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Reply to comment by Klump et al. on "Noble gases and stable isotopes in a shallow aquifer in southern Michigan: Implications for noble gas paleotemperature reconstructions for cool climates"

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1. Introduction

[1] In their comment, *Klump et al.* [2006], hereinafter referred to as KBK, make three main points concerning *Hall et al.* [2005]: (1) that the model of excess air that accounts for fractionation via the mechanism of diffusive loss should have produced significant changes from normal isotopic ratios; (2) the suggestion that the presence of excess He in the gas phase in the unsaturated zone is incorrect; and (3) the observed offset in noble gas temperatures (NGTs) from measured ground temperature can be explained by locking in noble gas concentrations during the annual snow melt. Point 3, which is by far the most relevant portion of the comment, deserves most of our attention in this reply. It is important to note up front that the model, as suggested in KBK is completely unworkable for the site studied in the work of *Hall et al.* [2005]. KBK note that more data would resolve some of the unresolved issues from *Hall et al.* [2005], but this is true for any preliminary study.

2. Diffusive Loss Model

[2] The authors of the comment point out that the model based on the partial diffusive loss of excess air would create isotopic ratio anomalies, which is correct. As noted by KBK, the degree of noble gas fractionation required for NGTs to match ground temperature is sufficiently large to have created significant changes in the ^{22}Ne/^{20}Ne and ^{40}Ar/^{36}Ar ratios, and these were not observed.

3. He in the Unsaturated Zone Gas Phase

[3] In KBK, an alternative estimate of the helium residence time in the groundwater is made which is virtually identical to the estimate of 30 years made by *Hall et al.* [2005], paragraph 9. The authors of the comment claim that this estimate is more "natural" and proceed to estimate the residence time of He in the unsaturated zone. It appears that the authors of the comment believe that *Hall et al.* [2005] argue that the long residence is due to excess He in the gas phase, when in fact *Hall et al.* [2005] argue that the He data require that the gas-water interface must be out of equilibrium with the atmosphere for decades.

[4] The He diffusion analysis made in KBK is correct but superficial. Although the mean residence time of 4 months for He in the unsaturated zone seems reasonable, it assumes that there is no source of excess He in the groundwater. If diffusion were the only transport mechanism in the water phase, the mean transport distance within groundwater near the water table over 4 months would only be a few cm [*Jähne et al.*, 1987] and groundwater at the water table would quickly reach equilibrium with respect to the atmosphere. This, however, ignores one of the key findings of *Hall et al.* [2005], which is that, although the excess He implies a residence time of decades, the water composition can change over days or weeks [*Hall et al.*, 2005, Figure 3b] and diffusion in the liquid phase cannot be the sole He transport mechanism. This implies extremely efficient mixing of the existing excess He with modern recharge water continuously entering the aquifer, likely due primarily to advection.

[5] Unlike excess air, which may show some evidence of seasonality (see KBK, Figure 1), excess ^{3}He and ^{4}He concentrations show remarkable consistency [*Hall et al.*, 2005, Figure 3a]. Thus there must be elevated He concentrations in groundwater near the water table and this water must be out of equilibrium with the atmosphere. Therefore there should be outgassing of He from groundwater into the unsaturated zone, leading to a concentration gradient with net He transport vertically upward. Elevated ^{4}He and ^{3}He concentrations in the gas phase also would increase the efficiency of the He mixing process as new recharge water will acquire excess He in its passage through the unsaturated zone.

