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Discussions

Interactive comment on "Hydrological, chemical and isotopic budgets of Lake Chad: a quantitative assessment of evaporation, transpiration and infiltration fluxes" *by* C. Bouchez et al.

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The originality of this paper is to combine several mass balances approaches, but, as raised by J. Gibson, such an integrative approach prevents us to detail thoroughly each method. Moreover, albeit this study is based on an exhaustive compilation of data, mainly dating back to the sixties/seventies and completed by few data acquired by our or other teams in more recent time, we should recognize the scarcity of data that makes each approach sometimes under constrained. As an example, it will be unrealistic to develop a simulation of the isotopic behavior of the lake at the daily time step. However, we show that we can assess the seasonal and inter annual evolution

of the lake, by combining hydrological, chemical and isotopic mass balances. The objective of the study is to make the best use of all the available information in a region where it will presumably not be possible to make further detailed sampling and continuous monitoring in a close future because of the political and security conditions in the investigated area.

The changes proposed by J. Gibson are very helpful to improve the presentation and the discussion of the paper and we thank our colleague for his insightful comments. All the issues raised are gathered, numbered and addressed below.

1- One issue for the isotope balance is that it is not specified whether humidity has been normalized to the surface temperature of the lake.

Humidity has not been normalized to the surface temperature of the lake because lake temperatures are not available. However, we assume that the surface temperature is similar to air temperature because the lake is shallow, well mixed by the wind and the seasonal variations of air temperature in central Sahel remain low. Consequently, the following sentence could be added in the manuscript (p. 11187 line 2): "We assume that the lake temperature is similar to air temperature because the lake is shallow, well mixed by the wind and seasonal variations of air temperature in central Sahel remain low."

2- The sensitivity of the input variables, as summarized in Figure 2, especially vapour do not appear to be reasonable for a daily time step.

We built a model at a daily time scale because it is the appropriate time step to avoid numerical oscillations of the water balance. However, we do not pretend to evaluate the daily evolution of the water isotopic composition. Our sensitivity analyses are thus based on the average lake isotopic composition between 1968 and 1970, which is the period with the most accurate data. Based on this comment, the following comments could be added in the manuscript (p.11182, line 21): "The model is built at a daily time scale because it is the appropriate time step to avoid numerical oscillations of the water balance. However the results of the water, isotope and chemical mass balances are further evaluated and discussed at seasonal and annual time scales." (p. 11198, line 15): The sentence should be clarified as "The sensitivity analyses are based on the average lake isotopic composition and concentration between 1968 and 1970, which is the period with the most accurate data".

3- It is also not clear what value is used herein for θ. The value used by Gat for the Mediterranean Sea is referred to but this value is not likely appropriate for a lake.

The choice of an appropriate value for the θ parameter is often tricky, as few studies have focused on the determination of this parameter. It was estimated at 0.88 in the Great Lakes of North America, (Gat et al., 1994) and 0.5 in the Mediterranean Sea, (Gat et al., 1996). For body whose strong upward evaporation fluxes perturb the atmospheric boundary layer, this value is generally lower than 1 (Horita et al., 2008), especially when humidity is not measured near the lake surface (Gat et al., 1996). Since the Lake Chad evaporative conditions are likely closer to the conditions of the eastern Mediterranean Sea than to those of the Great Lakes, we chose a value of 0.5. In addition, since the θ parameter drives the proportion of kinetic fractionation on total evaporative fractionation, for both isotopic species, it also controls the slope of the evaporation line. The value of θ= 0.5 yields a slope of 5 for the evaporation line, which matches the slope of the line obtained from measured water isotopic compositions in the whole Lake (Fontes, 1970 ; see Figure below), while θ=0.88 would lead to a lower slope (4).

