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## Sauna, sweat and science – quantifying the proportion of condensation water versus sweat using a stable water isotope ( $^2\text{H}/^1\text{H}$ and $^{18}\text{O}/^{16}\text{O}$ ) tracer experiment

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Most visitors of a sauna appreciate the heat pulse that is perceived when water is poured on the stones of a sauna stove. However, probably only few bathers are aware that this pleasant heat pulse is caused by latent heat being released onto our skin due to condensation of water vapour. In order to quantify the proportion of condensation water versus sweat to dripping water of test persons we conducted sauna experiments using isotopically labelled ( $\delta^{18}\text{O}$  and  $\delta^2\text{H}$ ) thrown water as tracer. This allows differentiating between 'pure sweat' and 'condensation water'. Two ways of isotope mass balance calculations were applied and yielded similar results for both water isotopes. Accordingly, condensation contributed considerably to dripping water with mean proportions of  $52 \pm 12$  and  $54 \pm 7$  % in a sauna experiment in winter semester 2011/12 and  $30 \pm 13$  and  $33 \pm 6$  % in a sauna experiment in winter semester 2012/13, respectively, depending on the way of calculating the isotope mass balance. It can be concluded from the results of our dual isotope labelling sauna experiment that it is not all about sweat in the sauna.

**Keywords:** condensation; hydrogen-2; isotope labelling; oxygen-18; phase transition; perspiration; sauna; tracer

### 1. Introduction

Most people visiting a sauna do so in order to enjoy and relax. While this also holds true for scientists, they sometimes additionally do research when visiting saunas. Indeed, a first book on sauna research was published in 1976 by Teir et al. [1]. That book is a collection of papers read at the VI International Sauna Congress in Helsinki on 15–17 August 1974. The papers cover a wide range of topics spanning from planning and building of saunas, sauna technology, topics dealing with medicine and sports and last but not least climatic conditions of the sauna [2]. In more recent studies, Vesala [2] and Hermans and Vesala [3] investigated the phenomenon of increased heat perception by a bather's skin after water is poured on hot stones of a sauna stove. Accordingly, this application does not only increase the air humidity by the evaporation of

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thrown water but also the total heat flux by over an order of magnitude. The authors found that the main responsible mechanisms for the increased heat flux onto the skin are, on the one hand, extra convection caused by hot steam coming off the stove. On the other hand, the perhaps even more important mechanism is latent heat being released during condensation of water vapour onto the skin. This finding may be surprising at first glance given that we sweat in the sauna and we all know that sweating is a reaction of our body in order to cool down by evaporative heat loss. However, our skin is one of the coldest surfaces in the sauna and the humidity can easily become 100 % near the skin thus causing condensation [2,3]. Still, a quantitative specification of this condensation phenomenon is lacking so far.

During the last decades, stable hydrogen and oxygen isotope ( $^2\text{H}/^1\text{H}$  and  $^{18}\text{O}/^{16}\text{O}$ , respectively) analyses became an invaluable tool in numerous scientific fields ranging from plant physiology over food authentication to (palaeo-)climate research, for example, [4–11]. Concerning experimental ecological studies, stable isotopes are successfully applied as tracers, both in natural abundance and artificially isotopically enriched or depleted, in order to trace element cycles and biochemical and physiological pathways [12–17]. For example, Dawson et al. [18] used deuterium labelling of trees to provide evidence for night-time transpiration, and Peñuelas and Filella [19] used deuterium labelling of roots to provide evidence for hydraulic lift by trees.

This inspired us to use stable water isotopes as tracers in a sauna experiment to answer the question: Is it possible to quantify the proportion of condensation water versus sweat to dripping water when water is poured on a sauna stove?

## 2. Experimental

### 2.1. Design of the sauna experiment and sampling

During winter semesters (WiSe) 2011/12 and 2012/13 we conducted two sauna experiments with students from the Martin Luther University of Halle-Wittenberg. The experiments took place in a  $\sim 16\text{ m}^3$  large sauna room that was heated to  $\sim 90^\circ\text{C}$ . Unless water is poured on the stones of the sauna stove, relative humidity is typically very low ( $\leq 10\%$ ). The experimental design was identical for both experiments and is illustrated in Figure 1. Accordingly, four test persons and two bottles were placed in the sauna. One bottle was filled with ice water ( $0^\circ\text{C}$ ), the other one with tap water of approximately  $20^\circ\text{C}$ ; both bottles were installed on a retort stand using clamps in the same height as the test persons and aimed at determining a ‘pure condensation signal’ (Figure 1). Pre-tests showed that bottles filled with warm water of around  $40^\circ\text{C}$  grow damp, too, however not enough to be sampled.

