Earth Planet. Sci. Lett. 626 (2024) 118534

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

journal homepage: www.elsevier.com/locate/epsl

Noble gases in groundwater reflect wet-season temperature in an arid, monsoonal, and mountainous environment

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ARTICLE INFO

Keywords:
Noble gas temperatures
Indian summer monsoon
Paleo climate
Arabian Peninsula

ABSTRACT

Comparing directly measured soil temperatures with noble gas recharge temperatures (NGTs) inferred from noble gas concentrations indicates that the infiltrating soil water equilibrates with soil air near the soil surface during the rainy season. Therefore, NGTs of groundwater recently recharged by the Indian Summer Monsoon (ISM) in the Dhofar Mountains in southern Oman reflect the soil temperatures of the 3-month period and do not represent an annual mean. This finding highlights the need to account for seasonality when interpreting NGT data in regions with pronounced dry and wet seasons.

We extend the observations from the southern flank of the Dhofar Mountains to three wells situated on the northern flank of the Dhofar Mountains. Two of these wells yield water of Holocene age that was recharged by the monsoon, their NGT signals are therefore classified as seasonal. The NGT calculated from a third well for recharge conditions during the Last Glacial Maximum (LGM), when the ISM was absent, is approximately 3 °C lower than that of the two Holocene wells. The lower LGM noble gas temperature corresponds well with the lower annual Sea Surface Temperature (SST) in the nearby Arabian Sea.

NGTs from published studies from northern Oman are 1–3 °C higher when compared with our data of the same period in the southern Oman. We explain this regional difference of reconstructed temperatures for the LGM and Holocene groundwater with a more continental climatic influence on the infiltration conditions further to the north. The published NGTs from northern Oman show a large temperature difference between the late Holocene and the LGM. In view of our finding of seasonal NGT signals under monsoonal climate, part of this difference may reflect a change in the precipitation regime rather than in air temperature.

1. Introduction

Temperature reconstruction on glacial timescales is crucial for our understanding of Earth's climate sensitivity and for simulating future climate scenarios (Tierney et al., 2020). A well-studied period in terms of temperature reconstruction is the last glacial maximum (LGM) (23 to 18 ka before present (BP)), which is the most recent extended period with a climate very different from that of today. One climate archive to study the LGM is groundwater, which can be dated by radiocarbon and offers climate proxies such as stable isotopes of water and dissolved noble gases. A recent global compilation of noble gas temperature (NGT) records in groundwater indicates that during the LGM, mean land surface temperatures in low to mid latitudes were around 6 °C lower than in the Late Holocene (Seltzer et al., 2021). NGTs in general closely match the mean annual soil temperature (MAST), which in turn is linked to mean annual air temperature (MAAT). However, studies in mountainous fractured rock aquifers have shown that these associations may not hold under all conditions (Manning and Solomon, 2003; Masbruch et al., 2012; Niu et al., 2017; Warrier et al., 2012).

The fundamental assumption of the noble gas thermometer is that infiltrating soil water equilibrates with soil air such that the dissolved noble gas concentrations reflect the conditions at the groundwater table,

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https://doi.org/10.1016/j.epsl.2023.118534
Received 4 September 2023; Received in revised form 30 November 2023; Accepted 3 December 2023
Available online 12 December 2023

where the cut-off from temperature-dependent gas exchange occurs (Stute and Schlosser, 1993). This assumption has been empirically validated in coarse-grained sediments (Klump et al., 2007). The NGT should then correspond to the water table temperature (WTT), which is expected to closely match the surface MAST except for very shallow water tables, when WTT exhibits seasonal variation, or for very deep water tables, when geothermal heat and gravitational separation may influence NGTs (Stute and Schlosser, 1993). The coupling of MAST or WTT to MAAT depends on various factors such as snow cover and vegetation (Cey, 2009; Stute and Schlosser, 1993) and is arguably the weakest link connecting NGTs to the climatologically relevant surface air temperatures (Aeschbach-Hertig and Solomon, 2013). Our study investigates the relationships between soil, air, and noble gas temperatures for a coastal, mountainous site in the south of the Sultanate of Oman, which is strongly influenced by the indian summer monsoon (ISM).

The primary objective of our study is to investigate how present day ISM-influenced infiltration conditions are reflected by NGTs of recently