4. NGT Offset Model Based on Recharge During Spring Melt

[6] KBK argue that mean annual air temperature (MAAT) or mean annual soil temperature (MAST) are not necessarily equal to NGTs recorded in groundwater, a possibility that was addressed by *Hall et al.* [2005]. The discussion of the model accounting for this phenomenon that is presented by KBK can be broken into 4 sections: (1) air vs. ground temperature; (2) thermal issues; (3) timing

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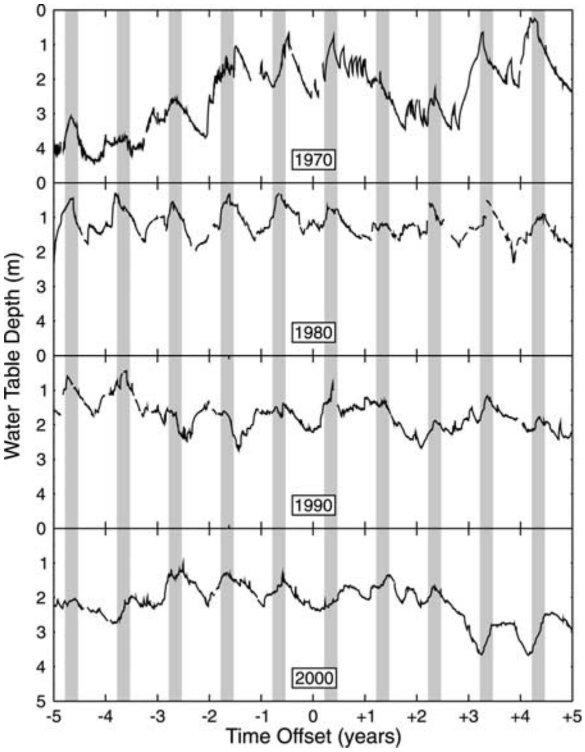

Figure 1. Nearly continuous 40 year record (1965–2005) of well water depth at Ann Arbor Airport (located at lat. 42° 13′ 22″, long. −83° 44′ 13″), south of the City of Ann Arbor. Areas shaded in gray are the spring season (3/21–6/21). Note that maximum water table height typically occurs in mid-spring, but sometimes as late as early summer, especially in the last decade. This site is not in the Ft. Wayne terminal moraine and it has a much shallower water table than the original study site. The data are shown to indicate the timing of recharge in the area.

of recharge; and (4) stable isotope constraints. We discuss these below.

5. Air Versus Ground Temperature

[7] The question of how to relate air temperature, and thus climate, to ground temperature is central to the use of NGTs as an indicator of paleoclimate. As noted by *Stute and Schlosser* [1993], "for practical purposes", NGTs typically record mean annual ground temperature. In order to relate climate to measured NGTs, therefore, it is necessary to connect MAAT to MAST in the recharge zone, and one of the aims of *Hall et al.* [2005] was to make this connection for the aquifer studied in the work of *Ma et al.* [2004]. In the work of *Hall et al.* [2005], the large apparent offset between NGTs and MAAT noted in the latter study was confirmed and it was also shown that there is no offset between measured groundwater temperature and MAAT. Therefore there must be another mechanism which explains the ~4°C drop in NGT relative to ground temperature.

[8] This offset of NGTs to values below MAAT may be a more ubiquitous issue than previously thought. *Stute et al.* [1992] linked NGT values at the recharge zone of the Carrizo aquifer to MAAT values, but as noted by *Castro et al.* [2005], ground temperatures near the water table are ~4°C higher, a similar offset documented by *Hall et al.* [2005]. Similarly, *Aeschbach-Hertig et al.* [2002] give continuous equilibration (CE) model NGTs in the recharge area of the Aquia Aquifer, Md., as being 12–13°C, similar to the MAAT, but they appear to dismiss the ground temperature data which give values of 15–16°C, thus, once again, displaying a bias to low NGTs of ~3°C.

[9] It is interesting to note that the oxygen depletion (OD) model suggested by *Hall et al.* [2005] can easily account for the NGT discrepancy by *Aeschbach-Hertig et al.* [2002]. Their sample MD9.1's OD NGT can match its measured ground temperature with an enhanced noble gas pressure that is 1.13 times normal and sample MD6.2 matches its ground temperature with an OD model noble gas pressure that is 1.11 times normal. The latter precisely matches the CE model excess air pressure factor "q" listed in the work of *Aeschbach-Hertig et al.* [2002]. The CE model error minimization procedure sometimes pushes the air volume parameter "A" to extremely large values, precisely what happened for sample MD6.2. When this happens, the CE model becomes identical to the OD model, but with zero excess air and the parameter "q" is then equivalent to the over pressure factor in the OD model. The best fit OD model with a pressure factor of 1.11 for sample MD6.2 gives a NGT of 15.3 ± 0.2°C (1σ) and only 1.3% excess air Ne, in excellent agreement with the ground temperature at this site of 15.0°C. It is clear that significant NGT offsets from ground temperatures do occur at a number of studied sites under contrasting climates, and snow melt cannot be used to explain the observations from the above cited studies.

