The residence time of water in the atmosphere revisited

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Response to Harald Sodemann

We would to thank Harald Sodemann for his extensive comment concerning the differences between the results of Läderach and Sodemann (2016), henceforth LS16, and our paper, henceforth VT16. Despite the fact the we disagree with almost all points raised in his comment we appreciate the constructive attitude that was expressed in the comment as well as during personal discussions we had during the 8th EGU Leonardo Conference (25–27 October, Ourense, Spain). Below we discuss all the point raised by Harald Sodemann in the sequence of the posted comment. Points raised by Harald Sodemann are in italic and our replies are in normal text. The detailed adjustments to the revised manuscript will follow after the public discussion period. Due to the length of this discussion we would like to point out that the most fundamental issues in our opinion are discussed in Section 2 of this response.

Introduction

Until recently, it was commonly accepted knowledge that the residence time of water vapor should be about 8–10 days on a global average. In our recent study published in Geophysical Research Letters (Läderach and Sodemann, 2016, henceforth LS16) we challenged this viewpoint with regard to different aspects. First, we pointed out deficiencies in the use of depletion time constants if used as a local measure of the time water vapour resides in the atmosphere between evaporation and precipitation. From a modified Eulerian estimate taking into account horizontal moisture flux between grid cells, we derive more plausible patterns that are in correspondence with prevailing weather systems. Using a Lagrangian method that identifies the sources of moisture for precipitation events in the ERA-Interim data set (Dee et al., 2011), we obtain the same patterns, but with a substantially shorter time scale of 4–5 days as a global average.

We also state in our manuscript that LS16 are correct that location depletion times (van der Ent and Savenije, 2011; Trenberth, 1998) are not equal to actual residence times. Van der Ent and Savenije (2011) stated that their calculated metrics are to be interpreted as local timescales for precipitation and evaporation, which give an indication for the residence time of atmospheric moisture if horizontal moisture transport is small. As their stated objective was to calculate local metrics there was, however, in our opinion never any controversy about the fact that these could not be interpreted as actual residence times.

Besides the Lagrangian method used by LS16, from which they obtain a 4–5 days residence time estimate, it is interesting to note that LS16 also use a local Eulerian method including a transport approximation and find a global annual mean value of the time 'constant' to be 8.3±4.2 days (spatial variability indicated by 1 standard deviation). While LS16 disregard this Eulerian estimate as incorrect, because “precipitation processes are strongly oversimplified”, we interpret this result as supporting evidence that the 8–10 days must be correct due to the most elemental physical concept that an average residence time can be calculated from dividing a stock by its average influx or outflux under the assumption that there is negligible net stock change over a longer period, and that this applies to the atmosphere as well (e.g., Chow et al., 1988; Hendriks, 2010; Jones, 1997; Savenije, 2000; UCAR, 2011; Ward and Robinson, 2000).

We argue that the difference to the 8–10 days that are derived from estimates based on depletion time constants results from several implicit assumptions on how water turnover in the atmosphere can be described. In their discussion paper, van der Ent and Tuinenburg (2016), henceforth VT16, criticize our estimate as incorrect, but do not provide supporting evidence that would indicate that errors have been introduced in our analysis. I reply to some of the statements by VT16 concerning LS16 in this public comment, and suggest several major modifications to their discussion manuscript, which may help to turn it into a more constructive contribution regarding the residence time of atmospheric water vapour.

Sodemann uses the word “constants” often in his arguments, but we will argue below that we do in fact not make any assumption of constant fluxes. Assuming that global estimates of evaporation, precipitation and atmospheric storage are correct (within a certain uncertainty range, see VT16 Fig. 1), we will argue that deviations from a constant flux can only cause changes in the probability density function of global average residence time, but not in the actual average, as that would violate mass balance.