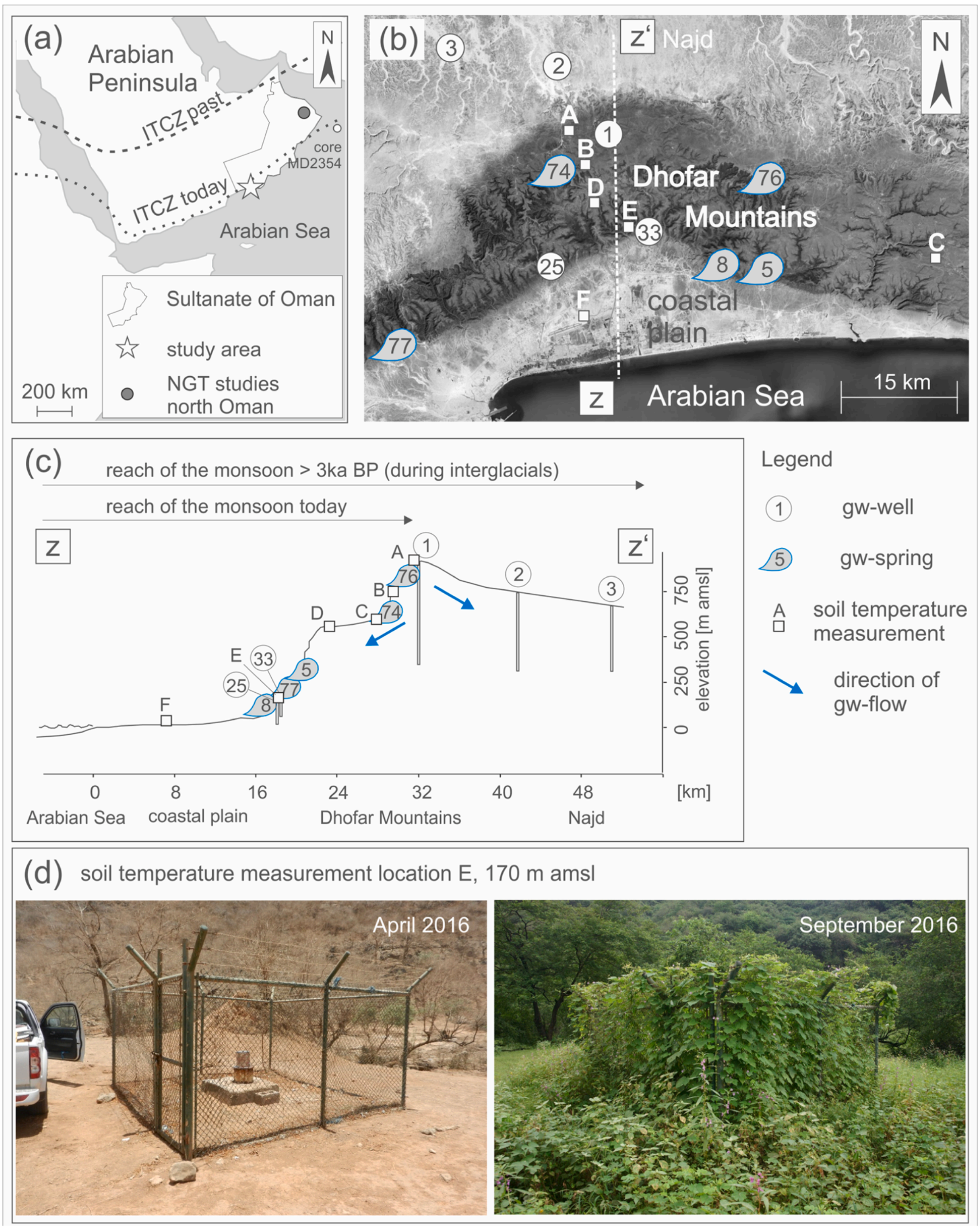

Fig. 1. (a) The study area is located on the south of the Arabian Peninsula. Dashed line - ITCZ summer position during the early Holocene (b) Dhofar Mountains separate Arabian Sea from the arid Najd. (c) Cross-section displaying the measurement and sampling locations along the mountain profile. (d) Site conditions at soil temperature measurement location E before (left) and at the end (right) of the monsoon season.

recharged groundwater. Additional data of NGTs from groundwater recharged during the last glacial (without ISM influence) and the Holocene (under ISM influence) was investigated to elucidate glacial-interglacial temperature differences of soil temperatures in the southern Oman. Spatial and temporal variability of NGT data for the southern Arabian Peninsula is discussed by comparing our results with published data for northern Oman. For this reason, (paleo)-hydrologic conditions for northern Oman are also briefly described.

2. Geological and climatological setting

2.1. Study area

The study area is the coast-facing south side of the Dhofar Mountains in the Dhofar Governorate in southern Oman (Fig. 1a). Reaching heights of 900 to 1300 m above sea level, the Dhofar Mountains separate the Arabian Sea in the south from the inland area in the north (Fig. 1b, 1c). In the center, the mountains delimit a coastal plain. To the north, a rocky arid desert joins the mountains, which merges into the dunes of the Rub Al-Khali Desert further north.

Annual rainfall is around 100 mm on the coastal plain and 250 mm in the mountains (Hildebrandt et al., 2007), with 90% of these amounts delivered by the monsoon (Fleitmann et al., 2003). Year-to-year variability is significant, with up to 500 mm recorded during one monsoon season.

Data from 2017 and 2018 show highest rainfall at elevations from 300 to 700 m (Michelsen et al., 2023). Monsoon precipitation consists of heavy fog and light drizzle and is a persistent source of moisture from mid/late June to early September, peaking in July and August. The persistent but low monsoon rainfall rates prevent infiltration excess overland flow, so that all precipitation is absorbed into the soil. Hildebrandt et al. (2007) showed that, in 2004, a wetting front entered the soil at the start of the monsoon and took about 12 days to travel from 10 to 60 cm depth. The water contents at both these depths remained fairly constant for the duration of the monsoon (also confirmed for 2003). In combination with the continous infiltration from monsoon rains this indicates a relatively steady downward flow of water through the soil during the monsoon. The period of higher wetness at 60 cm depth lasted about 40 days in 2003, and about 80 days in 2004. When the monsoon was over, the water content at both depths receded exponentially in both years. For both years, 150 days after the monsoon started, the water content at 60 cm depth was back at or very close to pre-monsoon levels. Downward flow at and below this depth will likely be negligible after this time, until the start of the next monsoon.

How groundwater flows deeper to the main aquifer is not yet completely understood. At the mountain top the groundwater level in the main aquifer is between 500 and 600 m above mean sea level (m amsl) and groundwater flow takes place in a southerly and northerly direction (Friesen et al., 2018). Groundwater level data from wells in the mountains are not available. Groundwater levels in wells at the foot of the mountain increase every year during the monsoon season. Water level data for well 25, which was also used in the present study, show for the time period 2012–2018 (2014 missing) water level rises between 2.1 and 8.2 m during the monsoon season and response times after monsoon onset from 22 to 52 days (see Fig. S1–1). The limestones of the Dhofar Mountains are also known to exhibit karst features like sinkholes (Al-Kindi and Hird, 2020) and groundwater springs (Strauch et al., 2014). Summarizing this information, one explanation for the groundwater flow to the main aquifer could be, that after the infiltration front has passed the soil layer, the water follows preferential pathways.

Lush vegetation develops in the mountains during the monsoon season (Fig. 1d). With the end of the monsoon and the absence of precipitation, the vegetation changes. Due to the drought, but above all due to the grazing - the entire area is openly grazed primarily by camels and cows - the vegetation decreases sharply in a short time, baring parts of the soil within 2 to 3 months.

Annual mean air temperature in the coastal plain is about 26.5 °C and 21.2 °C at the top of the mountain (for more information see SI-2). Except for the southern flanks of the mountains and the coastal plain, both of which are influenced by the monsoon, the area is arid to hyperarid. Summer air temperatures in the interior of Oman are well above 25 °C (up to 40 °C at station Thumrait in the centre of Dhofar and almost 45 °C at station Nizwa (Directorate General of Meteorology, 2022). Station Nizwa is close to the study areas of the published noble gas studies for northern Oman (Fig. 1a), presented in Section 2.3.

