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A Late Pleistocene-Holocene Record of Tropical Monsoon Climate from Groundwater Noble Gases and Isotopes in the Leizhou Peninsula, Southern China

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Key Points:

- Noble gas temperatures from Leizhou groundwater indicate a minimum ~5°C–6°C glacial-to-Holocene warming in tropical East Asia
- Covariation of $\delta^{18}O$ with excess air shows that isotopes primarily record monsoon precipitation and recharge dynamics, not temperature
- The groundwater record documents Last Glacial Maximum aridity, a short Younger Dryas weakening, and an early Holocene monsoon maximum, consistent with the regional lake and speleothem archives

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract Groundwater from the Leizhou Peninsula in tropical South China provides one of the first noble-gas based paleoclimate reconstructions from the East Asian monsoon region. Radiocarbon dating establishes a robust chronology spanning the Late Pleistocene to the Holocene. Noble gas temperatures reveal a minimum glacial-to-Holocene warming of ~5°C–6°C, consistent with global low-latitude groundwater records. Stable isotopes ($\delta^{18}O$) covary with excess air, indicating that they primarily reflect monsoon-driven precipitation changes rather than temperature. These records point to suppressed recharge during the Last Glacial Maximum, a short-lived weakening of the summer monsoon during the Younger Dryas, and intensified precipitation in the early Holocene. By jointly resolving temperature and precipitation signals, fossil groundwater offers a dual constraint on tropical paleoclimate that complements existing continental records and provides benchmarks for testing climate model sensitivity in East Asia.

Plain Language Summary Reconstructing past climate in tropical East Asia is essential for understanding glacial-interglacial transitions in low-latitude regions. Here we use ancient groundwater from the Leizhou Peninsula in South China as a natural archive. When rainwater infiltrates the ground, it traps noble gases and isotopes that preserve the temperature and rainfall conditions at the time of recharge. Our results indicate that temperatures at the time of groundwater recharge during the last ice age were at least ~5°C–6°C colder than today. The isotope record further reveals suppressed recharge during the peak of the Last Glacial Maximum, a short-lived weakening of the summer monsoon during the Younger Dryas, and intensified precipitation in the early Holocene. Together, these findings demonstrate that ancient groundwater provides a powerful and underutilized archive of tropical paleoclimate change.

1. Introduction

The East Asian monsoon plays a vital role in the global climate system, and understanding its past variability is essential for predicting future changes in regional water resources and climate dynamics (Chen et al., 2023; Sun et al., 2022). While speleothems, lake sediments, and ice cores have revealed major hydroclimatic events during the Late Pleistocene to Holocene transition, including glacial-interglacial warming and the Younger Dryas (Cheng et al., 2020; North Greenland Ice Core Project members, 2004), reconstructing past temperature change in low-latitude monsoon regions remains challenging. Common proxies such as stalagmite $\delta^{18}O$ are influenced not only by temperature but also by precipitation amount and moisture source variability. In this context, groundwater archives offer a valuable yet underutilized resource that can simultaneously capture and disentangle thermal and hydrological signals (Edmunds, 2005).

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When rainwater infiltrates and becomes groundwater, it preserves geochemical signatures of environmental conditions at the time of recharge. Dissolved noble gas (e.g., Ne, Ar, Kr, Xe) record the temperature at the water table during infiltration (Cey et al., 2009), referred to as the noble gas temperature (NGT), which closely approximates mean annual (ground) surface temperature (MAST). In addition, excess air (EA), formed from trapped air bubbles during recharge, offers insights into recharge dynamics and can reflect climatic extremes (Aeschbach-Hertig et al., 2002), such as episodic rainfall or prolonged droughts. Stable isotopes ($\delta^{18}O$, $\delta^{2}H$) in groundwater provide complementary signals, especially in tropical regions where $\delta^{18}O$ is more sensitive to precipitation amount due to monsoon-related amount effect. The combined use of nobles gases and stable water isotopes provides independent constraints on temperature and precipitation at the time of groundwater recharge.

Here, we present a groundwater-based paleoclimate reconstruction from the Leizhou Peninsula in southern China, a low-latitude coastal region influenced by the East Asian monsoon. This region hosts extensive multilayered aquifer systems that preserve Pleistocene to Holocene groundwater, making it an ideal archive for long-term paleoclimate reconstruction. Using a multi-tracer approach—including noble gas analysis, stable isotopes and ^{14}C dating—we reconstruct past recharge temperatures and monsoon intensity from the Late Pleistocene to present. Our objectives are to (a) quantify glacial-to-Holocene warming, (b) identify hydroclimatic transitions (drying/wetting events), and (c) compare groundwater-derived signals with other regional paleoclimate archives. This study provides one of the first noble gas-based paleoclimate reconstructions from a tropical monsoon region in East Asia and highlights the value of groundwater as a climate archive for constraining low-latitude climate sensitivity.