We purposely chose not to discuss the possible issues in the applied methodology of LS16 that lead to an underestimation of the global average residence time, as we thought that VT16 Section 3 provides enough proof of the 4–5 day estimate to be incorrect, and then it is up to Läderach and Sodemann to find out how they can improve their methodology. As Sodemann is not convinced we will provide some more detailed criticism of their applied methodology. Our latest insights into the reason for the underestimation of the global average residence time by LS16 come from Stohl and James (2004), who evaluated the FLEXPART methodology. FLEXPART is generally only used to look at specific humidity changes (evaporation – precipitation, or $E-P$), but they found that when FLEXPART is used to evaluate E and P separately, globally averaged, $E=1380\,\mathrm{mm\,yr^{-1}}$, which corresponds to $E=704\cdot10^{3}\,\mathrm{km^{3}\,yr^{-1}}$. Since LS16 track precipitation backward with FLEXPART they essentially suffer from this likely overestimation of evaporation, and hence the underestimation of the residence time. LS16 did not evaluate how much evaporation they attributed in total in their runs, however, using the numbers obtained by Stohl and James (2004) and ERA-Interim atmospheric storage, a global average residence time of $12.4\cdot10^{3}\,\mathrm{km^{3}}/704\cdot10^{3}\,\mathrm{km^{3}\,yr^{-1}}=0.017\,\mathrm{years}=6.4\,\mathrm{days}$ is obtained. The assumption that the applied methodology can accurately attribute evaporation and estimate precipitation, thus has likely major influence on the results by LS16. Moreover, Sodemann et al. (2008) themselves note that a number of moisture transport processes is neglected, which are moisture changes due to convection, turbulence, numerical diffusion, and rainwater evaporation. Stohl and Seibert (1998) even note that specific humidity fluctuations along a trajectory may be entirely unphysical. In contrast to FLEXPART – WAM-2layers and 3D-Trajectories – do not suffer from this issue as evaporation and precipitation fields are used explicitly.

1. Discrepancies to LS16

a. *On pg. 6, L. 11-15, VT16 state: "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±0.8 days (spatial difference indicated by one standard deviation). Based on the arguments provided above we believe that the latter estimate is incorrect."*

The authors claim that the results presented in LS16 are "incorrect" - but no actual evidence is provided that would support that statement. The "arguments provided above" referred to in the quoted paragraph probably relate to an explanation of the estimation of residence times for lakes (see Sec. 3 below). Otherwise the basis of their argument seems to be the reiteration that previous studies have found longer residence times, most of them using the same methods as in VT16. We already were aware of this discrepancy before LS16 was published, and discussed the possible reason for the differences in the paper and the supplement at length. It would be very helpful if the authors could respond to our arguments brought forward in that supplement.

The basis for our arguments evolves around VT16 Eqs. (2) and (3). Based on that, the likelihood of the global average residence time of atmospheric moisture to be lower than 3.9 days corresponds to $1 \cdot 10^{-30}$. This is so highly improbable that in non-statistical terms this may be translated into incorrect. We simply note that the estimates of all other studies do fall within the 1^{th} and 99^{th} percentile of this estimate (7.9 and 9.8 days respectively). In the revised version we will write more explicitly that Eqs. (2) and (3) for the basis for our argument. These equations, together with the notion that all atmospheric water sooner or later participates in the hydrological cycle (i.e., no dead storage), also implicitly falsifies the arguments that were brought forward in the supplement of LS16. These arguments by LS16 are repeated below and we will argue that these are not valid.

The experiment of Bosilovich et al. (2002) and similar studies also provide a depletion time, rather than a residence time. The same is the case for the WAM method that relates fluxes in a grid cell to the total column water. We do not argue that these calculations are wrong, but that the quantity that is estimated from these methods is not an accurate measure of the residence time as we define it. Bosilovich et al. (2002) by the way even state that "actual residence times should be calculated by taking a Lagrangian approach."

In WAM-2layers we use water tagging; in the forward(backward) scheme water is tagged as it evaporates(precipitates) from a certain masked area, transported through the atmosphere in two layers and at each time step the ratio of tagged to total water is calculated as well as the age of this water (VT16, Eq. (1)). The assumption is indeed that precipitation stems from the total column water. Surely this is not likely to be true everywhere, but performs generally well in monsoon regions (Fitzmaurice, 2007). In any case, this cannot be seen as a counterargument for the validity of the 8–10 day estimate. If certain precipitation events are not "well-mixed" but stem only from let's say the bottom 75 % of the atmospheric water then this would only influence the probability density function (PDF) of precipitation residence time: 75 % of the particles have lower residence times, but other 25 % of the particles reside even longer in the atmosphere contributing to even longer tails than the ones we found in VT16 Fig. 4.