2.2. The indian summer monsoon at the Arabian Peninsula

The indian summer monsoon (ISM) today only brings monsoon rains to some coastal regions in Yemen and southern Oman, but during interglacials it reached further into the Arabian Peninsula. Closely connected to the position of the intertropical convergence zone (ITCZ), the ISM consists of strong southwest winds and occurs between June and September. The southwesterly winds lead to upwelling of cold water along the south-east facing coast of the Arabian Peninsula (see Fig. 1 in Saher et al., 2007) and a significant reduction of the sea surface temperature (SST) offshore Dhofar to 24–25 °C during summer (SI Fig. S3–1; Fig. 1A in Böll et al., 2015). The cooler sea water caused condensation in the warm moist air carried towards the coast, giving rise to rainfall on the windward side of the Dhofar Mountains. The daily rainfall intensity is low (<5 mm d^{-1}, Fleitmann et al., 2004), but moisture is continuously provided from late June to early September, making the ISM the main source of precipitation in the area. In winter the ITCZ migrates to the south, and dry northeastern winds dominate that cross the Arabian Sea and the northern Indian Ocean. A bimodal temperature distribution of SST is characteristic for the Dhofar area (SI Fig. S3–1) but is absent at the north-facing coast offshore Muscat (SI Fig. 3–1, 3–2), which is north of the upwelling region.

The regional boundaries of ITCZ and ISM varied according to the occurrence of glacials and interglacials. The summer monsoon reached further north than today during peak interglacials such as the early Holocene (Fig. 1a). The occurrence and pronounced seasonality of the ISM has been described based on marine sediments (e.g. Core MD2354 in Fig. 1a, Böll et al., 2015; Clemens and Prell, 2003) and continental archives, i.e. speleothem growth (Burns et al., 2001; Fleitmann et al., 2003; Fleitmann and Matter, 2009). The speleothem studies relevant here are from the same areas for which also noble gas data are available. Two speleothem studies were done in caves at the southern rim of the Arabian Peninsula (Kahf Defore and Qunf Cave), close to our study area (star in Fig. 1a). Speleothem data from Hoti Cave provide evidence for paleoclimatic changes for the northern Oman Mountains, from where NGTs were presented by Weyhenmeyer et al. (2000) (black circle in Fig. 1a).

Concentrating on the last 25 ka, marine and continental archives indicate that monsoon intensity during the LGM was weaker than during the Holocene. Depending on the type of paleoclimatic archive used, monsoon occurrence in the northwestern Arabian Sea or the southeastern Arabian Peninsula is described somewhat differently for the period from 25 to 10 ka BP. This is because marine records of SST describe the intensity of the monsoon winds, while terrestrial records of speleothem growth indicate the occurrence of monsoon rains above 300 mm per year (Fleitmann et al., 2011) or variations in intensity above that lower limit. In the LGM, SSTs (alkenone-based) in the western Arabian Sea were generally low, which was caused by the glacial conditions (Böll et al., 2015). Then SST in the Arabian Sea rose by about 3 °C above the glacial SST at the LGM-Holocene transition from 17 to 15 ka BP. After about 14 ka BP SST in the western Arabian Sea slightly decreased due to increasing monsoon intensity and thus increasing coastal upwelling of cold Indian Ocean Water. With decreasing monsoon intensity after 9.5 ka BP, SST slightly rose again but with the monsoon and the upwelling still present, no major rise in SST occurred. Speleothem growth indicating monsoon activity after the LGM is first observed at 10.5 ka BP in the northeastern Arabian Peninsula (Burns et al., 2001; Fleitmann et al., 2003).

Both archives have in common that they describe the peak of the monsoon activity for the early Holocene (approx. 9.5 ka BP) with significantly greater intensity of precipitation than today (Böll et al., 2015; Fleitmann et al., 2022). The studies also agree that monsoon intensity decreased and that ITCZ and ISM have gradually retreated southwards since then (Böll et al., 2015; Burns et al., 2001; Fleitmann et al., 2003, 2007). According to the speleothem studies the last time the ISM reached northern Oman was the early Holocene at around 10.6 ka BP (Fleitmann et al., 2022, 2007). The minimum distance from Hoti Cave in northern Oman to the coast in the direction of the prevailing ISM winds (south-westerlies) is 500 km. Accordingly, this is the distance the ISM winds had to travel over land before reaching the Hoti Cave or the study areas of the northern NGT studies described in Section 2.3.

From about 6.3 to 2.7 ka BP, there has been a gradual southward shift of the ISM to the present-day position (Lézine et al., 2017). In north Oman the ISM was replaced by a moisture source from the north (Fleitmann et al., 2022). Nowadays the ISM is only present in southern Oman. Compared to the early Holocene, when ITCZ and ISM were further north, the duration of the monsoon in the south was probably longer (Böll et al., 2015), but otherwise the monsoon was also characterized by a pronounced seasonality (Nicholson et al., 2020).

2.3. Previous noble gas temperature studies (northern Oman)

The LGM to late Holocene temperature increase for the Arabian Peninsula may be estimated from one data set of NGTs, that was obtained from a study area located in the north of Oman (Weyhenmeyer et al., 2000). Seltzer et al. (2021) have compiled and re-evaluated existing noble gas datasets for low-and-mid-latitudes, including the one of Weyhenmeyer et al. (2000) from northern Oman, using the CE excess air model and recent noble gas solubility data (Jenkins et al., 2019), as well as standardized criteria to calculate Holocene and LGM mean temperatures. For north Oman, they obtained 2 - 3 °C lower NGTs than the original study. In the present study the Seltzer et al. (2021) values will be used.

Based on ^{14}C groundwater ages, Weyhenmeyer et al. (2000) presented NGTs for the LGM and modern infiltration conditions for the coastal Al Khwad Fan aquifer in northern Oman. A third group of samples with Holocene ^{14}C ages were described as mixtures of late pleistocene and modern water. A study from a fractured rock aquifer (Samail ophiolite) in the mountain range bordering the coastal plain also presented NGTs, but without independent dating (Paukert Vankeuren et al., 2019). That study therefore used the NGT information to assign samples to different climatic periods. For both northern studies (black circle in Fig. 1a), the recharge areas are approximately 50–100 km from the coast. They are about 750 km away from the southern Dhofar Mountains, but have a similar setting, with recharge altitudes of 620 m (Paukert Vankeuren et al., 2019) and 1000 m (Weyhenmeyer et al., 2000).

