The residence time of water in the atmosphere revisited

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Response to Anonymous Referee #3

We thank Anonymous Referee #3 for reviewing our manuscript. It is a pity, however, that the comments consist of the referee's "feelings" and general statements without discussing any specific parts of our manuscript or stating anything concrete. Comments by the referee are in italic and replies are in normal text. The detailed adjustments to the revised manuscript will follow after the public discussion period.

Proof that the global average residence time of water in the atmosphere is 8–10 days

First, we would like to respond to the title of comments provided by Anonymous Referee #3, in which he or she claims that our paper does not provide a counterargument for the study of Läderach and Sodemann (2016), who claimed the global average residence time to be be 4–5 days (more precisely 3.9±0.8 days for 15-day backward trajectories). It is true that we do no provide a counter argument in the sense that we identify a flaw in their method, however, our counter argument consists of the finding that their outcome is inconsistent with the state-of-the-art data of the hydrological cycle, including the dataset they use themselves. In Section 3 of our paper we clearly explain how one can derive the global average residence time of water in atmosphere from relative simple mass balance calculations of well-established estimations of the stocks and fluxes in the global hydrological cycle. The following text (cited from Section 3) disproofs the estimate of Läderach and Sodemann (2016):

"If one would like to know the average residence time τ in any reservoir one simply divides its average mass $\overline{M}$ (or volume when assuming constant density) by its average outgoing mass flux $\overline{F}$ (which equals the ingoing flux when there is no change of mass):

$$\tau = \frac{\overline{M}}{\overline{F}}. \tag{2}$$

Whereas this is a simple formula, computation of reliable residence times in, for example, a surface water lake may be difficult due to many uncertainties in a lake's volume, hydraulic flow, precipitation, evaporation and seepage (Monsen et al., 2002). Moreover, a lake may be permanently stratified (i.e. there is permanent dead storage) and one could argue that the actual volume participating in the water cycle of the lake does not equal the lake's total volume, meaning that the actual average residence time becomes lower. If one can, however, reliably estimate a lake's volume and in- or outflow, it is not necessary for a lake to be well-mixed for Eq. (2) to hold, the mere necessity is that the entire volume participates in the water cycle. Of course, one could still have significant local differences, but the average can reliably be calculated by Eq. (2).

When the Earth's entire atmosphere is considered to be the reservoir of study, its residence time can actually be calculated much easier than that of a lake. In the global case the only inflow is evaporation and the only outflow is precipitation. Moreover, due to the turbulent nature of the atmosphere all water that resides in the atmosphere also participates in the atmospheric water cycle, i.e., there is no such thing as permanent dead water storage (e.g., Jacobson, 1999).

The use of Eq. (2) to calculate the global mean residence time of atmospheric water has been criticized by Läderach and Sodemann (2016). They argued that Eq. (2) is not a reliable estimator as it does not involve horizontal moisture transport. Whilst they are correct that location depletion times (van der Ent and Savenije, 2011; Trenberth, 1998) are not equal to actual residence times, we argued above that horizontal moisture transport is irrelevant for the global average value, and that the entire atmospheric volume participates in the hydrological cycle. Thus, Eq. (2) can safely be used to calculate the global average residence time of atmospheric water.

Applying Eq. (2) on estimates of the global hydrological cycle (Fig. 1) yields a global mean residence time of atmospheric water of $8.9 \pm 0.4\,\mathrm{days}$ (uncertainty indicated by one standard deviation). The calculation of the mean is as follows:

$$\tau = \frac{12.6 \cdot 10^3}{(403.5 + 116.5) \cdot 10^3} = 0.024 \text{ years} = 8.9 \text{ days}, \tag{3}$$

and the standard deviation was calculated by general uncertainty propagation theory. The 1^{th} and 99^{th} percentile of this estimate are 7.9 and $9.8\,\mathrm{days}$ respectively. All previous estimates referred to in this paper fall within this uncertainty range (Bosilovich and Schubert, 2002; Bosilovich et al., 2002; Chow et al., 1988; van der Ent et al., 2014; Hendriks, 2010; Jones, 1997; Savenije, 2000; UCAR, 2011; Ward and Robinson, 2000; Yoshimura et al., 2004), except for the estimate provided by Läderach and Sodemann (2016) which is less than half, namely $3.9 \pm 0.8\,\mathrm{days}$ (spatial difference indicated by one standard deviation). Based on the arguments provided above we believe that the latter estimate is incorrect."

Novel contributions

As one can read above, our proof for the residence time to be 8–10 days is not necessarily based on our own tracking methods (WAM-2layers and 3D-Trajectories). The results obtained with FLEXPART by Läderach and Sodemann do not make sense from a mass balance point of view (Eqs. (2) and (3)). If *Geophysical Research Letters*, wherein the work of Läderach and Sodemann (2016) was published, did not have the policy not to accept comments on published papers we could have submitted the text above.