2. Materials and Methods

2.1. Study Area and Sampling

The Leizhou Peninsula, located in tropical South China, is characterized by a humid monsoon climate, with a mean annual precipitation of ~1,500 mm and temperature of ~23°C. Approximately 80% of the total precipitation occurs during the summer monsoon season (May–September). The peninsula is underlain by a basaltic bedrock platform and mantled by Quaternary sediments and weathered volcanic soils, forming a multi-layered aquifer system comprising both unconfined and confined units. Groundwater recharge primarily occurs via direct infiltration in upland areas, followed by lateral subsurface flow toward coastal discharge zones.

Groundwater samples were collected from 40 monitoring wells across the peninsula (Figure 1), with well depths ranging from 34 to 350 m, selected to capture a range of hydrogeological settings and groundwater residence times. Prior to sampling, each well was purged to remove stagnant water and ensure collection of aquifer-representative groundwater. Of these, 30 wells were selected for noble gas analysis, with samples collected in copper tubes and immediately sealed to prevent atmospheric contamination. Isotopic and geochemical samples were collected in airtight polyethylene containers and stored at 4°C until laboratory analysis.

2.2. Analytical Methods

Groundwater residence times were estimated using radiocarbon (^{14}C) analysis of dissolved inorganic carbon (DIC), measured via accelerator mass spectrometry at the Australian Nuclear Science and Technology Organisation. Analytical precision is typically ±0.3 pMC (1σ). Radiocarbon ages were corrected following the Han-Plummer graphical method (Han & Plummer, 2016; Han et al., 2012), which integrates ^{14}C activity, $\delta^{13}C$, and DIC concentrations to identify dominant geochemical processes influencing DIC composition, including carbonate dissolution, isotopic exchange, and water-rock interaction. In this study, $\delta^{13}C$ end-member values of −25‰ for soil CO_2 (consistent with C_3 vegetation dominating the study area) and 0‰ for carbonate-derived carbon were adopted. The correction followed an isotopic mass-balance approach within the Han & Plummer framework, which accounts for carbon exchange between soil CO_2, DIC species, and carbonate dissolution under near-equilibrium conditions. Tritium (^{3}H) measurements were conducted at the Institute of Hydrogeology and Environmental Geology, Chinese Academy of Geological Sciences (CAGS), using a Quantulus 1220 ultra-low-background liquid-scintillation spectrometer, with a precision of ±0.3 TU, to confirm post-1950 recharge in younger samples. For a subset of older groundwater, radiogenic ^{4}He accumulation was additionally used to evaluate consistency with ^{14}C-derived ages.

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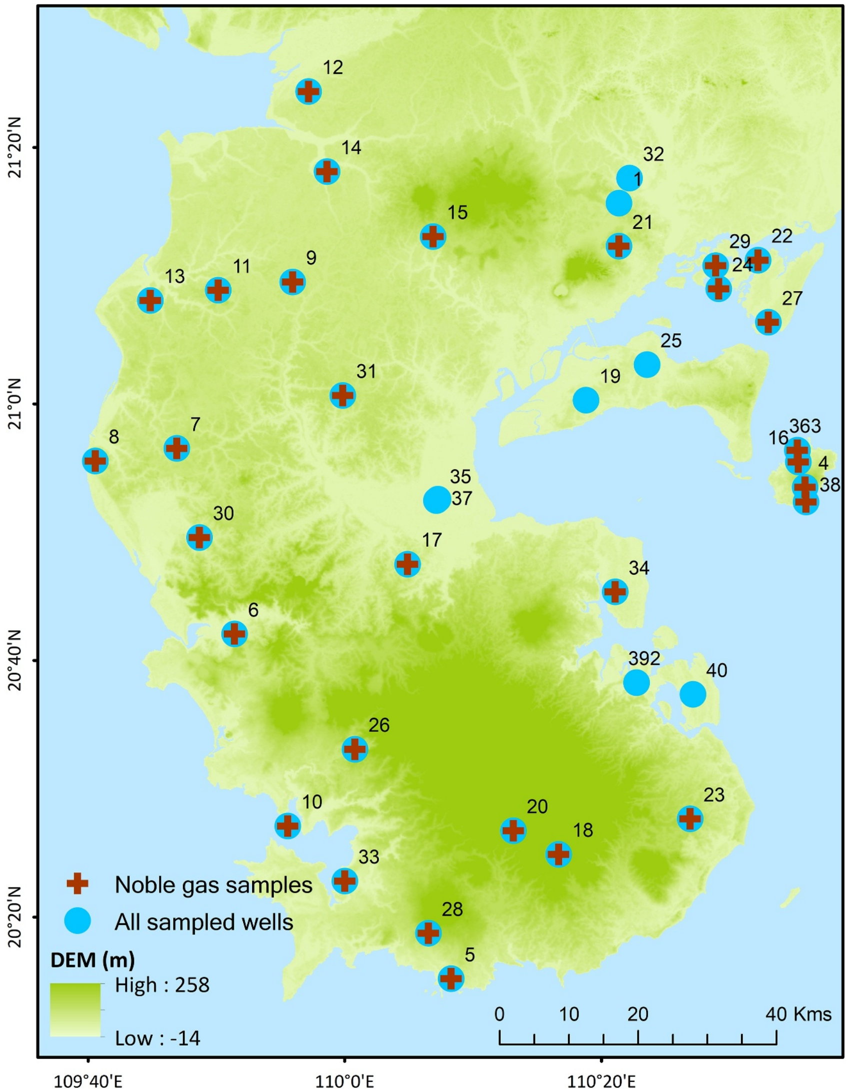

