The residence time of water in the atmosphere revisited

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Response to the review of Kevin Trenberth

We thank referee Kevin Trenberth for the prompt review of our manuscript. We agree with several of the comments, however, we argue here that some comments regarding our data, methods and metrics are not very constructive, not true or not relevant considering the scope of our paper. Nonetheless, it is our job to clearly outline the objectives of this paper, justify the methods used and explain our results. Therefore, we will adjust the revised version of the manuscript wherever appropriate, but first we provide a detailed response here below. 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.

General comments

This paper addresses the issue of residence time of atmospheric moisture and concludes that the value originally proposed by Trenberth (1998) of 8.9 days still applies. It provides a partial commentary on an earlier paper by Läderach and Sodemann (2016) which suggested that the residence time was less than half, namely 3.9 days. Two methods are used to assess the lifetime and age of moisture in the atmosphere and the basic fields used come from ERA-Interim reanalyses.

Indeed, the referee is correct that we conclude that the traditional estimate for global average residence time of water in the atmosphere is 8.9±0.4 days. However, we would like to point out that it is hard to speak of a single original estimate as Trenberth (1998) actually provided two estimates, namely 8.9 days and 9.1 days, depending on whether global average evaporation or precipitation is considered. Moreover, the earliest reference in our manuscript is in fact to Chow et al. (1988), which suggested 8.2 days, but in Läderach and Sodemann (2016) one can find references to even earlier estimates.

Although some issues in addressing these scientific questions are discussed, many outstanding issues and reasons for different results are not.

It is not entirely clear to us what the referee means with this general and non-constructive comment. Our paper comprehensively discusses many aspects related to the residence time of water in the atmosphere, which was the main objective of the paper.

The tracking models used in this paper deal with particles and not finite volumes; and hence they do not appear to deal with the water budgets and precipitation processes or the storms and how they reach out to gather in moisture. Tracking a parcel is *not the same as tracking the overall moisture flow from source to sink. Mixing and convection do not appear to be dealt with and "precipitation events" are not defined. These processes are not reversible (one cannot go backwards, but in this paper they do). It is not that the exercise in this paper is without merit, but rather that it involves huge unstated assumptions and many questions are left outstanding.*

There appear to be a few big misunderstandings here. The first model (Water Accounting Model – 2 layers) actually keeps account of the tagged and total water volumes in two layers of each grid cell globally and thus explicitly deals with water budgets. The second model (3-Dimensional – Trajectories) uses many water parcels, which in our definition are infinitesimal water volumes, to represent the total moisture budget of the atmospheric column. Both models are forced with climate data (ERA-Interim in this case), which does contain the dynamics of precipitation events and storms, as that will be reflected in the precipitation, humidity and wind data. Vertical mixing, however, is indeed a difficult issue to tackle for all atmospheric moisture tracking models and is likely to be a major cause for differences between WAM-2layers and 3D-T. The assumptions involved and effect on the outcome are comprehensively discussed elsewhere (van der Ent, 2014; van der Ent et al., 2013; Tuinenburg, 2013). In contrast to some other models, for example FLEXPART, which tracks (E-P) parcels (Stohl et al., 2005), the two models we used in this research do track atmospheric moisture from source to sink, which is clearly explained in their respective references (van der Ent, 2014; Tuinenburg, 2013). Backward tracking of atmospheric moisture surely comes with assumptions, but it is widely applied in so-called offline moisture tracking models, see e.g., Gimeno et al. (2012) for a non-exhaustive overview, and additionally Keys et al. (2012). Unless the referee makes the "many outstanding questions"' explicit we cannot react to this comment. We propose the following changes to our manuscript:

- In Section 2.2, add a sentence where we explicitly state that both models track moisture from source to sink;
- Add a paragraph to the Supplement that discusses the differences between WAM-2layers and 3D-T (Fig. S1) in terms of their underlying assumptions.