Depletion times could be calculated with WAM-2layers if all water was tagged at time step t_0, without renewal of tagged water, but this is not the experiment that we performed. Bosilovich et al. (2002) performed exactly such an experiment and found this to be 9.2 days. They write "... indicates an average global residence time of 9.2 days from this simulation." Strictly speaking Sodemann is correct that they calculated a global average depletion time, but there is no physical reason why – globally averaged – depletion time should be different from residence time. The quote that "actual residence times should be calculated by taking a Lagrangian approach." is actually from van der Ent and Savenije (2011) whereby they refer to the Semi-Lagrangian scheme of Bosilovich et al. (2002), but this quote is outdated as van der Ent et al. (2014) have shown that an Eulerian moisture tracking method is also capable of calculating residence times.

Our method, as all other methods, has uncertainties that we discuss in our manuscript. Because of these uncertainties, we assume that our estimate may be biased low by up to one day, and suggest a range of 4–5 days for the global residence time of moisture. This is far from the range of the residence times expected from depletion time constant calculations. These results are technically correct, and we argue that the disagreement stems mainly from differences between the Lagrangian residence time from evaporation to precipitation as we define it in LS16, and global or local depletion time constants. Of course our diagnostic, as all other methods, is not perfect and relies on some assumptions. Whether the results thus are a "true" residence time will require further work to confirm using other model data sets, and if possible, observations. We argue however that our shorter moisture residence times are in better agreement with global weather system characteristics and thus more plausible than 8–10 days.

See our reply under the introduction of this response. In addition, the length of the trajectories of 15 or 20 days used by LS16 is insufficient to calculate the global average residence time reliably (see VT16, Fig. 4). The value of 8.9±0.4 days (uncertainty indicated by one standard deviation) that we present in VT16 is a best estimate given our current knowledge of the global hydrological cycle.

b. *On pg. 6, L. 29-30, VT16 state: "Their [Läderach and Sodemann (2016)] spatial patterns are very similar, however, we observe that they underestimate the residence time everywhere with a factor 2–3. This observation leads us to suspect a fundamental irregularity in their method."*

In the LS16 paper, we extensively discuss the difference between patterns for the local and global residence time obtained from three different approaches. We restate that our calculations are technically correct, and can be explained in a meaningful manner. To suspect "fundamental irregularities" in the LS2016 method seems far beyond what can be concluded from only using one's own data and methods. A more in-depth analysis would seem appropriate before jumping to such far-reaching conclusions. It may be tempting to suspect calculation errors, but it misses the point. Instead, it may be worthwhile to consider the arguments that we have brought forward.

We will remove this speculative statement about "fundamental irregularities". In the introduction, however, we will add the notion that the methodology by LS16 suffers from the assumption that the applied methodology can accurately attribute evaporation and estimate precipitation, likely overestimates evaporation (Stohl and James, 2004), and that this has not been validated by LS16.

From a more fundamental perspective, the mere fact that our results are in disagreement with previous results does not allow to conclude on which one is correct or incorrect; it only allows to state disagreement. Consider the (not so small) possibility that because of the many assumptions and data limitations inherent in all methods, it may well be that both estimates are incorrect! As the above two statements in the discussion manuscript are currently written, they represent just a personal opinion, or in the authors' words, a "believe" and "suspicion". In my opinion, such unsubstantiated claims and opinion statements should not be allowed to pass the review process.

As explained in Section 1a of this response, the conclusion that the results of LS16 are incorrect does not stem from mere comparison with previous research.

It is unfortunate that the authors have not discussed the arguments we brought forward, which do point to the weaknesses and assumptions of depletion time calculations. Admittedly, we only briefly stated this in the main manuscript and fully exemplified them in the electronic supplement due to space limitations. But one would have wished that before submitting their comment the authors would have carefully read the entire publication, including the supplementary material. For ease of discussion, I restate and extend in section 2 below the critical points raised in the supplement to LS16. It would be very valuable if the authors could address these points.