Figure 1. Map of the Leizhou Peninsula showing the distribution of sampled wells. Blue circles denote all wells analyzed for isotopes and geochemistry and red crosses indicate the subset analyzed for noble gases.

Stable isotope ratios of $\delta^{18}O$ and $\delta^{2}H$ in groundwater were measured at CAGS by isotope ratio mass spectrometry and reported relative to V-SMOW. Analytical precisions are ±0.1‰ for $\delta^{18}O$ and ±1‰ for $\delta^{2}H$. These isotopes record recharge-period precipitation composition and act as proxies for monsoon dynamics.

Noble gas concentrations (He, Ne, Ar, Kr, and Xe) were analyzed at Heidelberg University, Germany, using a GV Instruments MM5400 sector-field mass spectrometer following standard extraction and purification procedures. Analytical reproducibility is within ±1%–2%. Duplicate analyses yielded pooled standard deviations comparable to the internal precision from standard measurements. Noble gas temperatures (NGTs) and EA were derived using the closed-system equilibration (CE) model (Aeschbach-Hertig et al., 2000; Jung & Aeschbach, 2018). The CE model improves the estimation of recharge temperatures and EA by accounting for the partial dissolution of entrapped air bubbles under closed-system conditions during infiltration. The uncertainty in estimated NGTs was typically below ±2°C, reflecting both analytical precision and model fitting variability. Excess air, expressed as ΔNe (the deviation of dissolved neon from atmospheric equilibrium), was interpreted to reconstruct recharge processes and water table variability. Combined with ^{14}C-derived chronologies, these data sets yield a multi-proxy record of hydroclimatic conditions spanning the Late Pleistocene to Holocene in the study area.

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3. Results and Discussion

3.1. Establishing the Paleoclimate Chronology: Groundwater Residence Times

Radiocarbon activities in groundwater from the Leizhou Peninsula range from near or above 100 pMC in shallow unconfined aquifers, consistent with modern recharge, to as low as ∼1 pMC in deeper confined units. After dead-carbon correction using $\delta^{13}C$ and hydrochemical constraints, the resulting ages span from modern to ∼33 Ka, defining a chronology that extends across both the Holocene and much of the late Pleistocene. Tritium was detected only in a subset of shallow wells, confirming post-1950 recharge, while older samples fall within the range of ^{14}C-derived residence times. In addition, radiogenic ^{4}He accumulation was estimated from measured He concentrations after correction for equilibrium and EA components. The radiogenic ^{4}He content shows a systematic increase with decreasing ^{14}C activity, supporting the internal consistency of the derived ^{14}C ages. Further details of the ^{4}He-^{14}C relationship, including inverse modeling and regression analysis, are provided in a companion study currently under review.

The spatial distribution of ages follows regional flow patterns: young waters occur predominantly in upland recharge areas of northern and southern Leizhou, whereas older waters are found in confined aquifers discharging toward coastal margins and offshore islands. The systematic age increase along inferred flow paths supports the integrity of the chronology and indicates well-organized groundwater circulation. Together, these results establish a robust chronological framework (Figure 2) that anchors the subsequent analyses of noble gas temperatures and stable isotopes, enabling reconstruction of both thermal and hydrological changes across the late Pleistocene-Holocene transition.

