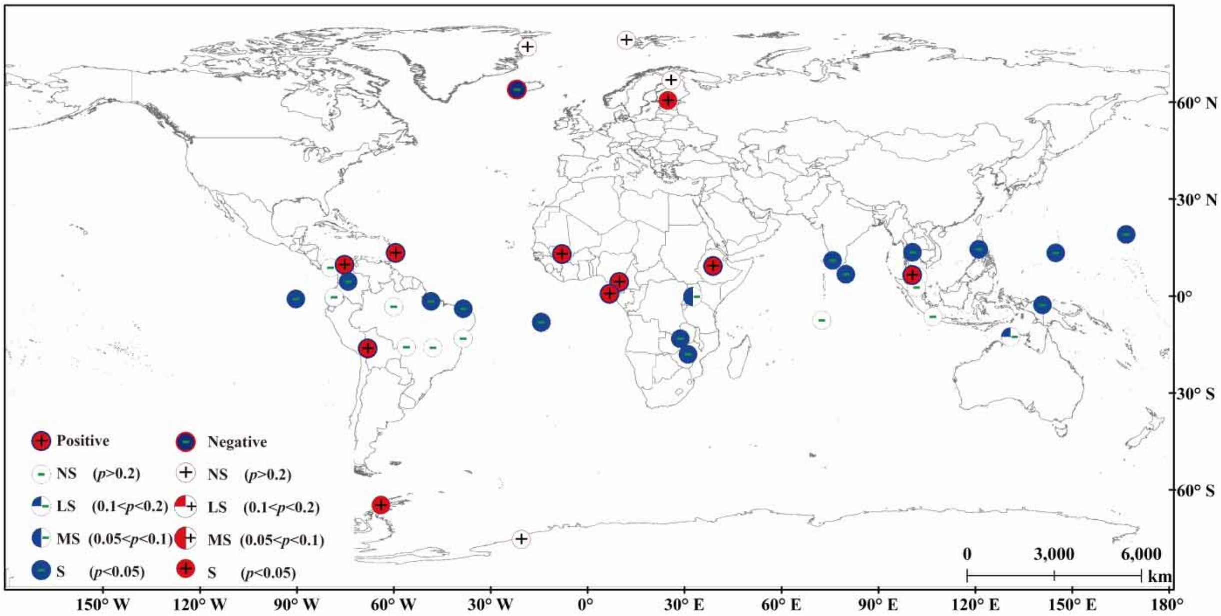

Figure 8 | Correlations between $\delta^{18}O_{wa}$ and T_a in the high latitudes and between $\delta^{18}O_{wa}$ and P_a in the low latitudes. The interpretation is the same in Figure 1. All the $\delta^{18}O_{wa}$ data from these stations used in this figure must be with the total of months precipitation which $\delta^{18}O_{mp}$ row data is used as weight to calculate the $\delta^{18}O_{wa}$ value must account for more than 80% of the annual precipitation. Detailed results of these stations and correlations are given in Supplementary Table S2 and Figures S1–S3.

studies also revealed the impacts of the tropical temperatures (Boyle 1997), precipitation seasonality (Werner *et al.* 2001), North Atlantic Oscillation and sea surface temperature (White *et al.* 1997), and shifts in vapour sources (Cole *et al.* 1999). In addition, inferred temperature variation discrepancies between the high-latitude ice core $\delta^{18}O$ and other proxies, such as the borehole paleothermometry (Cuffey *et al.* 1995), and $\delta^{40}Ar$ and $\delta^{15}N$ of gases trapped in the ice (Landais *et al.* 2004; Huber *et al.* 2006; Buizert *et al.* 2014), have also been reported.

In the low latitudes, the stalagmite $\delta^{18}O$ records from southern America (Wang *et al.* 2007) and leaf-wax compound-specific δD records from the lacustrine sediments from lacustrine (Tierney *et al.* 2008) and the marine sediments (Schefuß *et al.* 2005, 2011) from tropical Africa have been used in the reconstructions of the past precipitation amounts for the last climatic cycle. Some studies, however, showed that not only the precipitation amount, but also the influences from atmospheric circulation (Vuille *et al.* 2003) and water vapour sources (Lewis *et al.* 2010) controlled the precipitation isotopes in the low latitudes. For the Asian monsoon region, some simulations (Caley *et al.* 2014; Zhang & Wang 2016; Cai *et al.* 2018; Yang *et al.* 2018) suggest the effect of the hydrologic processes and the atmospheric circulation on the Asian stalagmite $\delta^{18}O$ records.