6. Thermal Issues

[10] *Stute and Schlosser* [1993] performed a detailed analysis of the effect of seasonally changing temperatures and recharge rate on expected NGT values during recharge. A key conclusion was that, in the absence of extremely rapid recharge, NGTs should record mean ground temperatures as long as the water table depth was greater than ~2 m. The reason for this can easily be seen in Figure 3 of *Stute and Schlosser* [1993]. For the model suggested by KBK to work, there must be at least a 4°C cooling at the water table during spring melt and annual recharge should occur almost exclusively at this time. This is, for all practical purposes, unlikely for depths much greater than 2 m. Even with the thermal diffusivity value assumed for the unsaturated zone in KBK, the amplitude of temperature variation expected for depths greater than ~5 m would be insufficient to explain the depression in NGT values documented by *Hall et al.* [2005].

[11] The authors of the comment claim that NGT data from seepage wells does track temperature changes throughout the year, but this is hardly surprising as the water table depth for such wells is essentially zero as water is discharging from below. However, the measured water table in *Hall et al.*'s [2005] study area is 14 m and the well location is within 50 m of the apex of a hill. Recharge waters are thus expected to be local. Given the highly permeable nature of the aquifer's sand and gravel, and the topography near the sampling site, it is not possible for the water table to be

shallower than ~8 m without flooding of the Huron River Valley. The water table is far too deep for the water temperature to be 4°C below the mean at the last gas/water partitioning. It is likely that the ground temperature at the water table never deviates more than 1°C from MAST and hence MAAT.

7. Timing of Recharge

[12] The model presented by KBK relies on the presence of a majority of recharge occurring during the "cold season," presumably as the snow cover melts. Snow melting events can happen from December to early April, whenever the air temperature rises significantly above freezing and if there is a significant amount of rain. Just such an event in February is mentioned by *Hall et al.* [2005]. However, well depth data (available at http://nwis.waterdata.usgs.gov) for a 40 year period at the Ann Arbor Airport, a site with a much shallower water table than the site studied by *Hall et al.* [2005], shows that the shallowest depths in this area are frequently recorded in mid spring to early summer, which is 2–4 months after the most important snow melting events (Figure 1). From these data, it is clear that significant recharge does occur during late spring and early summer and therefore the model proposed by KBK is unlikely on this basis alone. Also, the average temperature in Ann Arbor during spring over the period of 1971–2000 was 8.7°C, which was only 0.7°C below the annual average for the same period (http://www.ncdc.noaa.gov/oa/ncdc.html). This suggests that even sites with shallow water tables may not have ground temperatures of ~5°C during the most important episodes of recharge.

8. Stable Isotope Constraints

[13] KBK estimate that stable isotope data suggest that snow accounts for at least 30% of the local recharge. In fact, the suite of data from both *Hall et al.* [2005] and *Ma et al.* [2004] plot along the local meteoric line at a point very close to the local annual average for precipitation, indicating that recharge occurs throughout the year. There is no indication from the stable isotope data that snow accounts for a preponderance of the local groundwater recharge.

9. Conclusions

[14] The model presented in the comment is intriguing and it may be applicable to some sites. In particular, if a recharge zone experiences protracted periods when the water table depth is extremely shallow (<2 m) and if there is strong seasonality in the timing of recharge, then the mechanism described by KBK might be viable. An excellent test for the model would be if the groundwater's stable isotope ratios in turn become shifted toward values appropriate for the postulated season of high recharge. For the site studied by *Hall et al.* [2005], however, none of these conditions apply and the model is untenable.

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