NGTs of samples representing recently recharged groundwater are 30° to 33 °C for the Samail Ophiolite (Paukert Vankeuren et al., 2019) and 31.4 ± 1.7 °C for the Al Khwad Fan (Seltzer et al., 2021). The samples of Holocene age of the Al Khwad Fan are assigned with NGTs of about 27.1 ± 1.4 °C (Seltzer et al., 2021). The NGTs of the three LGM samples are given with 24.0 ± 1.0 °C (Seltzer et al., 2021). Two samples for the Samail Ophiolite aquifer confirmed this temperature range with NGTs of 24.7° to 25.1 °C, which by comparison with the data from the coastal plain was tentatively attributed to recharge during a glacial period (Paukert Vankeuren et al., 2019).

Both studies suggest that the precipitation sources changed over time. Based on stable isotopes, rain during past glacial periods likely originated from the Indian Ocean. With the ITCZ at a much more southern position during the LGM, the ISM is considered unlikely as a recharge source (Weyhenmeyer et al., 2000).

Samples representing modern water plot along the Northern Oman Groundwater Line (N-GWL, $\delta^2H=5.3 * \delta^{18}O+2.7$; (Weyhenmeyer et al., 2000), which represents groundwater recharged from today's precipitation, which occurs mainly in winter and spring (Fleitmann et al., 2022).

For the Al Khwad Fan aquifer and the Samail ophiolite aquifer it was observed that the modern NGTs agree well with measured groundwater temperatures at the water table (about 33 °C), which are assumed to represent the annual surface ground temperature (Paukert Vankeuren et al., 2019; Weyhenmeyer et al., 2000). The corresponding air temperature is 28.5° to 30 °C (Paukert Vankeuren et al., 2019).

3. Methods

3.1. In situ soil temperature measurements

We first examined present day monsoonal infiltration conditions. For this purpose, soil and air temperatures were measured over several monsoon seasons at different elevations in the recharge area. Soil temperatures were measured on the south slope of the Dhofar Mountains at locations A to E (Fig. 1b, 1c). Waterproof TidbiT® probes (Onset Computer Corporation, USA), which measure in the range of −20 to 70 °C (in air) with an accuracy of 0.1° to 0.2 °C, were used. The probes were buried at 15 (+/−1) cm below the ground surface. The measurement points are located at elevations between 169 and 890 m amsl (Table S4–1). Fig. S4–1 to S4–7 show the stations at different times of the year. Stations A, C, D and E are relatively flat sites covered with grass (up to 30 cm) during the growing season but bare for the remainder of the year. Site C is split into two measurements: C1 is located inside a fenced area with 5-m high trees, C2 is located outside the fence in grassland (Fig. S4–3 to S4–5). The locations are about 10 m apart. While site C1 is overgrown or shaded to a varying degree all year round, the vegetation at site C2 disappears from December to July. Site C1 likely approximates conditions similar to those before the start of deforestration and grazing. Soil temperature values were calculated for the individual months of the year and as annual means (MAST). Infiltration period soil temperatures (IPSTs) were calculated as the mean of the July and August soil temperatures.

3.2. Groundwater temperature detection

Groundwater temperatures were measured from 01/2012 to 11/2017 and 05/2018 to 07/2019 (well 33 at location E) and 04/2016–09/2018 and 09/2019–12/2021 (well 25) using HT Datalogger Type 575 (measuring range −5 °C to +50 °C, accuracy <0.1 °C). The temperature sensors were installed approximately 2 to 3 m below the lowest water level measured up to that point. During the observation period, the water levels at both wells fluctuated by up to 8 m. The sensor was therefore a maximum of 10 to 11 m below the water surface. It is assumed that, despite these fluctuations, the recorded temperatures are representative of the temperature at the water table (WTT) so that WTT can be used for the groundwater temperature. The observed WTTs are 29.7 °C for well 33 where the average water level is 15 m below the ground surface, and 28.9 °C for well 25 where the average water level is 20 m below the ground surface. The groundwater temperatures are almost constant (maximum fluctuations of 0.2 °C) and show no changes when water levels and soil temperatures change during the monsoon (for more details see SI-5.1). This supports the assumption that the recorded temperatures are accurate proxies for the WTT.

3.3. Water sampling for NGT determination

To investigate recharge conditions, noble gas temperatures of spring and groundwater in the Dhofar Mountains were determined. In summer 2017, five spring water samples and two groundwater well samples from the south slope of the Dhofar Mountains were taken (Fig.1b, 1c). The sampling locations (Table S5–1) were selected along the full elevation profile (Fig. 1c) according to the following criteria: On the one hand, relatively recently recharged water should be sampled. Here it was assumed that seasonal springs, which are relatively high up in the mountains, discharge such young/ recently recharged water. On the other hand, the different infiltration elevations should also be considered. Groundwater recharge takes place over the entire elevation profile.

In addition, three wells located on the north side of the Dhofar Mountains (Fig. 1b, c) dated to the end of the last glacial and to the Holocene, were sampled for subsequent NGT determination. These wells (site ID 1 to 3) were sampled in 2009 and were part of a multi-tracer study in which the ^{14}C ages of the wells were determined (Müller et al., 2016). Well 1 is located on the watershed, while wells 2 and 3 are 10 and 16 km north of it respectively.

Water samples for noble gas analysis were collected by tightly attaching a copper tube to the sampling hose connected to the well or spring (see SI-5–2). In order to seal the copper pipes in a vacuum-tight manner, they were squeezed together with stainless steel clamps (Werner Aeschbach-Hertig and Solomon, 2013). Noble gas isotopes were measured using mass spectrometry at the Institute of Environmental Physics, Heidelberg University, following the principles described by Beyerle et al. (2000).

3.4. Noble gas measurements and NGT evaluation

SI-5.3 gives detailed information on the applied methods for the determination of NGTs. The noble gas temperatures were determined using the software PANGA, following the recommendations by Jung & Aeschbach (2018). The standard choice of excess air model, the closed-system equilibration (CE) model (Aeschbach-Hertig et al., 2000) was used. The model parameters temperature T, entrapped air A, and fractionation F were treated as free fit parameters, whereas for the also unknown recharge elevation four levels (300, 500, 700, and 900 m amsl) were prescribed for each sample, provided the assumed recharge elevation exceeded the spring or well elevation. All samples yielded good fit results with the CE excess air model (Aeschbach-Hertig et al., 2000) for all possible recharge elevations. Most samples exhibit fractionated excess air, except those from the spring at site 76 and the water supply well 3, for which the CE model reduces to its limiting case of unfractionated excess air (UA).