Moreover, not considering the interpretation of proxies, the precipitation isotopic records since the last glacial from different natural archives, such as the Greenland ice core (NGRIP Members 2004), stalagmites from central Europe (Moseley *et al.* 2014), southern China (Wang *et al.* 2001; Yuan *et al.* 2004) and southern America (Cruz *et al.* 2005), and lake sediment from tropic Africa (Tierney *et al.* 2008; Figure 9), are characterized by global similarities, although their resolutions are variable. Recently, 63 published, global, independently dated speleothem $\delta^{18}O$ records have been used to compare and show that the abrupt warmings in Greenland were associated with synchronous climate changes in the low-latitude regions (such as the Asian Monsoon, South American Monsoon, and European-Mediterranean regions) (Corrick *et al.* 2020). And this synchrony can be precisely defined to occur within decades. It means the variability of speleothem $\delta^{18}O$ values during these abrupt warming events is globally (high-latitude-to-tropical) synchronous (Corrick *et al.* 2020). This global in-phase of speleothem $\delta^{18}O$ values during these abrupt events cannot be explained by the local microclimate changes, but more like a response to the changes in global atmospheric circulation (Corrick *et al.* 2020).

Finally, the discrepancy among monthly (Figure 1), interannual (Figures 6 and 8), and multidecadal to centennial/millennial correlations from the paleo-records (Figure 9) directly challenges the hypothesis that precipitation isotopes are mainly