- In order to obtain pure sweat, the test persons were sent into the dry sauna. No water was poured on the stones of the preheated sauna in order to keep the air humidity as low as possible. Sweat (1–2 ml, corresponding to 30–50 droplets) was collected from the four test persons in duplicate using GC-vials.
- In the first sauna round,  $\sim 500\text{ ml}$  of isotopically depleted water (mountain water from the Zugspitze in WiSe 2011/12 and water artificially depleted by distillation in WiSe 2012/13, respectively) was poured on the stones of the sauna stove. In the following minutes (maximum  $\sim 8\text{ min}$ ), dripping water was sampled in duplicate both from the four test persons and the two bottles.
- In the second round, after having ventilated the sauna thoroughly,  $\sim 500\text{ ml}$  of  $^{18}\text{O}$ -enriched water (prepared by mixing 10 %  $^{18}\text{O}$ -water from Sigma-Aldrich with deionised water) was poured on the stones. Again, in the following minutes (maximum  $\sim 8\text{ min}$ ) dripping water was sampled in duplicate both from the four test persons and the two bottles.

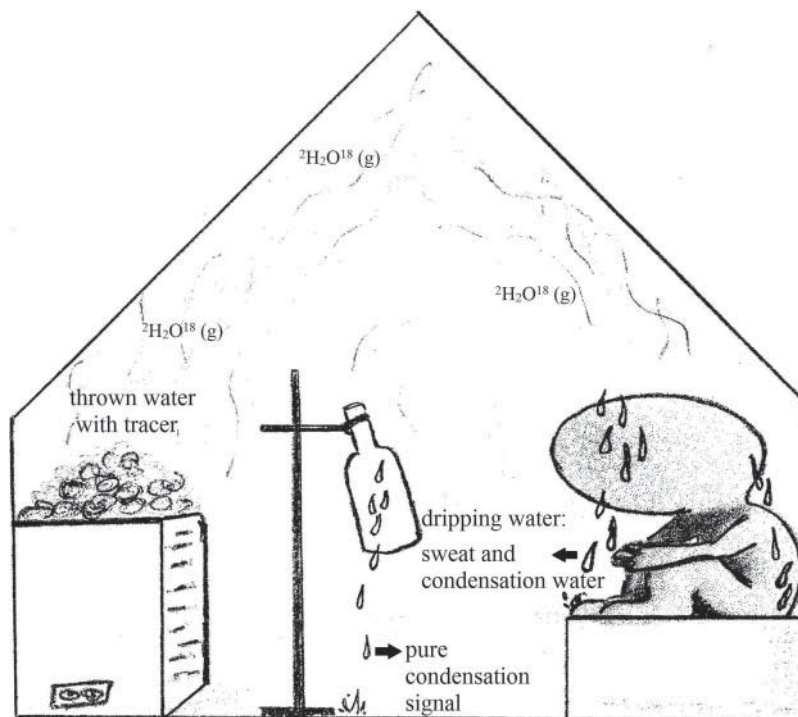


Figure 1. Schematic design of the sauna experiment. Isotopically labelled thrown water serves as tracer in order to distinguish between condensation water and sweat in dripping water.