3.2. Quantifying Glacial-to-Holocene Warming: The Noble Gas Temperature Record

Dissolved noble gas concentrations in groundwater from the Leizhou Peninsula yield noble gas temperatures that directly quantify past recharge conditions and resolve the magnitude of glacial-interglacial climate change. We analyzed 30 groundwater samples for noble gases using the PANGA software (Jung & Aeschbach, 2018) based on the CE model. Following the parameter ranges recommended by Jung and Aeschbach (2018)—$A < 0.05$ cm^3 STP g^{-1}, $0.1 \le F < 1$, and χ^2 probability > 1%—three samples (wells 5, 22, and 24) yielded strongly negative F values that fall outside the physically plausible range and were therefore excluded from interpretation. Among the remaining samples, modern waters show NGTs tightly clustered around values that are closely comparable to the present MAST of the peninsula (Figure 2). This agreement provides an internal validation of the noble gas thermometer and underpins the reliability of reconstructed NGTs for older groundwater.

Late Pleistocene waters reveal substantially lower recharge temperatures. The coldest NGTs occur at radiocarbon ages of ∼18 and ∼29 ka, bracketing the conventional Last Glacial Maximum interval (LGM, 19–26 ka BP) rather than falling within it. This pattern suggests a recharge hiatus (or strongly reduced recharge) near peak LGM conditions in Leizhou, consistent with reduced infiltration under colder/drier climates. The implications of this "LGM gap" are addressed in the stable isotope section. Taking modern samples as the present-day reference, the coldest Pleistocene NGTs indicate a glacial-to-Holocene warming on the order of ∼5°C–6°C for Leizhou. This magnitude aligns with low- to mid-latitude groundwater noble gas compilations and with several regional terrestrial reconstructions (Seltzer et al., 2021), while remaining smaller than mid-latitude continental estimates (Bekaert et al., 2023), consistent with a latitudinal gradient in terrestrial glacial cooling. Because NGTs provide a direct physical measure of recharge temperature, they enable reconstruction of past mean annual air temperature and help interpret stable-isotope records that may integrate both temperature and precipitation signals.

Beyond the glacial-interglacial contrast, the Leizhou NGT record suggests possible shorter-term temperature variability. A cold excursion centered at ∼9–10 ka may reflect the Younger Dryas, although age uncertainties inherent in groundwater dating preclude alignment with the conventional ∼11.7–12.9 ka interval. Another cooling phase near ∼3 ka may be broadly comparable to the widespread 4.2 ka event recognized in regional and global archives (Y. Liu et al., 2025; Xiao et al., 2018). Notably, well 20, which yields the lowest Holocene NGT (19.5°C), is the only site with a single screened interval (∼20 m), suggesting that this configuration may have reduced vertical mixing and preserved a more localized recharge signal. These features suggest that noble gas paleothermometry can capture not only orbital-scale temperature changes but may also record millennial-scale variability in tropical monsoon regions.