VT16 Eqs. (2) and (3), together with the notion that all atmospheric water sooner or later participates in the hydrological cycle (i.e., no dead storage), also implicitly falsifies the arguments that were brought forward in the supplement of LS16. These arguments by LS16 are repeated below and we will argue that these are not valid.

***c.** On pg. 5, L 1-6, VT16 state: "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."*

This is not correct. In LS16, we do not argue that horizontal moisture transport is important for Eq. 2. We show that when a depletion time constant approach is used locally, i.e. for individual grid points, it matters substantially for the spatial patterns whether horizontal transport is considered or not (Figs. 2b and c in LS16). The global residence time estimate with or without horizontal moisture fluxes remains, however, almost the same, as stated in Sec. 4.2 of LS16. This has also been pointed out by reviewer #2 for this discussion paper. In fact, in the supplement text 4 to LS16 we discuss in detail why a difference remains to the estimate of the residence time following Eq. 2 in VT16. We will refer back to this and expand further in the next section.

We will add a Section to our own Supplement were we answer the questions raised by LS16 (Supplement Section 4). The same points also appear in Section 2 below.

We intend to change this sentence into: “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 a) not a reliable estimator for local residence times as it does not involve horizontal moisture transport, b) should be corrected for the surface are of the Earth where most precipitation is observed, and c) that the temporal characteristics of global precipitation cannot measured by depletion time constants. However, a*) horizontal moisture transport is irrelevant for the global average value, b*) the surface area of the Earth is irrelevant as it is not in Eq. (2), but nonetheless all areas participate in the hydrological cycle as there is also transport even over the Sahara (e.g., Schicker et al., 2010; Goessling and Reick, 2013), and c*) the values in Eq. (2) correspond to the elemental physical concept that an average residence time can be calculated from dividing a stock by its average influx or outflux under the assumption that there is negligible net stock change over a longer period; whether these average fluxes are constant or not is irrelevant, and the temporal characteristics of precipitation and evaporation can only affect the PDFs of the residence time but not the average. In the Supplement we show that the counterexamples objecting to Eq. (2) by Läderach and Sodemann (2016, Supplement Section 4) can easily be falsified. Moreover, we argued above 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.”

2. Discussion of simple global mean estimates

A Poission process is a widely-used counting process where events happen at a certain rate, but completely at random. The depletion time constant of the global reservoir of water vapour through precipitation has been used widely to obtain ant estimate of the residence time of atmospheric water vapour. Using a value for global precipitation (which equals global evaporation) of 500 $\mathrm{km}^3/\mathrm{year}$ *= 1.37* mm/day *and a volume of the global moisture in the atmosphere of 12.7 thousands of* km^3 *(Trenberth et al., 2011), one obtains a global depletion time constant of* $12.7/1.37 = 9.3\,\mathrm{days}$*. Assuming a more extreme case within the range of uncertainty for both quantities, the numbers change to a global precipitation of 616*kmyr^{-1} *= 1.69* $\mathrm{mm\,day}^{-1}$ *and the global amount of moisture in the atmosphere of 12.3 thousands of* km^3*. This would result in a global average depletion time constant, assumed to be identical to the residence time of moisture, of* $12.3/1.69 = 7.3\,\mathrm{days}$*.*

First of all, Sodemann is mixing up units here. The likely value for the precipitation/evaporation flux is a factor 1000 off and should be $500 \cdot 10^3\,\mathrm{km}^3/\mathrm{yr}$. Divided by 365.25 days this equals $1.37 \cdot 10^3\,\mathrm{km}^3\,\mathrm{day}^{-1}$. Averaged over the Earth’s surface area ($510 \cdot 10^6\,\mathrm{km}^2$), this equals $2.68\,\mathrm{mm\,day}^{-1}$. The calculated corresponding residence times where, however, computed correctly as 9.3 and 7.3 days, respectively for a normal and extreme case. It should als be noted that the extreme case is indeed quite extreme as it is 4 standard deviations away from the most likely value of 8.9±0.4 days, computed by us based on the numbers provided by Rodell et al. (2015) and Trenberth et al. (2011).