In contrast to the work of Läderach and Sodemann (2016) our tracking methods yield trustworthy estimates of residence time in the range which is to be expected. However, this paper goes beyond being a commentary on another paper as our novel contributions include:

- Extension of the standard global hydrological cycle picture to show not only the fluxes, but also the atmospheric residence time associated with these fluxes, split out over land and ocean;

– Spatial maps of global residence time of atmospheric water. This study is the first to look at this from both the evaporation and precipitation perspective. Moreover, interesting summer vs. winter patterns are revealed for the first time;

– Global probability density functions of residence time of atmospheric water, from a land and ocean perspective, are shown for the first time.

Response to subsequent comments of Anonymous Referee #3

This paper looks to address the question regarding the residence time of water in the atmosphere recently raised by Läderach and Sodemann (2016). I feel this study does not provide enough evidence to significantly contribute to the discussion.

Indeed we address the question of residence time of water in the atmosphere, but the issue of atmospheric residence time was raised by many others before. Our paper revisits this literature and demonstrates with different methods – global water balance and two tracking models – that the global average residence time is 8–10 days, and thus, that the main result of Läderach and Sodemann (2016) – suggesting it to be 4–5 days – is erroneous. We provide the main evidence in Section 3, which we even called "Why the global average residence time of water in the atmosphere is 8–10 days".

1) There are large limitations to using tracking models to track atmospheric moisture. The authors need to go into a lot more detail as to how the models were applied to this dataset. Specifically, how the water in the model is tagged, how this tagged water relates to the evaporation and precipitation in the subsequent time step, whether mixing of this water is taken into account. Without going into more detail as to how the tracking models specifically deal with water it is not possible to address question of the residence time of the water.

The tracking methods we apply here – WAM-2layers and 3D-Trajectories – have been tested and validated (see van der Ent et al., 2013). There are obviously some assumptions in the methods applied, but by applying both we also test the sensitivity of the outcome to the tracking model used. We conclude that there is some sensitivity, but both methods yield global average numbers which make sense when compared to the global water balance (see Fig. 1). This cannot be said from the results produced by Läderach and Sodemann (2016), which use a single method (FLEXPART) and yields too low estimates that cannot physically be true if one looks at the numbers of the global water balance, including the estimates from their own input data (ERA-Interim). The devil is not in the details, as the referee suggests, but whether the results match with the fundamental mass balance equation (see Eqs. (2) and (3)), or not, and ours do.

2) The authors highlight the difference in the assumptions made by Laderach and Sodermann (2016), but more discussion as to why the authors disagree with these differences is needed. No evidence is provided to support the authors' choice in assumptions over the choice by Laderach and Sodermann.

Actually, we do not highlight the difference in the assumptions made, where did the referee read this? The only thing we can and did say is that the length of their trajectories is is too short, namely 15 or 20 days, while we find that about 5 % of the atmospheric moisture has a residence time of more than 30 days (Fig. 4). In the revised manuscript we will highlight this more in Section 5, which deals with the probability density functions of atmospheric residence time. However, this is by far not enough to explain the factor 2 difference. As we both find very similar spatial patterns (compare our Fig 2c to Läderach and Sodemann, 2016, Fig. 2a), and we both use ERA-Interim data, we can only conclude that there is a fundamental irregularity in their method. For all we know they could have accidentally divided all their results in the post-processing by a factor 2 using a wrong time step, flux or stock. However, this is wild speculation, and it is not within our possibilities nor our task to get to the bottom of this out within the scope is this paper. The only thing we can and did do is highlighting the difference in obtained results and showing that theirs is unphysical (see Section 3).

3) The analysis of the results conclude that ERA-Interim shows close agreement to the previous studies of residence time, however does not provide a response to Laderach and Sodermann.

In Section 3 we show that using data from the state-of-the-art estimates of the global hydrological cycle (Rodell et al., 2015; Trenberth et al., 2011) yields a global mean residence time of atmospheric water of 8.9 ± 0.4 days (uncertainty indicated by one standard deviation), with the 1th and 99th percentile of this estimate being 7.9 and 9.8 days respectively. That is the response and proof that the estimates of Läderach and Sodemann (2016), namely 4–5 days or 3.9 ± 0.8 days (spatial variability indicated by one standard deviation) for 15-day backward trajectories or 4.4 days for 20-day backward trajectories, are so far outside the uncertainty range that they cannot be true.

The paper needs to go into more detail of the tracking methods, a more detailed analysis of the results and a greater discussion regarding the assumptions made by Laderach and Sodermann, and to provide evidence as to why the authors disagree with these assumptions.