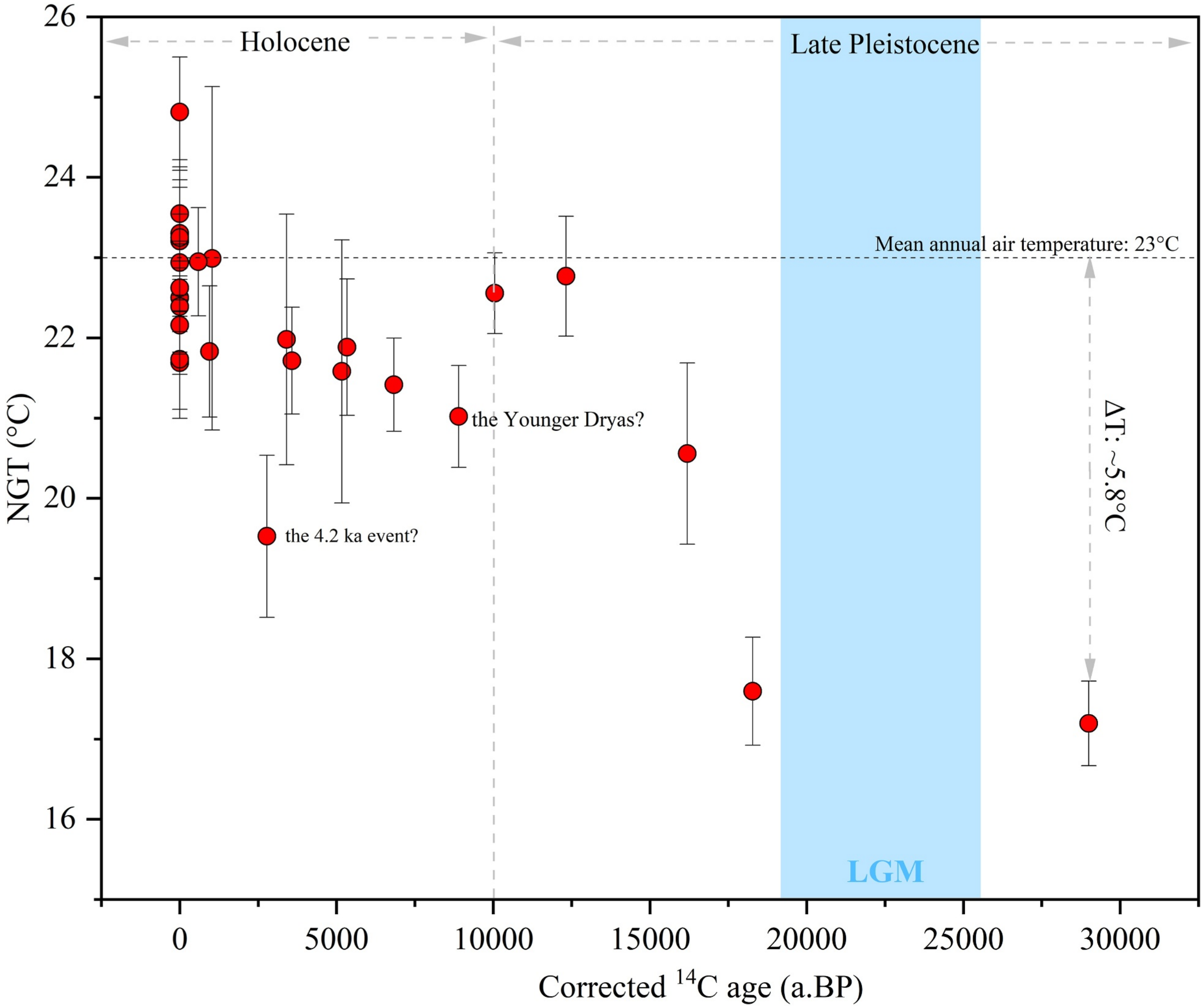

Figure 2. Noble gas temperatures versus corrected ^{14}C ages in the Leizhou groundwater. Results indicate a minimum ~5°C–6°C glacial-to-Holocene warming, a recharge gap during the Last Glacial Maximum, and shorter-term excursions that may reflect the Younger Dryas and 4.2 ka event.

3.3. Reconstructing Monsoon Variability: Evidence From Stable Isotopes and Excess Air

The relationship between $\delta^{18}O$ and other tracers provides important insights into the climatic meaning of isotopic variability in the Leizhou Peninsula aquifer. A comparison of $\delta^{18}O$ with NGTs shows a scattered distribution with no clear trend, suggesting that stable isotopes in this setting are not strongly controlled by recharge temperature (Figure 3). By contrast, a clear negative correlation between $\delta^{18}O$ and ΔNe is observed, with lower $\delta^{18}O$ values corresponding to higher ΔNe. This relationship suggests that stronger monsoon precipitation-indicated by isotopically lighter recharge water-enhanced water table fluctuations and air entrapment, producing greater EA in groundwater. This coupling between $\delta^{18}O$ and ΔNe provides independent evidence that more negative $\delta^{18}O$ values in tropical archives reflect stronger monsoon intensity. This proxy-proxy relationship establishes the basis for interpreting stable isotope variability as a signal of precipitation amount and/or associated hydroclimatic changes in paleoclimate archives such as speleothems (Z. Liu et al., 2014; Yang et al., 2016) or leaf waxes (Thomas et al., 2014; Yamoah et al., 2016). For this analysis, only pre-modern samples (corrected ^{14}C ages > 0) were included, as modern groundwater may reflect short-term climatic variability and anthropogenic influences rather than long-term recharge conditions.

Building on this interpretation, temporal variations in $\delta^{18}O$ may reflect monsoon-related hydroclimatic variability, including changes in precipitation amount and/or effective recharge. In the Holocene, samples from 0 to