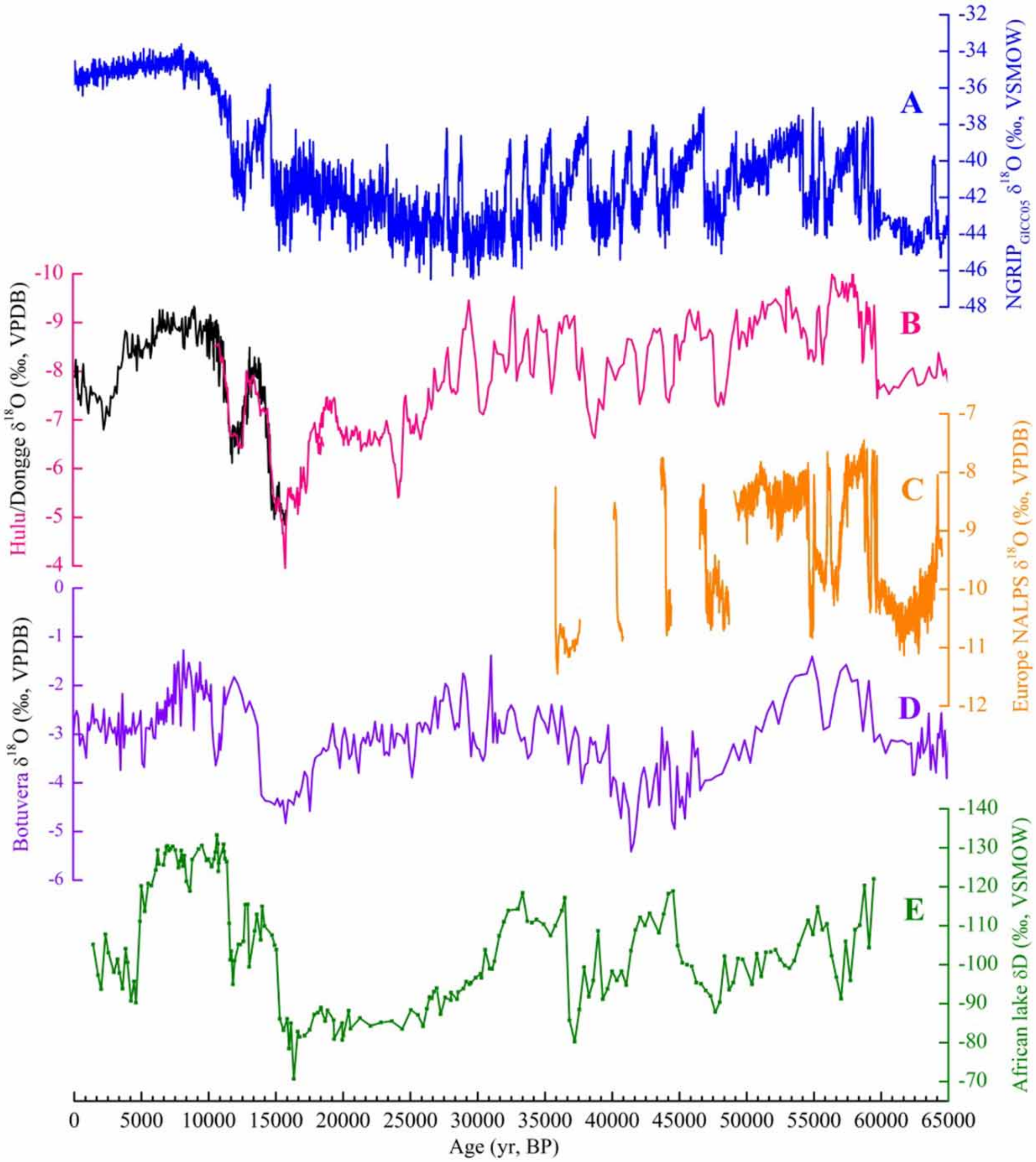

Figure 9 | Comparison of typical precipitation $\delta^{18}O$ and δD records since the last glacial. (a) NGRIP ice-core $\delta^{18}O$ record (North Greenland Ice Core Project Members 2004). (b) Stalagmite $\delta^{18}O$ record from southern China (Wang *et al.* 2001; Yuan *et al.* 2004). (c) Stalagmite $\delta^{18}O$ record from central Europe (Moseley *et al.* 2014). (d) Stalagmite $\delta^{18}O$ record from southern America (Cruz *et al.* 2005). (e) Lacustrine leaf wax δD record from tropical Africa (Tierney *et al.* 2008).

governed by a 'temperature effect' in the high latitudes and an 'amount effect' in the low latitudes. This could be attributed to the scale difference of controlling factors between climatic variables and isotopic value (Sjolte *et al.* 2011). Therefore, it might not be fully appropriate to interpret the paleoprecipitation isotope records just based on the relationships at the monthly time-scale or even shorter timescale (like daily and hourly).

An open question then is at what timescale the modern relationship is the most suitable for interpreting the geological records, and whether it is feasible at such long timescale to implement modern analysis? The classic geological principle of 'The present is the key to the past' is commonly used in the studies of past earth environmental reconstruction, and we support this research method without any doubt. However, when it is not that powerful to interpret proxies by using modern relations, the model simulation and replication test between paleo-records could complement the rationality of the interpretation (Dorale & Liu 2009; Liu *et al.* 2014). That is, based on the relationships obtained by the modern monitoring, a model simulation can be preliminarily constructed. When the reliability of reconstruction records is assured by the replication test, the paleoclimate reconstruction records could be used to verify the accuracy of the model simulation results and improve the designment of the models. And then the model simulations could provide more information and mechanistic explanations, which modern monitoring and paleoclimate reconstruction could not provide or solve. However, the importance of the modern monitoring and the paleoclimate reconstruction cannot be denied, and should be subject to the same attention as the model simulations, because they are a basic, critical component of the relevant research item. In conclusion, more modern observations, model simulations, and paleoclimatic reconstructions (but not confined) may help to clarify the enigmatic nature of precipitation isotope ratios in different natural archives and their potential applications in the paleoclimatic studies.

4. CONCLUSIONS

108 stations at the high latitudes (≥60°) and the low latitudes (≤20°) in both hemispheres covering the past about 60 years have been selected from GNIP. And the linear correlations between $\delta^{18}O_p$ and climatic variables (temperature and precipitation amount) from these stations, on the monthly timescale and interannual timescale, respectively, have been conducted. The results show: (1) The monthly $\delta^{18}O_p$ values show a significant positive correlation with T_m for all stations in the high latitudes (≥60°), and a negative correlation with precipitation amount in the low latitudes (≤20°), which is consistent with previous results. (2) Whereas on the interannual timescale, the relationships between $\delta^{18}O_{wa}$ and T_a in the high latitudes, and between $\delta^{18}O_{wa}$ and P_a in the low latitudes, are not as strong and spatially uniform as those on the monthly timescale. (3) And the paleo-records associated with the precipitation isotopic composition presented broadly global similarities and were synchronous during the abrupt climate events since the last glacial, implying the change of precipitation isotopic values may not be dominated by the local climate change, but more likely a response to the global atmospheric circulation. (4) Lines of evidence indicate the relationships between the different timescales could be different and more complicated than previously thought. To establish the robustness of paleoclimatic implications of the related natural archives (e.g. ice cores, sediments, and carbonates), further modern observations, model simulations, and paleoclimatic reconstructions are required and should complement one another.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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