Evaporation, as the source of moisture, is continuous and rates are modest. In contrast, precipitation is inherently intermittent; it typically precipitates only about 7 to 10 % of the time (depends on threshold), and the precipitation processes vary enormously. Most precipitation occurs in the Tropics and is convective in nature, and this is generally true in summer over continents as well. Weather systems are typically much smaller in scale in summer over land than in winter where large extratropical baroclinic storms provide the main storms. None of these aspects are addressed in this paper.

We totally agree with the observations made by the referee regarding evaporation and precipitation. However, for as far as the differences between evaporation and precipitation are relevant for atmospheric residence time we feel that they are already discussed in Section 4.

Atmospheric and climate models, including high-resolution numerical weather prediction models, have grid scales of tens to hundreds of km, and convection is parameterized. It has been shown in many studies that precipitation in models occurs too frequently and with insufficient intensity owing to the convective parameterizations, so that the lifetime of moisture in the *atmosphere is much too short in all models. The easiest way to show this is via the strong summer diurnal cycle in precipitation and it's timing, which is too early in the day in all models (see Trenberth et al. 2003 for a discussion of all these points.).*

Again, we totally agree with the observations made by the referee. Most likely the ERA-Interim data is also affected by having too frequent and not intense enough rainfall, but a detailed investigation of this is beyond the scope of this paper. We believe that the largest effect on our findings would be on the probability density functions of residence time (Fig. 4). Namely, we think that the amplitude of the diurnal cycle that we observed could be slightly higher in this case. We propose the following change to our manuscript:

- In Section 5, add a sentence about a likely bias in precipitation frequency and intensity in our data, with reference to Trenberth et al. (2003), and how that could potentially (slightly) increase the amplitude of the diurnal cycle observed in Fig. 4.

Because precipitation rates (when raining) average 10 to 25 times evaporation rates (see Trenberth et al. 2003) (owing to the fact that most of the time it does not rain), any moderate or intense precipitation comes from advection and convergence of water vapor, not local evaporation. Monsoons are an example where moisture is transported great distances in reality to supply the monsoon rains, and a chronic error in most models is that the precipitation is deficient in monsoon areas (see Christensen et al. 2013), because the moisture falls out prematurely.

We again absolutely agree. Unfortunately, the referee does not make clear how he thinks these comments are related to our paper. If it is to say that our forcing data is uncertain then he is of course right, but this is an issue of any paper that uses data. We also address uncertainty in this paper, but we do not see the need to repeat over and over again that our results depend on uncertain forcing. We think that most, if not all, readers of HESS are very much aware of all uncertainties associated with climate and weather data, or, in fact, any type of data.

The difficulty of dealing with precipitation processes realistically, and especially convection, is a major outstanding issue in all studies that address the lifetime of moisture in the atmosphere. No doubt the problems in the Läderach and Sodemann (2016) paper stem from these issues. The methods applied in this paper do not appear to suffer from the premature onset of convection because they do not deal with realistic precipitation processes at all!

We use ERA-Interim forcing data just as Läderach and Sodemann (2016) do. Obviously, the tracking methods are different as we come up with a very different estimate. Yet, the spatial patterns are quite similar as discussed on P6:L28-30 of our manuscript. In contrast, however, to the estimates of Läderach and Sodemann (2016), our estimates actually makes sense from a global average water budget calculation (see Section 3). In our opinion, the comment that we do not deal with realistic precipitation processes at all is unfounded and inappropriate.

Results should be reconciled with estimates of "recycling" of moisture, which refers to the amount of moisture over a particular area that is precipitated from evaporation within that area (see Trenberth 1999). That paper also discusses and presents *estimates of the older concepts of "intensity of the hydrological cycle", "precipitation efficiency" and "moistening efficiency" which have unfortunately been lost in this paper.*