4. Results and discussion

4.1. Soil and air temperatures

Surface soil temperature measurements in the Dhofar mountains show seasonal minima in winter and during the monsoon season in late summer (Fig. S4–8 to S4–10). Except for one atypically vegetated site, the soil is markedly (about 3 to 5 °C) warmer than the air throughout the year, but the difference is reduced to 0–3 °C in the monsoon period (Fig. S4–8, S4–9, Table 1). Mean annual soil temperature (MAST) is typically 2 to 3 °C higher than the infiltration period soil temperature (IPST), i.e., the mean surface soil temperature during the monsoon months July and August, but the offset is variable (Table 1).

4.2. Recharge temperatures

Modeled estimates of NGTs for samples from the southern slope vary between 22.4 °C (spring E, infiltration elevation 900 m) and 26.7 °C (well 33, infiltration elevation 300 m) when considering recharge elevations of 300 to 900 m (Table 2). The modeled NGTs depend systematically and nearly linearly on the assumed recharge elevations, with a slope of (-0.36 ± 0.01) °C per 100 m elevation for all samples that have a range of possible recharge elevations.

Table 1

Mean annual air temperature (MAAT), mean annual soil temperature (MAST), infiltration period (months July and August) air (IPAT) and soil (IPST) temperature for locations A to F (cf. Fig. 1). Sea surface temperatures offshore Salalah represent annual (AT) and seasonal (ST, mean of July and August) values.

Station	Elevation (m amsl)	T (°C)	2016	2017	2018	2019	2020	2021	1996–2021
A	890	MAAT	21.4	21.4[a]	21.2	21.5	-	22.7[b]	21.2
		MAST	-	-	26.4	-	-	-	-
		IPAT	20.6	21.7[a]	21.2	21.9	-	22.0[b]	21.1
		IPST	-	24.0	23.5	25.7	-	-	-
B	700	MAAT	(22.5)	(22.6)	(22.3)	(22.8)	-	(23.6)	(22.4)[d]
		MAST	-	-	26.7	27.6	26.8	27,7	-
		IPAT	-	23.0	-	-	-	-	(22.1)[e]
		IPST	-	24.6	23.6	24.9	24.8	24.1	
C1	620	MAAT	(23.0)	24.1[c]	(22.8)	(23.3)	-	(23.6)	(22.8)[d]
		MAST	-	25.4[c]	-	-	24.8	-	-
		IPAT	-	23.1	-	-	-	-	(22.6)[e]
		IPST	25.1	25.5	23.7	25.3	24.3	24.1	-
C2	620	MAAT	(23.0)	24.1[c]	(22.8)	(23.3)	-	(23.6)	(22.8)[d]
		MAST	-	28.2[c]	-	-	28.2	-	-
		IPAT	-	23.1	-	-	-	-	(22.6)[e]
		IPST	24.5	25.1	24.3	25.4	25.3	24.6	-
D	510	MAAT	(23.7)	(23.9)	23.5	(24.0)	-	(24.6)	(23.6)[d]
		MAST	-	-	27.8	-	-	-	-
		IPAT	-	23.0	22.4	23.5	-	-	(23.2)[e]
		IPST	-	25.3	24.4	-	-	-	
E	169	MAAT	(25.7)	(26.1)	(25.4)	(26.3)	-	(26.3)	(25.6)[d]
		MAST	-	-	-	31.3	-	-	-
		IPAT	-	-	-	-	-	-	(25.0)[e] -
		IPST	-	-	25.6	27.9	27.0	-	
F	22	MAAT	26.6	27.0	26.3	27.3	26.9	27.0	26.5
		MAST	27.6	29.2	28.8	30.7	30.2	30.8	-
		IPAT	25.3	26.2	25.5	26.7	27.0	26.5	25.8
		IPST	26.3	28.2	27.5	29.3	29.2	29.7	-
SST	0	AT	26.4	26.4	26.0	26.7	26.5	26.4	
Sal		ST	24.3	24.2	23.8	24.3	25.8	25.2	

[a] 02.08.–05.08. no data; [b] 23.07., 26.07., 28.07., 30.07., 31.07., 01.08., 04.08. no data; [c] time period 01.05.2017 - 30.04.2018; [d] calculated with −0.61°C per 100 m; [e] calculated with −0.54°C per 100 m; numbers in parentheses are calculated based on the measured data at station A and F.

4.3. Present day infiltration conditions

Comparing the NGTs with soil temperatures (MAST, IPST) and with groundwater temperatures shows a good accordance between monsoonal infiltration conditions (IPST) in the Dhofar Mountains (Table 1) and NGTs (Table 2).

The good agreement of NGT and IPST (Fig. 2) indicates that the noble gas concentrations of recently recharged groundwater in the Dhofar Mountains represent surface soil conditions during the monsoon season (IPST) and do not measure an annual average, such as the MAST. Since groundwater tables in the study area are far below the zone that is influenced by seasonal soil temperature changes (top few meters, e.g., Stute und Schlosser, 1993), the cut-off from gas exchange apparently happens before the infiltrating water reaches the groundwater body, directly in the top soil, within the depth range that experiences seasonal temperature fluctuations. The characteristics of the monsoon, with a dense cloud cover delivering a slow drizzle that falls nearly uninterrupted for weeks, provides long lasting and continuous high humidity and low evapotranspiration rates with relatively stable air- and soil temperatures (Fig. S2–1, S4–8, S4–9). The NGT signal reflects this environment, and preserves it while the water travels toward the groundwater body. The reasons why the signal is preserved are not entirely clear, but could be due to the karst features of the underlying limestones and the resulting preferential pathways (Al-Kindi and Hird, 2020; Strauch et al., 2014).

The presence of seasonality in NGTs has previously been discussed in two settings of mountainous fractured rock aquifers: Mountains in cold climates where pulsed recharge driven by snowmelt was proposed to lead to soil and NGTs below mean air temperatures (Manning and Solomon, 2003; Masbruch et al., 2012); and tropical volcanic islands, where rapid recharge through fractured basalts was inferred as a mechanism to preserve wet season temperatures in the noble gas signatures (Niu et al., 2017; Warrier et al., 2012).

The data presented here show that the stronlgy seasonal precipitation regime can result in the NGT describing a seasonal (IPST) instead of an annual mean value (MAST).