We have also evaluated the sensitivity of the model to this parameter. There is a clear impact of the choice of the kinetic parameter on the isotopic budget as it leads to an increase of 3‰ of the δ18O in the Northern Pool and in the Archipelagos, where the evaporative flux is dominant. However, the calibration of FE using θ=0.88 yields larger ratios of T/ET in the three pools. For example, this ratio reaches 55% in the Northern Pool, which is not consistent with an open water body with few vegetation such as the Northern Pool between 1968 and 1970. Therefore, although questionable, a value of

0.5 for θ leads to more realistic results for Lake Chad.

On the basis of this comment, we propose to add the following sentence in the manuscript: (p. 11181 line 6) " Few studies have focused on the determination of the θ parameter. Its value is generally lower than 1 for water body whose strong evaporation flux perturbs the atmospheric boundary layer (Horita et al., 2008), with a value of 0,88 estimated for the Great Lakes (Gat, 1994), and commonly used elsewhere. Nevertheless, a lower value (θ = 0.5) has been estimated for the Eastern Mediterranean (Gat 1996), attributed to the high contrast between the air column above the sea surface and the advected air masses. Thus, since low values may be expected when humidity is not measured near the lake surface (Gat et al., 1996), and because the Lake Chad evaporative conditions are closer to the conditions of the eastern Mediterranean Sea than to those of the Great Lakes, we chose a value of 0.5. The choice of the θ value is also supported by the simulated slope of the evaporation line. Indeed, as the θ parameter drives the proportion of kinetic fractionation on total evaporative fractionation, for both isotopic species, it also controls the slope of the evaporation line. The value of θ= 0.5 yields a slope of 5 for the simulated d2H-d18O line, which matches the line obtained from measured water isotopic compositions in the whole Lake (Fontes, 1970, and Figure below), while θ=0.88 leads to a lower slope value (4)

4- It appears also that isotopic composition of regional atmospheric moisture was measured approximately monthly and only during 2012. What additional assumptions were used to estimate the isotopic composition of atmospheric moisture and evaporate when the analysis was extended on a daily basis back to 1950s?

Our estimate of the isotopic composition of the atmospheric moisture is based on the only available isotopic record in Sahel today (Tremoy et al., 2012) obtained using a laser spectrometer, at a sub-daily time step. However, we believe that, regarding the uncertainty associated to the use of data from Niamey (Niger) for the Lake Chad, it is unnecessary (and unrealistic) to use a more detailed time resolution. Therefore, we only based our model on isotopic orders of magnitude and monthly variations. To fit the daily time step required for the input variables, monthly values were interpolated to a daily time step. As explained above, the daily time step of our model is justified by numerical reasons, but the results are expressed in terms of monthly and annual variations. The uncertainty associated to the isotopic composition of the atmospheric moisture is then discussed through sensitivity analysis in the paper (Section 6.2.1).

5- One issue that is not discussed is if any corrections or adjustments were made in applying the regional atmospheric moisture estimates to solve the lake isotope balance. Due to the large size of the lake, the isotopic composition of the lake evaporate likely plays a significant role in modifying the local atmosphere of the lake, an effect described and quantified by Jasechko et al. (2014) for the Laurentian Great Lakes. Feedback of evaporate to the atmosphere likely also varies depending on the lake state, either normal or shrinking. Were any such corrections made in the analysis, and how sensitive is the model to such uncertainties? It would be beneficial to illustrate and/or discuss this sensitivity. I suggest that if this is too much of a diversion from the context of the paper that some information on this be included in the supplementary material.

We agree that the recycling of evaporated moisture is able to influence the local atmosphere above the lake (Vallet-Coulomb et al., 2008, Jasechko et al., 2014). The impact of Lake Chad (normal size) and of its desiccation on regional climate has been investigated, using a mesoscale regional atmospheric model coupled to a soil-vegetation-atmosphere transfer model (Lauwaet et al, 2012). This study shows that whatever the size of the lake, lake evaporation does not affect significantly the atmospheric hydrological cycle and the total precipitation amounts. The authors calculate a moisture recycling ratio of less than 7% in the total studied area, that remains unchanged regarding the size of the lake. Even during episodes of Mega Lake Chad, covering 340 000 km2, which is over a hundred times its current surface area, the contribution of Lake Chad to regional moisture remains low (Contoux et al., 2013). In addition, the humidity around Lake Chad, documented both from global data (CRU) and local studies (Olivry