We agree that recycling of moisture is indeed an important aspect when studying the time component of atmospheric water. However, we would like to point out that recycling of moisture has much broader definitions than the one proposed by Trenberth (1999). See, for example, earlier work on more regional scales (Brubaker et al., 1993; Eltahir and Bras, 1994; Savenije, 1995; Schär et al., 1999), but also later work (e.g., Bisselink and Dolman, 2008; Dominguez et al., 2006; Tuinenburg et al., 2012) , which place recycling in a local, regional and continental context. On a global scale, recycling has also been discussed extensively in previous papers from us as well as from others using the same, or similar methods, as the ones used here (e.g., Dirmeyer et al., 2009, 2014; van der Ent and Savenije, 2011, 2013; van der Ent et al., 2010, 2014) and some of these papers added the perspective of evaporation recycling. The concepts of precipitation efficiency and moistening efficiency, as globally calculated by Trenberth (1999), are surely useful as well for some purposes, but they remain local metrics, which are not helpful for our research objectives as stated on P3:L15-16: “The objective of this paper is to revisit the current knowledge and provide a state-of-the-art view in time and space of the residence time of water in the atmosphere”. Läderach and Sodemann (2016) explain quite well why local metrics are not good estimates of residence time.

There remain major issues also in the datasets used in all such studies. Here, the evaporation and precipitation are from ERA-interim, which is a model-based assimilated set of values. Over land, evaluation of precipitation using Global Precipitation Climatology Centre (GPCC) high resolution data (Becker et al. 2013) shows considerable shortcomings in the reanalysis values (Schneider et al., 2013); also Trenberth et al. (2011). Globally, the Global Precipitation Climatology Project (GPCP) analyses are most widely accepted as having best values, although these are monthly means. Evaporation analyses suffer from shortcomings associated with bulk flux estimates, and are only useful in the context of a complete water cycle (as in Rodell et al. 2015).

Surely the people of GPCC and GPCP are doing a tremendous job in providing as good as possible precipitation estimates. Whether those estimates are the best is quite arbitrary, although we agree that they are probably better than ERA-Interim. However, ERA-I precipitation is given in a 3-hourly resolution and is most consistent with the other data from ERA-I. As can be seen from Fig. 1, ERA-I falls within the uncertainty ranges estimated by Rodell et al. (2015) on a global scale, as is discussed on P6:L16-20. As mentioned before, we think that most, if not all, readers of HESS are very much aware of all uncertainties associated with data of the climate, or, in fact, any type of data, without the necessity of repeating this over and over again.

Specific comments

Some further questions that arose for me are as follows. It makes no sense to me to separately compute a "precipitation residence time" and "evaporation residence time". Perhaps they should be called something else (e.g. see Trenberth 1999)? The fact that Fig. 2c is so different from Fig. 2d illustrates that it makes a lot of sense to define an atmospheric residence time for both precipitation and evaporation. This is actually analogous to defining both depletion and restoration times (Trenberth, 1998), precipitation and moistening efficiency (1999), or precipitation and evaporation recycling metrics (van der Ent and

Savenije, 2011; van der Ent et al., 2010). However, atmospheric residence times are clearly different from all of these metrics, thus it is necessary to define them. We propose the following change to our manuscript:

- In Section 4, related to Figs. 2c,d, we will mention that the definition of an atmospheric residence time – for both precipitation and evaporation – is analogous to the definition of other metrics for the atmospheric branch of the hydrological cycle, which are also defined for both the precipitation and evaporation perspectives (e.g., Trenberth, 1998, 1999; van der Ent and Savenije, 2011; van der Ent et al., 2010).

It states "The places of low precipitation residence times (Fig. 2c) coincide mostly with areas of low precipitation (Fig. 2a)." Yet if it does not rain, then perhaps moisture hangs around for a long time? It seems count-intuitive? Or is it because in subtropical high pressure systems perhaps the moisture is transported away?

Our observation is exactly as it reads here, and not the other way around, i.e., areas of low precipitation do not always coincide with areas of low precipitation residence time. In the Sahara, for example, atmospheric moisture indeed hangs around for a long time without being replenished with evaporation. We propose the following change to our manuscript:

- Add a remark that the reverse statement (i.e., low precipitation coinciding with low precipitation residence time) is not necessarily true.