Measurements at site C1 show that the differences between IPST and MAST as well as MAST and MAAT are significantly smaller when the soil is vegetated (Fig. S4–9), demonstrating the impact vegetation can have on MAST.

4.4. Paleotemperature interpretations in south Oman

To compare modern NGTs from the southern flank of the Dhofar mountains with temperature conditions in the past, we include wells containing older waters from the northern flank (for locations see Fig. 1b, c). According to their ^{14}C ages, well 1 (7.3 ± 2 ka) and well 2 (4.4 ± 2 ka) were recharged in the early and middle Holocene, while well 3 (17.2 ± 1ka) was recharged at the end of the LGM (Müller et al., 2016).

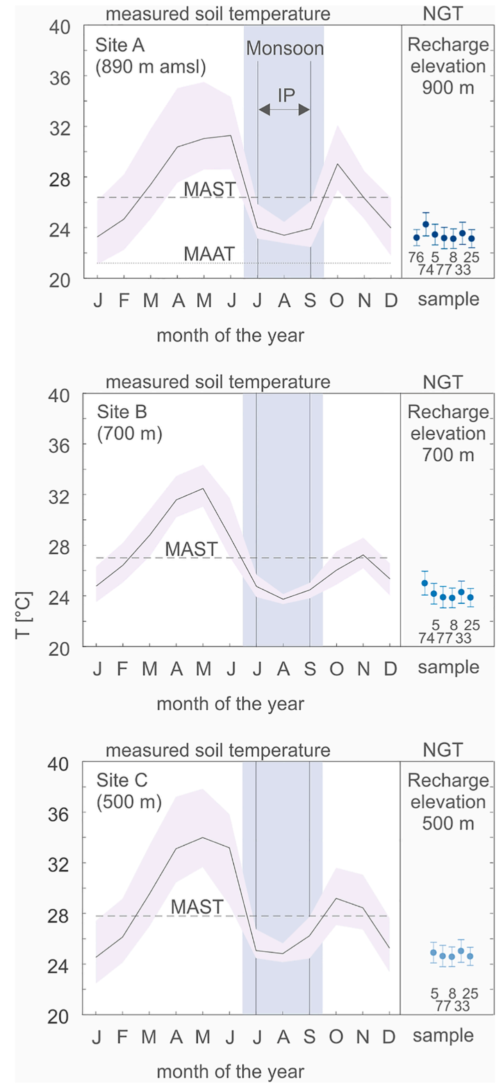

Fig. 2. Soil temperatures (windowed means) with shaded areas representing lower and upper quartile, Mean Annual Air (MAAT) and Mean Annual Soil (MAST) temperatures versus time for locations A to C in the Dhofar Mountains. Calculated Noble Gas Temperatures (NGTs) for the recharge elevations 900 m (Site A), 700 m (Site B) and 500 m (Site C) show a good agreement with the soil temperatures during the Infiltration Period (IP). NGTs for location 76 (785 m amsl) and location 74 (635 m amsl) are only displayed for recharge elevations above the site location (900 m and 700 m, respectively).

Table 2
Groundwater Noble gas temperatures with uncertainties[a] considering different recharge elevations.

Location (elevation)	Recharge elevation 900 m amsl NGT [°C]	Recharge elevation 700 m amsl NGT [°C]	Recharge elevation 500 m amsl NGT [°C]	Recharge elevation 300 m amsl NGT [°C]
76 (785 m amsl)	23.25±0.64			
74 (635 m amsl)	24.30±0.92	25.03±0.94		
5 (273 m amsl)	23.49±0.82	24.19±0.82	24.89±0.81	25.60±0.80
77 (193 m amsl)	23.22±0.85	23.91±0.85	24.62±0.85	25.33±0.84
8 (116 m amsl)	23.16±0.78	23.85±0.79	24.56±0.78	25.28±0.78
33 (169 m amsl)	23.59±0.88	24.31±0.89	25.03±0.90	25.76±0.91
25 (132 m amsl)	23.17±0.72	23.88±0.72	24.60±0.73	25.33±0.73
1 (810 m amsl)	24.98±0.88	25.70±0.89		
2 (655 m amsl)	24.39±0.86	25.10±0.87		
3 (624 m amsl)	21.43±0.74	22.30±0.76		

[a] uncertainties represent error propagation from the analytical 1 sigma errors of the measured noble gas concentrations to the estimated parameters and are calculated from the covariance matrix of the fit parameters evaluated in PANGA.

The calculated NGTs are 25.0 ± 0.9 °C for well 1 (at 900 m recharge elevation), 24.4 ± 0.9 °C for well 2 (900 m) or 25.1 ± 0.9 °C (700 m), and 21.4 ± 0.7 °C for well 3 (900 m) or 22.3 ± 0.8 °C (700 m), respectively (Table 2). The Holocene infiltration conditions, represented by the NGTs of the northern slope wells 1 and 2 are within approximately 1 °C of today's infiltration conditions, which are represented by the NGTs of samples 5 to 76 from the southern slope (Fig. 3, left panel). For both time periods Holocene and modern day, the ISM was the main rainfall source (Fleitmann, et al., 2003). The temporal consistency in the precipitation system suggests consistent or at least similar infiltration conditions. Following this line of argument, it is likely that the Holocene NGTs also represent a seasonal soil temperature.

The values for well 3, representing infiltration conditions at the end of the LGM, are ~3 °C lower than the values in the Holocene (Fig. 3, left panel). This temperature difference is thus much smaller than the temperature shift of ~6 °C from LGM to the late Holocene for mean low-latitude land surface temperatures (Seltzer et al., 2021). A major uncertainty for the interpretation is that the LGM precipitation system (source, duration, yearly distribution) is unknown and thus it is also unclear whether the glacial NGT describes a seasonal or an annual mean. However, some information is available about source characteristics for wells 1–3 (Müller et al., 2016). Stable isotopes ($\delta^{18}O/\delta^{2}H$ -H_2O) of well 3 (LGM) are only slightly depleted (Müller et al., 2016) compared to the values of wells 1 and 2 (Holocene), which represent monsoon precipitation. ISM precipitation can therefore not be completely excluded. However, so far there is no evidence of monsoon precipitation during or shortly after the LGM. Given the proximity of the study area to the Arabian Sea, well 3 most likely received precipitation formed over the Arabian Sea, which did not necessarily had to be delivered during monsoons. Vegetation cover, whose influence on MAST was shown above, is also unknown, as are other paleorecharge conditions.