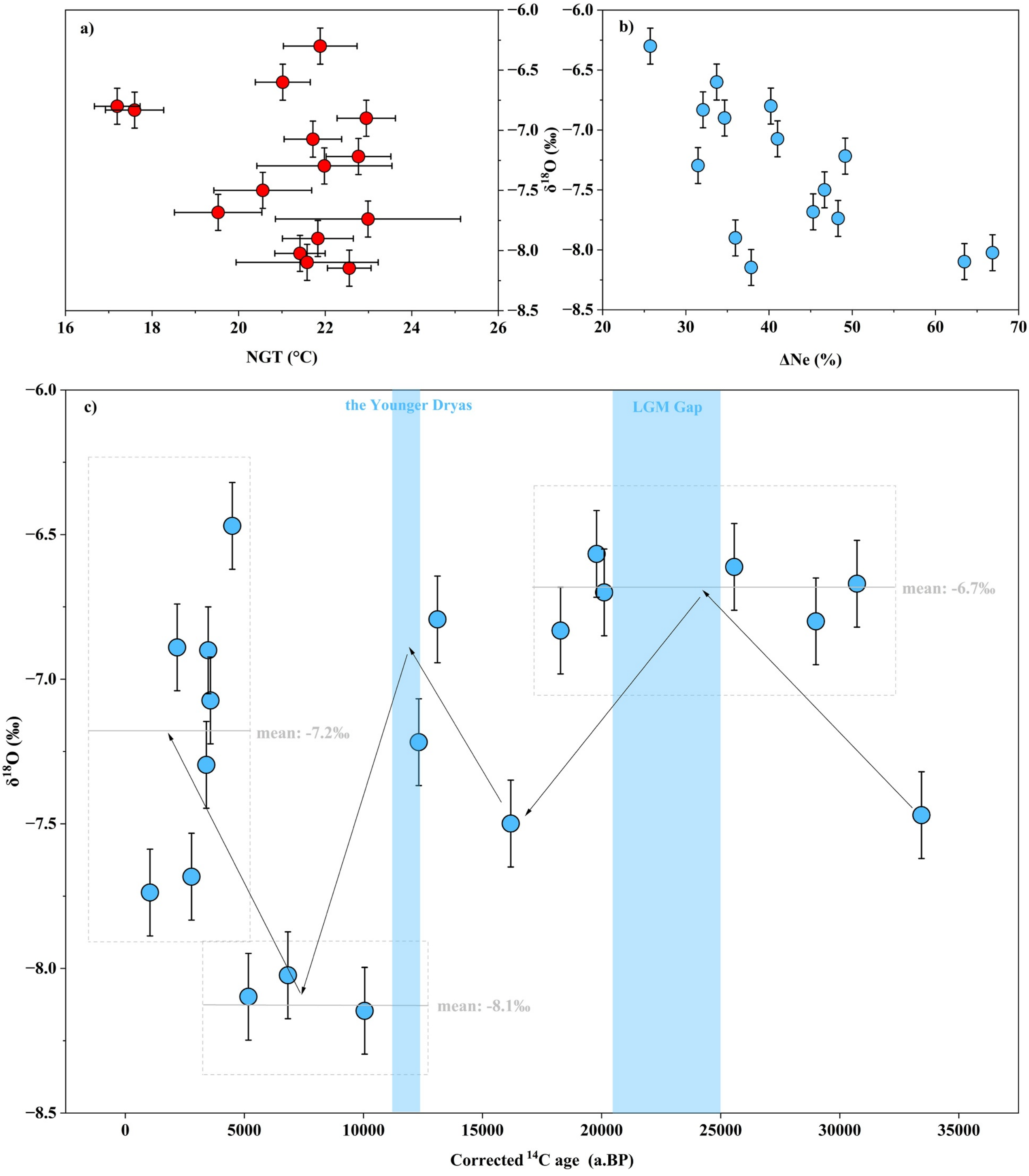

Figure 3. Relationships among groundwater tracers in the Leizhou Peninsula. (a) $\delta^{18}O$ versus noble gas temperature showing no clear correlation, (b) $\delta^{18}O$ versus excess air (ΔNe) showing strong covariance, and (c) temporal variations in $\delta^{18}O$ indicating suppressed recharge during the Last Glacial Maximum, a short-lived excursion at the Younger Dryas, and intensified precipitation in the early Holocene.

5 ka show a mean $\delta^{18}O$ value of ~-7.2‰, but individual points are scattered within a relatively wide range, suggesting variability in recharge conditions on shorter timescales. Between 5 and 10 ka, $\delta^{18}O$ values become markedly more negative (down to -8.1‰), consistent with intensified monsoon precipitation and stronger amount effects. A transitional interval from 10 to 16 ka shows moderately depleted values, reflecting intermediate recharge conditions during the deglaciation. Within this interval, one enriched excursion around $\sim$12 ka may

reflect the Younger Dryas, indicating a short-term return to drier and colder conditions. In the Late Pleistocene, isotopic patterns highlight a distinct structure around the LGM. Samples dated to ∼18–30 ka yield relatively enriched values (mean ∼−6.7‰), contrasting with more negative $\delta^{18}O$ before ∼30 ka. The age distribution shows an absence of samples dating to the peak LGM, which may reflect reduced recharge under colder and drier climatic conditions.