## 2.2. Water isotope analyses

The collected dripping water samples were closed immediately with GC-vial screw caps. Water isotope analyses in WiSe 2011/12 were carried out in the Laboratory of Isotope Biogeochemistry of the Bayreuth Center of Ecology and Environmental Research (BayCEER, University of Bayreuth, Germany) using a liquid autosampler and a TC-IRMS coupling (via a ConFlo IV interface, Thermo Fisher Scientific, Bremen, Germany) of a HTO pyrolysis oven (HEKAtech, Wegberg, Germany) with a Delta V Advantage IRMS (Thermo Fisher Scientific). All  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  results are expressed in per mil (‰) relative to the Vienna Standard Mean Ocean Water (VSMOW) based on an in-house reference gas ( $\text{H}_2$  from Rießner-Gase GmbH, Lichtenfels, Germany, purity 6.0), which was calibrated using standards obtained from IAEA (VSMOW2 and SLAP2). While the standard deviation of the  $\delta^2\text{H}$  analyses was reported to be typically less than  $\pm 2$  ‰, the  $\delta^{18}\text{O}$  analyses were less precise. Presumably, this is due to organic contaminants in the sweat samples (e.g. urea and fatty acids). Measurements were therefore repeated three times yielding mean  $\delta^{18}\text{O}$  standard deviations of 3.2 ‰.

Water isotope analyses in WiSe 2012/13 were carried out in the Isotope Laboratory of the Institute of Agronomy and Nutritional Sciences (Department of Soil Biogeochemistry, Martin Luther University Halle-Wittenberg, Germany) by manual injection of the samples (1  $\mu\text{l}$ ) into a TC-IRMS coupling (via a ConFlo IV Interface, Thermo Fisher Scientific) of a pyrolysis oven in a Flash 2000 HT Plus elemental analyzer with a Delta V Advantage IRMS. Also these  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  results are expressed in per mil (‰) relative to the VSMOW. Calibration was done by establishing three-point calibration curves using water isotope standards obtained from IVA (IVA Analysentechnik e.K., Meerbusch, Germany. Product number: IVA 33802192, IVA 33802193,

IVA 33802194). Mean standard deviations for duplicate to quadruplicate measurements were 3.5 and 6.5 ‰ for  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  analyses, respectively.

### 3. Results and discussion

#### 3.1. Isotopic composition of pure sweat

The isotopic composition of sweat collected from the test persons ranges from  $-2$  to  $+2$  ‰ for  $\delta^{18}\text{O}$  and from  $-41$  to  $-19$  ‰ for  $\delta^2\text{H}$  in WiSe 2011/12 and from  $+5$  to  $+11$  ‰ for  $\delta^{18}\text{O}$  and from  $-31$  to  $-10$  ‰ for  $\delta^2\text{H}$  in WiSe 2012/13, respectively (Figures 2 and 3). Note that there is one outlier in WiSe 2012/13 with considerably more negative  $\delta$ -values. This sample may be contaminated by shower water that was not removed by towels before starting the sampling, and the respective data point was therefore excluded from further data evaluation. The variance of the data points can be attributed to (i) analytical uncertainties, (ii) differences between test persons caused by presumably different isotopic compositions of body water, (iii) slight differences in skin temperature and (iv) slight differences in the degree of evaporative enrichment of the sweat drops on the skin. Except for the excluded data point, all sweat samples plot clearly on the right side of the Global Meteoric Water Line (GMWL). This is in agreement with the finding that body water is enriched in  $^{18}\text{O}$  compared to intake water [20]. According to Vesala [2] and Hermans [21], humidity can drop to some few per cent in a dry sauna provided that no water is added. Also tests had shown that bottles filled with warm water of around  $40^\circ\text{C}$  grow only slightly damp so that the dew point must have been below  $40^\circ\text{C}$ , which is about the skin temperature of people in dry saunas [2,3]. The water on the skin of the test persons in the dry sauna is therefore assumed in approximation to be ‘pure sweat’ and unaffected by condensation. We are aware, though, that they might be affected to some degree by evaporative enrichment.

#### 3.2. Isotopic composition of condensation water

At the beginning of the first and the second sauna round, additional water was poured onto the stones of the sauna stove in order to increase the humidity in the sauna. In WiSe 2011/12, we used firstly mountain water from the Zugspitze, which is isotopically depleted due to the altitude effect [22], and secondly commercially acquired  $^{18}\text{O}$ -enriched water. Surprisingly, the mountain water plots clearly right of the GMWL (Figure 2). Given that it was obtained by melting snow, this finding may be attributed to evaporative enrichment having occurred during the melting (J. Keil, personal communication). For the sauna experiment in WiSe 2012/13, much stronger depleted water ( $\delta^{18}\text{O} = -144.0 \pm 0.6$  ‰ and  $\delta^2\text{H} = -402.9 \pm 1.36$  ‰) produced using a distillation column was available for the first sauna round (Figure 3).