"The intertropical convergence zone (ITCZ) has increasing precipitation residence times" yet it is pouring with rain? Is this because the moisture has been transported from afar? Isn't the age of atmospheric moisture dependent on the precipitation processes?

Indeed the moisture has been transported from afar, this is somewhat more clear in Fig. 2d than in Fig. 2c, and, therefore, we wrote on P7:L5-6 "The atmospheric residence time of evaporation (Fig. 2d) can often be seen as an indication of the moisture travel distance towards an area of high precipitation such as the ITCZ". The age of atmospheric moisture is not dependent on the precipitation processes. When you take away water from any reservoir with a certain age, the age itself is not directly influenced, but only when it is again mixed with new water.

Several of the results here related to regional residence times also do not appear to make sense from a standpoint of the physical process associated with precipitation and the water cycle. The seasonal differences over the southern hemisphere in Figure 3 are surprising to say the least (I am from New Zealand), and seem very suspicious elsewhere too (such as over the northern ocean storm tracks). Extratropical storms are every bit as active in summer in the southern hemisphere as they are in winter, just for a narrower latitudinal band (Trenberth 1991). The results cry out for explanations.

Unfortunately, the referee is not very specific about what he thinks is suspicious in our results. It is not clear to us whether he would expect lower or higher atmospheric moisture ages in the Southern Hemisphere during January or July and in which latitudinal band specifically. Below we added Figure S3, which may be able to provide some clarification. In much of the Southern Hemisphere the atmospheric moisture storage (i.e., precipitable water) is lower in July (Fig. S3b) compared to January (Fig. S3a), precipitates rates are higher in July (Fig. S3d) compared to January (Fig. S3c), and evaporation rates or also higher in July (Fig. S3f) compared to January (Fig. S3e). The higher evaporation rates in July in the ERA-Interim data may seem counterintuitive, but correspond to previous studies (e.g., Yu, 2007). Is it quite logical that lower storage and higher fluxes lead to lower moisture ages in the Southern Hemisphere in July (Fig. 3c) compared to January (Fig. 3a). Note that Animation 1 in the Supplement provides a nice view of moisture age throughout the year. Moreover, the seasonal patterns we observe for precipitation residence times (Fig. S2a+c in the Supplement) are quite similar to Läderach and Sodemann (2016, Fig S3 in the Supplement), albeit that their figures are for DJF and JJA while ours are for January and July, and, as for the yearly average figures, their absolute values are much lower. We propose the following change to our manuscript:

- Add Figure S3 here below to the Supplement and provide more explanation similar to the explanation above in Section 4 (around the discussion of Fig. 3).

Technical corrections

There appear to be problems in Eq. (1) since it deals with t, t-1, and t. The units are inconsistent because "1" has no units.

We thank the referee for noting this. We will rewrite the equation to avoid possible confusion as follows:

The model calculates the age N_g of the tagged moisture present in a grid cell layer according to the following formula:

$$N_g^t = \frac{\begin{pmatrix} W_g^{t-1}\left(N_g^{t-1}+\Delta t\right)+\sum F_{g,\mathrm{in}}\Delta t\left(N_{g,\mathrm{in}}^{t-1}+\Delta t\right) \\ -\sum F_{g,\mathrm{out}}\Delta t\left(N_g^{t-1}+\Delta t\right)-P_g\Delta t\left(N_g^{t-1}+\Delta t\right)+E_g\Delta t\frac{\Delta t}{2} \end{pmatrix}}{W_g^t}, \tag{1}$$

where, the subscript $_g$ stands for tagged water. The superscripts ^{t} and $^{t-1}$ are the current and previous time step respectively. Δt is the length of the time step. $N_{g,\mathrm{in}}$ stands for the age of the tagged water coming into the grid cell layer. $F_{g,\mathrm{in}}$ and $F_{g,\mathrm{out}}$ are the incoming and outgoing fluxes over the (vertical and horizontal) boundaries of a grid cell layer.