These isotope-excess air relationships provide a hydrological counterpart to the NGT record. Whereas NGTs constrain the thermal history of recharge, $\delta^{18}O$ and ΔNe capture shifts in precipitation amount and recharge processes tied to monsoon variability. By combing these proxies, the Leizhou record documents both the thermal history and hydroclimatic variabilities, providing a comprehensive view of monsoon dynamics in tropical East Asia.

3.4. Climate Transitions Revealed by Groundwater: Regional Proxy Comparison

The joint interpretation of NGTs and stable isotopes provides an integrated view of both thermal and hydrological aspects of past climate change in the Leizhou Peninsula. For regional comparison, we focus on two well-established monsoon-sensitive archives (Figure 4). The first is the $\delta^{13}C_{TOC}$ record of organic matter from Huguangyan Maar Lake (21.15°N, 110.28°E) in Leizhou Peninsula, widely interpreted as a proxy for effective precipitation and catchment hydrology (Q. Liu et al., 2005; Mingram et al., 2004). The second is the speleothem $\delta^{18}O$ record from Sanbao Cave (31.67°N, 110.43°E) in Hubei Province, which forms part of the East Asian monsoon reconstruction extending back 640 ka (Cheng et al., 2016). Both proxies primarily reflect precipitation amount and monsoon intensity, with more negative values corresponding to stronger monsoon rainfall and more positive values indicating weaker monsoon activity and reduced precipitation, making them directly comparable to the hydrological signal preserved in Leizhou groundwater isotopes.

Between 33 and 26 ka (pre LGM), groundwater $\delta^{18}O$ values are relatively depleted (∼−7.5‰), suggesting cooler but somewhat wetter conditions compared to the subsequent peak glacial stage. During the conventional LGM, NGTs indicate a minimum cooling of ∼5°C–6°C relative to present, while groundwater $\delta^{18}O$ becomes enriched and an apparent recharge gap emerges, consistent with suppressed infiltration under cold and arid conditions. Both Huguangyan and Sanbao records reveal weaker monsoon intensity and drier climate, underscoring the regional extent of glacial aridity.

In the deglacial interval (∼19–10 ka), NGTs show progressive warming and groundwater $\delta^{18}O$ becomes more negative, reflecting enhanced precipitation and strengthening of the summer monsoon. Superimposed on this trend is a positive isotopic excursion around ∼12 ka that may reflect the Younger Dryas, indicating a short-term return to drier and colder conditions. Similar features are evident in both lake and speleothem records, suggesting a synchronous regional expression of this abrupt event.

The early Holocene (∼10–5 ka) marks a hydroclimatic optimum in the groundwater record, with NGTs reaching near-modern values and $\delta^{18}O$ shifting to the most depleted levels, indicative of strong summer monsoon precipitation. This period coincides with low $\delta^{13}C_{TOC}$ in Huguangyan sediments and highly negative $\delta^{18}O$ in Sanbao speleothems, both consistent with intensified monsoon precipitation. The agreement among these independent archives highlights the robustness of the early Holocene monsoon maximum.

Since ∼5 ka, NGTs remain stable near modern values, while groundwater $\delta^{18}O$ gradually shifts toward more enriched values, pointing to reduced precipitation amounts. Regional records also show a weakening of the East Asian monsoon during the mid-to-late Holocene, with Huguangyan and Sanbao both recording a drying trend punctuated by centennial- to millennial-scale fluctuations, including a notable dry and cold event around 3–4 ka.

Together, the integration of groundwater NGTs and isotopes with lake and speleothem records provides a dual constraint on past climate, capturing both temperature and hydroclimatic variability. The close correspondence among these archives underscores the value of groundwater as a complementary paleoclimate record in tropical East Asia, bridging terrestrial and regional perspectives on monsoon dynamics.

4. Conclusions

Groundwater from the Leizhou Peninsula extends noble gas paleothermometry into the tropical East Asian monsoon region, providing a rare constraint on low-latitude climate sensitivity. Our results demonstrate a