Pouring water did not only cause an increase in air humidity, visible by condensation on the surface of the installed  $0$  and  $20^\circ\text{C}$  water bottles, it also changed the isotopic composition of the water vapour in the sauna. Although the humidity and the isotopic composition of water vapour could not be determined successfully using Picarro laser spectrometry,<sup>1</sup> this is reflected by the distinct isotopic compositions of dripping water collected from the bottles (Figures 2 and 3). In all four cases, the dripping water from the bottles is shifted towards thrown water in the  $\delta^2\text{H} - \delta^{18}\text{O}$  diagrams, indicating that the water vapour in the sauna is a mixture of evaporated isotopically labelled thrown water and water vapour that was in the sauna already before.

Note that temperature-dependent isotopic fractionation occurs during condensation of water vapour on the bottles and, therefore, the isotopic composition of dripping water is not identical with the isotopic composition of the respective water vapour. This is also highlighted by dripping water of the  $20^\circ\text{C}$  bottles being systematically enriched compared to the dripping water of the



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0 °C bottles (not labelled/specified in Figures 2 and 3). Nevertheless, the dripping water from the bottles can be considered to reflect the (temperature-dependent) isotopic composition of ‘pure condensation water’ *sensu* not being contaminated by sweat.<sup>2</sup>

### 3.3. Isotopic composition of dripping water from test persons when water is poured on the sauna stove

Figures 2 and 3 illustrate that dripping water collected from the test persons during the first and the second sauna round clearly plots in-between ‘pure sweat’ and ‘pure condensation water’ (dripping water from bottles) both in WiSe 2011/12 and WiSe 2012/13. This finding suggests that this dripping water is neither ‘pure sweat’ nor ‘pure condensation water’, but a mixture of both. Thus, this finding is furthermore in agreement with Vesala [2] and Hermans and Vesala [21] reporting that apart from forced convection by increased humidity and waving a towel, latent heat flux (by condensation) is likely the most important mechanism for the heat pulse that we feel when water is poured on the stones of the sauna stove. In the following we present and discuss two ways how the proportion of condensation water versus sweat can be quantified.

### 3.4. Quantification of condensation water versus sweat: isotope mass balance calculation I

The first option is to calculate the proportion of condensation water uses ‘pure sweat’ and ‘pure condensation water’ as end members in an isotope mass balance calculation (Figure 2).

Accordingly, the proportion of condensation water corresponds to the ratio *a/c* (exemplarily shown for deuterium results of the first sauna round WiSe 2011/12 in Figure 2) and can be calculated as

$$\% \text{ condensation water} = \frac{\delta^2\text{H}_{\text{sweat}} - \delta^2\text{H}_{\text{dripping water}}}{\delta^2\text{H}_{\text{sweat}} - \delta^2\text{H}_{\text{condensation water}}}. \quad (1)$$

This calculation can be done both for the results of the first and the second sauna round and for all test persons. Equation (1) can also be written in terms of  $\delta^{18}\text{O}$ . Ideally, condensation water would have been sampled also for bottles of around 40 °C in order to serve as the end member due to (i) the above-mentioned temperature-dependent isotope fractionation occurring during condensation and (ii) the observation that the sauna-warmed temperature of our skin is up to 43 °C [3]. Lacking respective data, we were seeking to extrapolate the isotopic composition of condensation water at 40 °C.  $\delta$ -Values were more enriched at 20 °C than at 0 °C (not labelled/specified in Figures 2 and 3). This is opposite to the equilibrium fractionation between water and vapour [23]. It does, however, comply with the maximum possible enrichment of a water surface, which also depends on temperature [24]. Lower vapour pressure at lower temperature inverts the temperature dependence in this case so that the maximum enrichment is greater at higher temperatures. However, assuming that water had condensed with equilibrium fractionation and then started to evaporate towards maximum enrichment, this resulted in too high  $\delta$ -values to allow explanation of our dripping water results. We therefore chose a simple linear extrapolation, which made end member calculations possible for most of the sauna rounds.