Nevertheless, we propose that even without influence of the ISM the temperatures of the western Arabian Sea had a significant influence on the air temperatures in the study area. Fig. 3 (left panel) shows the SST of the western Arabian Sea for the last 25 ka according to Böll et al. (2015). Lower temperatures during the LGM were followed by a temperature rise of about 3 °C at the transition from the LGM to the Holocene. After that, no further significant temperature increase occurred, which coincides with the onset of upwelling due to the monsoon winds. The LGM - Holocene SST difference reported for the Oman upwelling area in the western Arabian Sea is 2–3 °C (Böll et al., 2015; Gaye et al., 2018). The estimated NGTs from wells 3 to 1 show the same trend of temperatures when compared to SST-calculations (Fig. 3, left panel).

4.5. Comparing NGTs in north and south Oman

The NGT data from northern Oman (Seltzer et al., 2021) are generally at least 2 °C above those for southern Oman (Fig. 3). For the LGM the north - south difference is 2–3 °C while the modern northern NGTs are 6° to 7 °C higher than the NGTs of recently recharged groundwater in the south. The samples classified as mixed water (Weyhenmeyer et al., 2000) with ^{14}C ages of Holocene age, are 2–3 °C above the southern samples from the Holocene. In the following, these samples are discussed as Holocene samples, whereby it is pointed out that this interpretation is subject to uncertainties due to their initial classification as mixtures (Weyhenmeyer et al., 2000). However, the stable isotope values of the wells indicate that the water stems from the Indian Ocean. They plot also within the values for early holocene monsoon precipitation (see Fig. S6–1) derived from stalagmites from the nearby Hoti Cave (Fleitmann et al., 2022). Our interpretation is that the northern Holocene samples were recharged mainly by the ISM.

As for the LGM sample 3 from the northern flank of the Dhofar Mountains, it is difficult to discuss the NGT data for the LGM in north Oman without knowing the precipitation regime (seasonality, source) or site conditions (vegetation). One explanation for the 2–3 °C higher NGTs of the northern LGM samples when compared to sample 3 from south Oman could be a continental influence. Climate models calculated that the Arabian Peninsula was up to 5 °C warmer than the SST of the Arabian Sea during the LGM (DiNezio et al., 2018). The northern LGM noble gas temperatures possibly reflect these higher continental temperatures as the coast is ~100 km away and the cooling influence by the sea is reduced. In contrast, in the southern coastal study area the SST of the nearby Arabian Sea determined the ambient onshore temperatures during the LGM.

During transition from LGM to the Holocene the NGTs increased by about 3–4 °C in Northern Oman (Fig. 3, right panel). The trend of NGT warming agrees with the increase in SST outside the upwelling area in the Arabian Sea (Fig. 3, core SO90–93KI, core location given in Fig. 1 of Böll et al., 2015). The NGTs of the northern holocene samples are 2–3 °C above the southern samples from the Holocene, with the ISM as the main recharge source in south and north Oman during that period. We also explain the higher NGTs in north Oman with a continental effect, assuming that summer air temperatures in central Oman during the Holocene were roughly similar to those of today (25–45 °C). To reach the northern study areas the moist wind had to travel over the heated central area (min. 500 km transit). Although we have no information about e.g. wind speeds, turbulent mixing of air masses, etc. we consider warming of the air masses from about 24°−25 °C at the southern coastal upwelling areas to IPSTs of 27°−28 °C at the northern recharge areas to be not unlikely. As for the southern monsoon influenced samples, the NGTs of the Holocene monsoon-fed samples from the north presumably also present a seasonal value and not an annual mean.

We assume that infiltration conditions during the monsoon in the north were most likely similar to those observed today in the south, with the equilibration of soil water and soil air taking place in the topsoil. That changed with the absence of the monsoon in the north from about

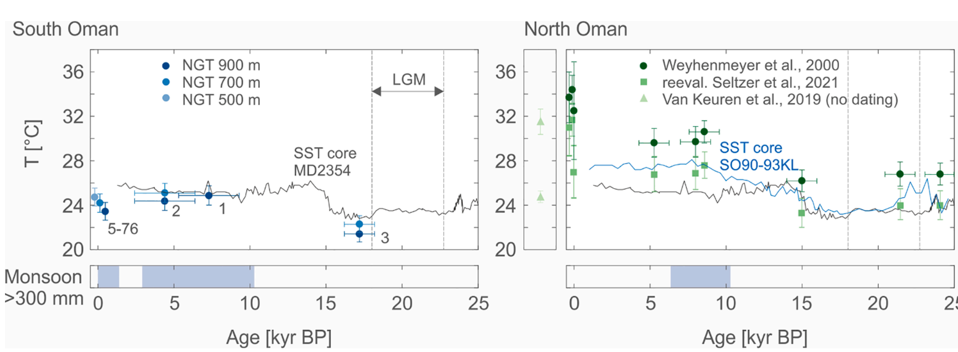

Fig. 3. left: Sea Surface Temperatures (SSTs) in the western Arabian Sea (core MD 2354) rose by only 2–3 °C from the LGM to the Holocene. Noble gas temperatures (NGTs) in groundwater covering this period show a similar trend. Colors indicate possible recharge elevations. right: NGTs in the north are above the values in the south. SST outside the upwelling area (core SO90–93KL) rose until the middle of the Holocene. SST data for core MD 2354 and core SO90–93KL were taken from Böll et al. (2015). Lower panel shows monsoon occurrence indicated by speleothem growth. From about 6.3 ka BP monsoon rains did not reach north Oman.