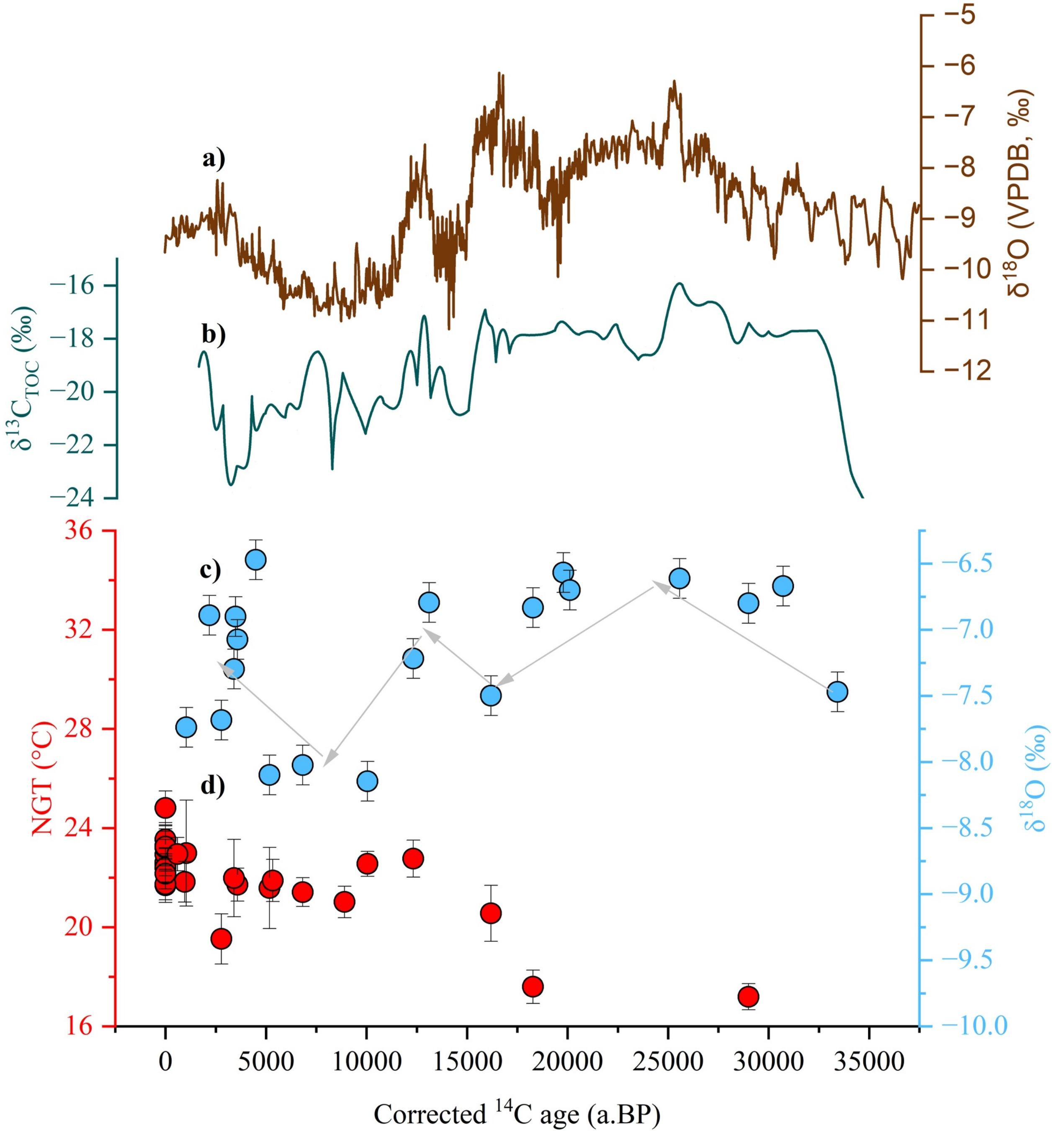

Figure 4. Comparison of Leizhou groundwater records with regional monsoon proxies. (a) Sanbao Cave speleothem $\delta^{18}O$, (b) Huguangyan Maar Lake sediment $\delta^{13}C_{TOC}$, and (c, d) Leizhou groundwater $\delta^{18}O$ and noble gas temperatures. All record show weakened monsoon and reduced recharge during the Last Glacial Maximum, enhanced precipitation in the early Holocene, and short-term variability such as the Younger Dryas.

minimum glacial-to-Holocene warming of ∼5°C–6°C and reveal that stable isotopes, when interpreted together with EA, primarily track changes in precipitation amount and recharge dynamics. This dual-proxy approach highlights the value of fossil groundwater as an integrated archive of both thermal and hydrological history. Importantly, the Leizhou groundwater record shows strong coherence with regional monsoon archives, including the Huguangyan Maar Lake $\delta^{13}C_{TOC}$ record and Sanbao Cave speleothem $\delta^{18}O$, reinforcing the interpretation of glacial aridity, deglacial transitions, and the early Holocene monsoon maximum. Beyond the regional context, the Leizhou record fills a critical low-latitude-gap in continental paleoclimate reconstructions and provides quantitative benchmarks for evaluating climate model simulations of monsoon variability and glacial-interglacial change, complementing recent efforts to use noble-gas-derived temperature data to test model representations of terrestrial climate sensitivity (Seltzer et al., 2023).

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

All the noble gases, stable isotopes, and radiocarbon data used in this study from groundwater of the Leizhou Peninsula are publicly available in the open-access repository Zenodo via Li (2025).

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