Proportions of condensation water thus calculated are given in Table 1 and range from 35 to 78 % in WiSe 2011/12 and from 14 to 48 % in WiSe 2012/13. Note that we consider the  $\delta^2\text{H}$ -based results of the second sauna round in WiSe 2011/12 to be not very robust because the  $\delta^2\text{H}$  value of the extrapolated 40 °C condensation water (−43 ‰) is not distinctly different from pure sweat (mean  $\delta^2\text{H}$  value over all test persons = −28 ‰). Further evaluating only the results which are considered to be reliable yields a mean proportion of condensation water of  $52 \pm 12$  % for all test persons in WiSe 2011/12, with  $\delta^2\text{H}$ -based results suggesting more condensation ( $61 \pm 7$  %) than the  $\delta^{18}\text{O}$ -based results ( $43 \pm 8$  %).

Table 1. Proportion of condensation water versus sweat<sup>a</sup> to dripping water from test persons in wet sauna (application of thrown water, using isotopically labelled water as tracer) according to isotope mass balance calculation I (see Equation (1) and Figure 2).

	TP 1	TP 2	TP 3	TP 4	Mean $\pm$ sd
<i>WiSe 2011/12</i>					
First round $\delta^{18}\text{O}$	n.a.	n.a.	n.a.	n.a.	n.a.
First round $\delta^2\text{H}$	63 %	63 %	67 %	52 %	61 $\pm$ 7 %
Second round $\delta^{18}\text{O}$	44 %	53 %	39 %	35 %	43 $\pm$ 8 %
Second round $\delta^2\text{H}$	(78 %) <sup>b</sup>	(61 %)	n.a.	(61 %)	(67 $\pm$ 10 %)
Mean $\pm$ sd	54 $\pm$ 13 %	58 $\pm$ 7 %	53 $\pm$ 20 %	43 $\pm$ 12 %	<b>52 <math>\pm</math> 12 %</b>
<i>WiSe 2012/13</i>					
First round $\delta^{18}\text{O}$	45 %	45 %	23 %	34 %	37 $\pm$ 10 %
First round $\delta^2\text{H}$	46 %	48 %	16 %	28 %	34 $\pm$ 15 %
Second round $\delta^{18}\text{O}$	15 %	14 %	21 %	27 %	19 $\pm$ 6 %
Second round $\delta^2\text{H}$	n.a.	n.a.	n.a.	n.a.	n.a.
Mean $\pm$ sd	35 $\pm$ 18 %	36 $\pm$ 19 %	20 $\pm$ 4 %	30 $\pm$ 4 %	<b>30 <math>\pm</math> 13 %</b>

<sup>a</sup>Data for sweat (100 % – % condensation water) are not shown.

<sup>b</sup>Data in brackets are considered to be not very reliable (see text for explanation) and are therefore excluded from further data evaluation.

TP = test person.

For comparison, the sauna experiment WiSe 2012/13 yielded a lower mean proportion of condensation water to dripping water of 30  $\pm$  13 %. Given that the tracer signal applied in the first sauna round in that year was more depleted than in WiSe 2011/12, we suggest that the obtained results of WiSe2012/13 are more reliable than the results of WiSe 2011/12.

### 3.5. Quantification of condensation water versus sweat: isotope mass balance calculation II

In order to circumvent the uncertainty caused by extrapolating the  $\delta$ -values of condensation water to 40 °C, we here propose a second option for calculating the isotope mass balance. Accordingly, the proportion of condensation water can also be calculated as ratio  $d/e$  (exemplarily shown for  $\delta^{18}\text{O}$  results of WiSe 2012/13 in Figure 3) using the equation:

$$\% \text{ condensation water} = \frac{\delta^{18}\text{O}_{\text{dripping water}}(\text{third round}) - \delta^{18}\text{O}_{\text{dripping water}}(\text{second round})}{\delta^{18}\text{O}_{\text{condensation water}}(\text{third round}) - \delta^{18}\text{O}_{\text{condensation water}}(\text{second round})}. \quad (2)$$

Also this Equation (2) can of course be written in terms of  $\delta^2\text{H}$ . Visually speaking, 0 % condensation water would result in dripping water corresponding to pure sweat ( $d = 0$ ), whereas 100 % condensation water would result in dripping water corresponding to condensation water at the bottles ( $d = e$ ).