et al, 1996), is low (around 0.4 in average), unlike the environment encountered in the Great Lakes. A complementary sensitivity analysis shows that the lake isotopic model is increasingly sensitive to the composition of the atmospheric moisture with increasing humidity rates. The low humidity values characterizing Lake Chad environment may thus argue for a small influence of local vapor recycling on the simulation of lake water isotopic composition. Therefore, although available data is not enough for investigating the effect of local evaporation on the isotopic composition of regional atmosphere, we believe that we can reasonably neglect this effect and that the associated uncertainty is likely lower than the uncertainty we have on isotopic composition of regional atmosphere (discussed answer 4 and Section 6.2.1).

6- Cross plots of d2H-d18O showing the isotopic composition of atmospheric moisture, evaporate, lake water and modelled ranges would certainly assist in evaluating the realism of the isotope mass balance simulations.

This remark is very helpful and the d2H-d18O cross plot allows a relevant representation of the several components of the Lake Chad isotopic budget (Fig. below). Moreover, the realism of the isotope mass balance simulations is well illustrated by the good fit between the simulated linear regression between d2H and d18O and the observed evaporation line in Lake Chad (with a slope of 5). This reinforces the confidence in our model, despite all the assumptions made (see answer 3) and we agree with J. Gibson that this plot and this discussion should be added to the results in the revised manuscript.

7- Comparison between the three methods might be improved by showing some cross-plots of selected parameters to give the reader another perspective on uncertainty in the results.

The three methods are not used independently but all together to constrain evaporation, infiltration and transpiration over Lake Chad. Therefore, we do not know what cross plots could be added to give the reader another perspective of the results and we think this paper is long enough.

In conclusion, while some assumptions we made were not clear enough to satisfy the reader's expectations, we hope that the answers help clarifying the scopes of the paper as well as the resulting simplifications and assumptions.

We have also added a cross plot of d2h-d18O according to J. Gibson's comments and we have developed our sensitivity analysis (with a redraw of the table to make the reading easier). It helps discussing the impact of our assumptions on the lake isotopic simulation and strengthens the conclusions of our paper. We propose to expand the paragraph 6.2.1 of the revised manuscript, dealing with the sensitivity analyses in order to take into consideration the discussion on vapor recycling (answer 5). Other minor issues suggested, including figure enlargement, correction of "quaternary" and Table 1 with volumetric fluxes will be taken into account for the revised manuscript.

Below are the added references and captions.

Gat, J.R., Bowser, C.J., Kendall, C., 1994. The contribution of evaporation from the Great Lakes to the continental atmosphere: estimate based on stable isotope data. Journal of Geophysical Research 21 (7), 557-560, DOI: 10.1029/94GL00069

Gat, J.R., Shemesh A., Tziperman, E., Hecht, A., Georgopoulos, D., Basturk, O., 1996. The stable isotope composition of waters of the eastern Mediterranean Sea. Journal of Geophysical Research Oceans 101 (C3), 6441-6451, DOI: 10.1029/95JC02829

Lauwaet, D., Van Lipzig, N. P. M., Van Weverberg, K., De Ridder, K., Goyens, C., 2012. The precipitation response to the desiccation of Lake Chad, Q. J. Roy. Meteorol. Soc., 138, 707–719, DOI:10.1002/qj.942, 2012.

Jasechko, S., Gibson, J.J., Edwards, T.W.D., 2014. Stable isotope mass balance of the North American Great Lakes, Journal of Great Lakes Research 40, 336-346, DOI:10.1016/j.glr.2014.02.020

Contoux, C., Jost, A., Ramstein, G., Sepulchre, P., Krinner, G., Schuster, M., 2013.