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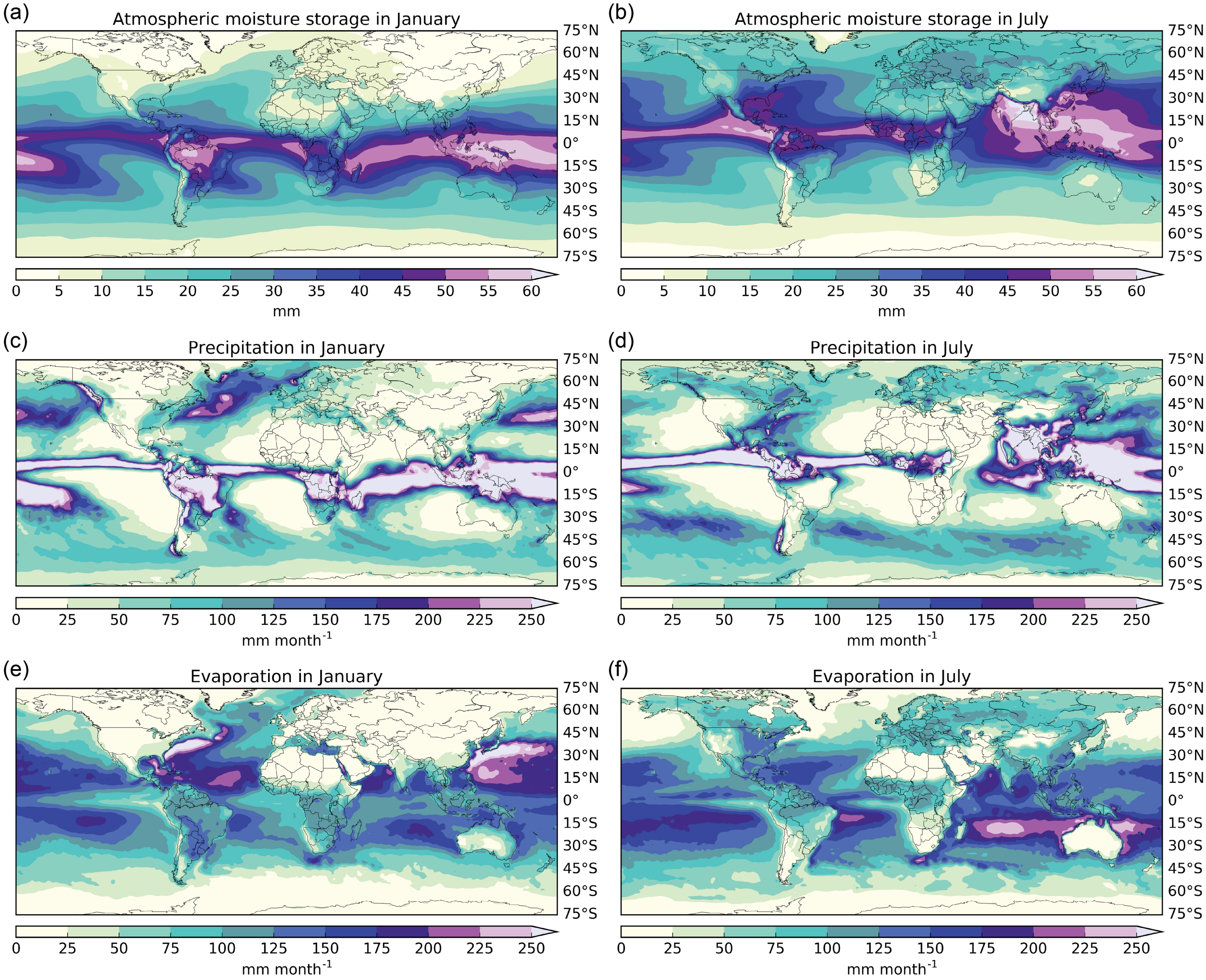

Figure S3. Atmospheric moisture storage, precipitation and evaporation in January and July (2002—2008, ERA-Interim).