Results are given for all test persons in Table 2 and suggest that the proportion of condensation water ranges from 45 to 66 % in WiSe 2011/12 and from 22 to 44 % in WiSe 2012/13. Mean values are 54  $\pm$  7 and 33  $\pm$  6 % for WiSe 2011/12 and WiSe 2012/13, respectively, thus corroborating the results of isotope mass balance calculation I suggesting that condensation played a more important role in the sauna experiment WiSe 2012/13 than in WiSe 2011/12.

As mentioned above, one may assume, on the one hand, that this reflects slightly different amounts of thrown water and therefore slightly distinct humidities of the sauna air between the two years. On the other hand, the thrown depleted water used as tracer in WiSe 2012/13 was much stronger labelled thus yielding the more reliable results.

Finally, it is worth mentioning that using a student's  $t$ -test and the results of both isotope mass balance calculations, significant differences could be asserted for the test persons 2 and 4 in



Table 2. Proportion of condensation water versus sweat<sup>a</sup> to dripping water from test persons in wet sauna (application of thrown water, using isotopically labelled water as tracer) according to isotope mass balance calculation II (see Equation (2) and Figure 3).

	TP 1	TP 2	TP 3	TP 4	Mean ± sd
<i>WiSe 2011/12</i>					
Based on $\delta^{18}\text{O}$	55 %	64 %	51 %	45 %	54 ± 8 %
Based on $\delta^2\text{H}$	46 %	66 %	56 %	45 %	53 ± 10 %
Mean ± sd	50 ± 6 %	65 ± 1 %	53 ± 4 %	45 ± 0 %	<b>54 ± 7 %</b>
<i>WiSe 2012/13</i>					
Based on $\delta^{18}\text{O}$	33 %	33 %	22 %	31 %	30 ± 5 %
Based on $\delta^2\text{H}$	40 %	44 %	29 %	32 %	36 ± 7 %
Mean ± sd	37 ± 5 %	39 ± 8 %	26 ± 5 %	32 ± 0 %	<b>33 ± 6 %</b>

<sup>a</sup>Data for sweat (100 % – % condensation water) are not shown.  
TP = test person.

WiSe 2011/12 ( $p = 0.009$ ,  $n = 4$ ) and for the test persons 3 and 4 in WiSe 2012/13 ( $p = 0.015$ ,  $n = 5$ ). This presumably reflects that visitors to the sauna tend to perspire distinctly and future research focus will be set on these individual physiological differences between test persons.

4. Conclusions

Using a dual isotope labelling of thrown water ( $\delta^{18}\text{O}$  and  $\delta^2\text{H}$ ) in sauna allows differentiating between ‘pure sweat’ and ‘condensation water’. This in turn allows quantifying the proportion of condensation water versus sweat to dripping water of test persons using isotope mass balance calculations. Accordingly, 14–67 % of dripping water was caused by condensation with mean proportions of  $52 \pm 12$  and  $54 \pm 7$  % in a sauna experiment in WiSe 2011/12 and  $30 \pm 13$  and  $33 \pm 6$  % in a sauna experiment in WiSe 2012/13, respectively, depending on the way of calculating the isotope mass balance.  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  yield generally very similar results and thus cross validate each other. While it is difficult to draw medical or health implications from our results, they are well in agreement with the finding of Vesala [2] and Hermans and Vesala [3] that latent heat flux (by condensation) is likely the most important mechanism for the heat pulse that we feel when water is poured on the stones of the sauna stove. The overall conclusion therefore reads: ‘It is not all about sweat in the sauna.’

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Disclosure statement

No potential conflict of interest was reported by the authors.

## Notes

1. We tried several times with two different Picarro instruments, but presumably the absolute water content of sauna air is too high and laser measurements are always automatically shut down. Also attempts to dilute the sauna air with dry gas did not yield reasonable isotope results.
2. This later statement is indeed only valid at the beginning of the sauna rounds. In fact, the replications of WiSe 2012/13 (both from bottles and test persons) reveal systematic trends presumably attributable to evaporating sweat from the skin of the test persons resulting in a dilution of the isotopic label of the thrown water. These data are therefore not shown in Figure 3 and excluded from further data evaluation.

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