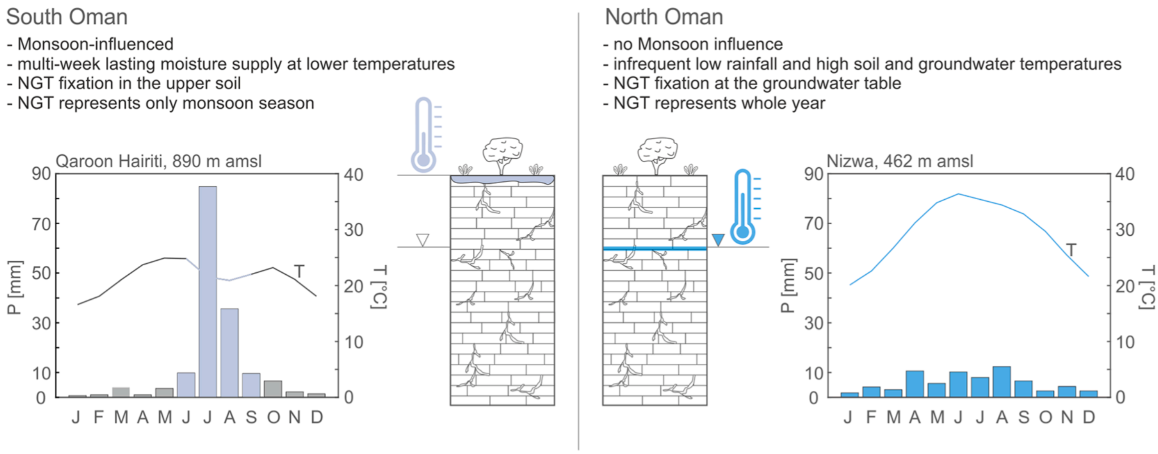

Fig. 4. Conceptual idea for NGT fixation under monsoon conditions (left panel) and without monsoon conditions (right panel) as they occur today in south and north Oman. Multi-week moisture supply at constant lower temperatures determines upper soil and noble gas temperatures. Hence NGTs reflect a seasonal value of the topsoil temperature (left panel). Without monsoon the infiltrating water equilibrates with soil air at the groundwater table and NGTs represent an annual average (right panel). Climate charts are based on the years 2001 to 2022, with extreme events (Cyclones May 2002, 2018, 2020 occurring in south Oman) not included. The northern station Nizwa at the base of the Hajar Mountains and at a distance of ~25 km to the Hoti Cave is shown as example for climate conditions outside the monsoon influence.

the middle Holocene (Fleitmann et al., 2022). With the modern precipitation regime, i.e., infrequent winter rains from the north, the infiltrating water equilibrates with soil air at the groundwater table (Paukert Vankeuren et al., 2019; Weyhenmeyer et al., 2000). The result is an early/middle Holocene to modern NGT rise of about 3 °C (Fig. 3, right panel) with the early Holocene NGTs representing seasonal temperatures from the upper soil, and the modern NGTs representing an annual average temperature from the groundwater table. Hence, the observed modern NGTs in northern Oman rather indicate a change in the infiltration regime than an additional increase in air temperatures compared to the conditions in the early to mid Holocene.

The difference in modern NGTs between north and south Oman is about 6–7 °C. The current air temperatures are in the range of 21–23.5 °C (890 m and 510 m amsl) for the south and 24.5–27.4 °C (1000 and 620 m amsl) for the north, respectively (see SI-7). The resulting difference in the air temperatures is about 4 °C and thus 2–3 °C lower than the differences in the NGTs. Our explanation for this deviation between NGT differences and air temperature differences is that the cut-off from the gas exchange during the recharge process occurs at different dephs in the soil (Fig. 4). In the south the noble gas concentrations are fixed in the top soil (Fig. 4, left panel). Although it cannot yet be explained why the NGT signal in the infiltrating soil water is preserved as the water migrates towards the groundwater body, the prevailing temperature is the upper soil temperature during the monsoon. In the northern recharge areas the infiltrating soil water equilibrates with soil air at the groundwater table (Fig. 4, right panel). The prevailing temperature is the groundwater temperature which represents an annual mean.

5. Summary and conclusions

Noble gas recharge temperatures (NGTs) of water recently recharged in the Dhofar Mountains in southern Oman correspond well to the infiltration period soil temperatures (IPSTs) of the Indian Summer Monsoon (ISM) and are clearly lower than mean annual soil temperatures (MASTs). This is in contrast to the classical assumption that NGTs reflect the annual mean of surface ground temperatures. Our data show that the conditions provided by the ISM, i.e. long-lasting moisture supply at constant low temperatures, can significantly depress soil and noble gas temperatures. This finding corroborates other indications of wet-season biased NGTs in mountainous fractured rock aquifers with seasonal soil temperature variations. It highlights the need to account for seasonality in both rainfall/snowmelt and soil temperatures when assessing NGT data.

The presence of a seasonal signal in NGTs together with large and variable offsets between soil and air temperatures complicates the paleoclimatic interpretation of NGT records at sites with such conditions. The seasonality of precipitation and recharge, vegetation cover, as well as soil – air temperature offsets may all have changed in the past, potentially creating NGT variability that does not reflect mean annual air temperature changes. This can be the case if most infiltration occurs at temperatures that are consistently lower (or higher) than the annual mean. The NGT data from northern Oman may present such a case. The LGM - late Holocene NGT increase occurred in two steps, at the LGM/Holocene transition and from the middle Holocene to today. The second step was caused by a change of the precipitation regime in the middle Holocene and led to different noble gas concentrations. Groundwater from the early to middle Holocene stems from ISM recharge, so its NGTs reflect the upper soil temperature of the monsoon season. The late Holocene to modern NGT increase for the northern recharge area was deciphered by using information on precipitation sources obtained from another paleo archive, the speleothem data.

With precipitation and recharge systems of the past largely unknown, there is considerable uncertainty about the relationship between the NGTs and the mean annual or seasonal temperature at the time they represent. This is particularly true for the LGM, due to the lack of information about precipitation regimes (other than the general dryness of the era) and recharge conditions. Therefore, caution should be exercised when using NGTs to interpret temperature changes on the glacial-interglacial time scale.

CRediT authorship contribution statement

Thomas Müller: Writing – review & editing, Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **Gerrit de Rooij:** Writing – original draft, Supervision. **Nico Trauth:** Writing – original draft, Data curation. **Mark Schmidt:** Writing – original draft, Methodology. **Humaid Al Badi:** Writing – original draft, Resources, Data curation. **Werner Aeschbach:** Writing – original draft, Supervision, Data curation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

Acknowledgement

This work was supported by the project "Submarine Groundwater Discharge: Adaption of an Autonomous Aquatic Vehicle for Robotic Measurements, Sampling and Monitoring", funded by The Research Council of Oman (TRC Research Contract No. TRC/RCP/15/001). Further funding was received from the SMART Project through the Helmholtz European Partnering Initiative (Project ID Number PIE-0004). Moreover, we thank the staff of the Ministry of Regional Municipalities and Water Resources of Oman for their continuous support. We thank Nils Michelsen for assistance during field work and fruitful discussions throughout the study.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.epsl.2023.118534.

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