As explained above, we believe that we have already made a very strong case for the results of Läderach and Sodemann (2016) to be wrong. Please note that we mean their absolute values, we do not doubt their spatial patterns, which we actually found innovative. As mentioned also in our response to Kevin Trenberth we will add a paragraph to the Supplement that discusses the differences between our own methods WAM-2layers and 3D-T (Fig. S1) in terms of their underlying assumptions. However, it is beyond our possibilities nor within scope of this paper to explore what went exactly wrong in the analysis of Läderach and Sodemann (2016). The latter are, in our opinion, the only ones that could figure that out. Rather than focusing on the tracking methods, however, if the referee or anyone else disagrees with our estimates we would like to dare them to challenge Eqs. (2) and (3).

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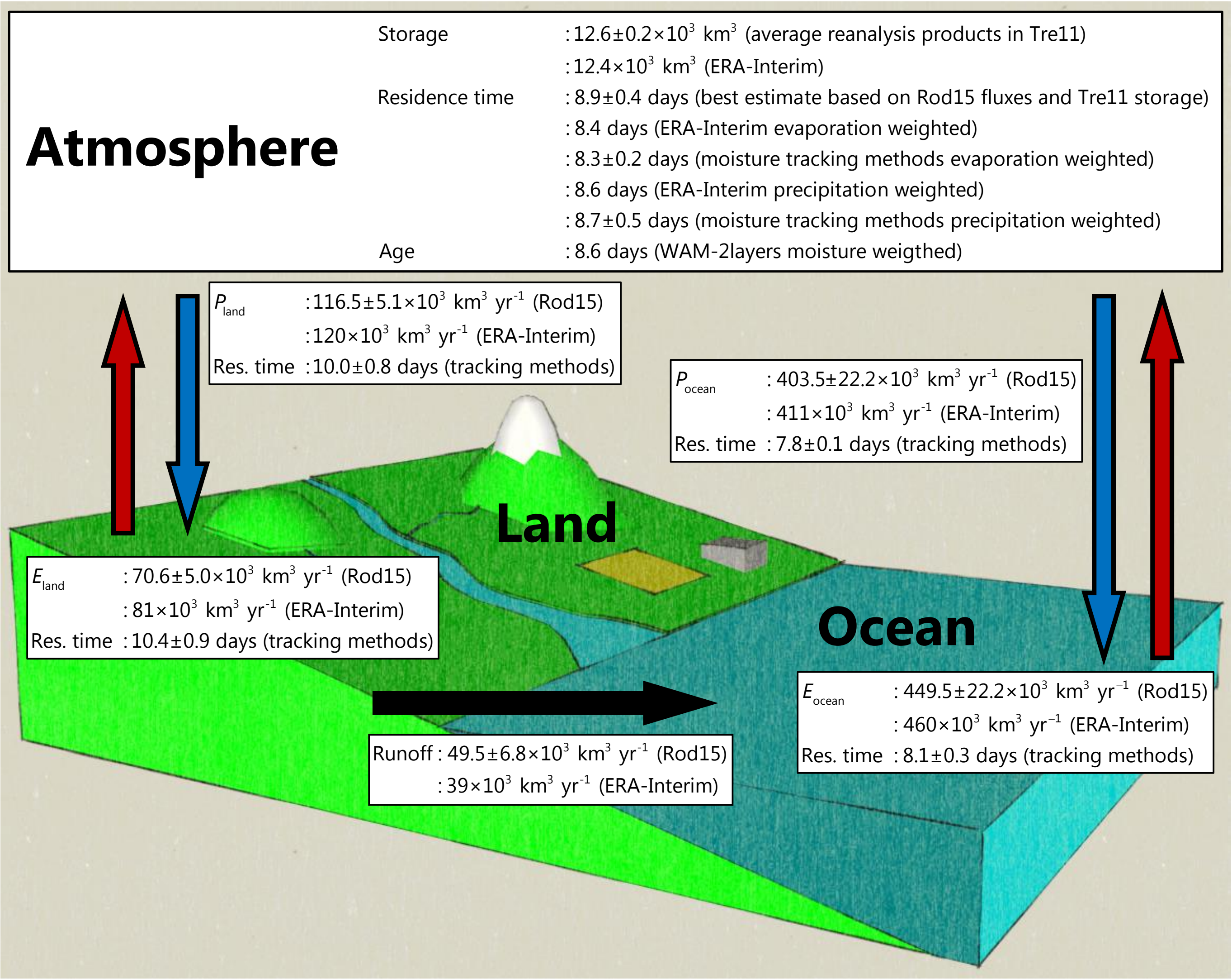

Figure 1. Earth's hydrological cycle with residence times (2002–2008). All residence times shown are weighted averages. The uncertainty ranges indicated for the residence times from the moisture tracking methods refer to the uncertainty associated with model choice (WAM-2layers or 3D-Trajectories). Tre11 stands for Trenberth et al. (2011) and Rod15 stands for Rodell et al. (2015). The land area is $147 \cdot 10^6\,\mathrm{km}^2$ and the ocean area is $363 \cdot 10^6\,\mathrm{km}^2$.