Megalake Chad impact on climate and vegetation during the late Pliocene and the mid-Holocene, Climate of the Past 9, 1417-1430, DOI: 10.5194/cp-9-1417-2013

Fig.1 Added Figure: d2H-d18O cross plot showing the comparison between the observed evaporation line in Lake Chad in blue (according to Fontes et al., 1970b) and the simulated linear regression between d2H and d18O in Lake Chad in red. In addition, average isotopic compositions are showed for atmospheric moisture (purple) and simulated evaporates (green) above each pool (SP: southern pool, AR: archipelagos, and NP: Northern pool).

Fig.2 Table of the sensitivity analysis (Table 2 in the paper) with supplementary information.

Interactive comment on Hydrol. Earth Syst. Sci. Discuss., 12, 11173, 2015.

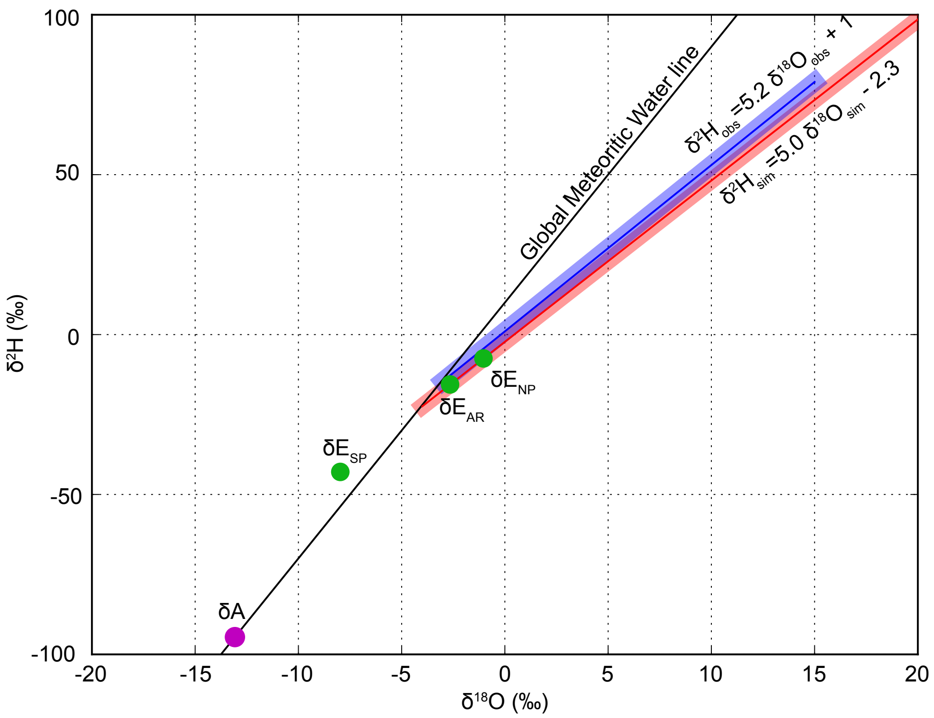

Fig. 1.

		Δ[Na+]/[Na+] lake (%)		
		Northern Pool	Southern Pool	Archipelagos
Δ [Na+]/[Na+] rivers	±10%	4%	10%	9%

		Δ $\delta^{18}O$ lake (‰)		
		Northern Pool	Southern Pool	Archipelagos
Δ δ18O rivers (‰)	±2 ‰	0.8 ‰	1.5 ‰	0.8 ‰
Δ δ18O rainfall (‰)	±2 ‰	0.2 ‰	0.1 ‰	0.3 ‰
Δ h (mean=51%)	+0.1	-2.3 ‰	-0.6 ‰	-2.0 ‰
Δ h (mean=61%)	+0.2	-4.8 ‰	-1.6 ‰	-4.2 ‰
θ	0.88	0.2 ‰	3.0 ‰	3.3 ‰
Δ δ18O vapor (‰)	±2 ‰	1.0 ‰	0.4 ‰	0.9 ‰

Fig. 2.