These calculations provide a valuable estimate of how long it takes until the global total column water has been depleted to 1/e by precipitation. But can we interpret this measure as a quantitative proxy for the actual moisture residence time, defined as the time water molecules spend in the atmosphere between evaporation and precipitation? Which assumptions go into considering global precipitation as a Poission process? We present here three arguments against such simple ‘back-of-the-

envelope' calculations. The first and second are related to the assumptions made when following the arguments of the simple estimate. The third one demonstrates that for systems where the assumptions of a Poission process are violated, depletion time constants do not allow to conclude on the moisture residence time.

All three arguments are falsified below. Moreover, it should be noted that whether or not evaporation and precipitation are Poisson-processes or not this would not affect the global average residence time of water in the atmosphere.

***a.** Precipitation is generated in weather systems of different kind and lifetime. Weather systems are formed, may move through the atmosphere, leading to an unequal distribution of precipitation in space and time, until they decay. This 'intermittent' nature of precipitation is a central aspect, and is also related to the atmospheric residence time of water vapor. Some areas of the world experience frequent and heavy precipitation, other areas, such as deserts, hardly experience any rain. Throughout one year, some areas will thus participate more strongly in the atmospheric water cycle than others. This obvious fact becomes important for the simple estimate when considering that the global mean precipitation of 1.69 mm day assumes that all areas of the Earth receive an equal amount of precipitation. According to ERA-Interim reanalyses, 100 % of the global precipitation in a year fall onto 95 % of the global surface area, whereas 96 % fall onto less than 80 % of the surface area (Fig. C1). If we redo the simple estimate from above taking this fact into account, we have to correct the global average rain rates for the actual surface area participating in the water cycle. This would lead us to conclude for example that 90 % of the effective global precipitation from the simple number example (1.37/0.8=1.71 mm day and 1.69/0.8=2.11 mm day, respectively) give depletion time constants of 7.2 and 5.8 days, respectively. While somewhat large values may have been selected here, this sensitivity points out that by considering the world's arid areas appropriately results in shorter residence times, in fact already quite a bit closer to the about 4-5 days we obtain from the LS16 method. The simple estimates rely thus on a global uniform distribution of precipitation, and global participation of all surface area, which is in fact not given. In terms of a Poission process, the spatial and temporal coherence of precipitation violates the randomness requirement.*

Again, Sodemann is mixing up units here. Global mean precipitation for the numbers used in the example by Sodemann should be $616 \cdot 10^3\,\mathrm{km}^3\,\mathrm{yr}^{-1} = 1.69 \cdot 10^3\,\mathrm{km}^3\,\mathrm{day}^{-1} = 3.31\,\mathrm{mm\,day}^{-1}$ for the extreme case and $500 \cdot 10^3\,\mathrm{km}^3\,\mathrm{yr}^{-1} = 1.37 \cdot 10^3\,\mathrm{km}^3\,\mathrm{day}^{-1} = 2.68\,\mathrm{mm\,day}^{-1}$ for the normal case.

To "correct" the global average value for the 80 % of the Earth's surface that receives most precipitation has no point when talking about the global average value. Recall that in VT16 Eqs (2) and (3) no use has been made of the surface area of the Earth. Intuitively, a global average value concerns a precipitation-weighted value or bulk value. When trying to "correct" for the wettest regions of the Earth only, one essentially calculates the spatial average residence time of precipitation for of the $\mathrm{x}\,\%$ wettest regions of the Earth, which is obviously not the same as the global average residence time of water in the atmosphere. In LS16 it is nowhere mentioned that they understand their estimate of 4–5 days as a spatial average precipitation residence time for the 80 % wettest regions, but instead present the 4–5 days estimate as the global mean atmospheric moisture residence time.

The mere fact that precipitation varies in space and time has nothing to do with the global mean value, nor does a bulk estimation invoke the necessity of being a Poisson process. In our manuscript (VT16) we clearly showed the spatial and

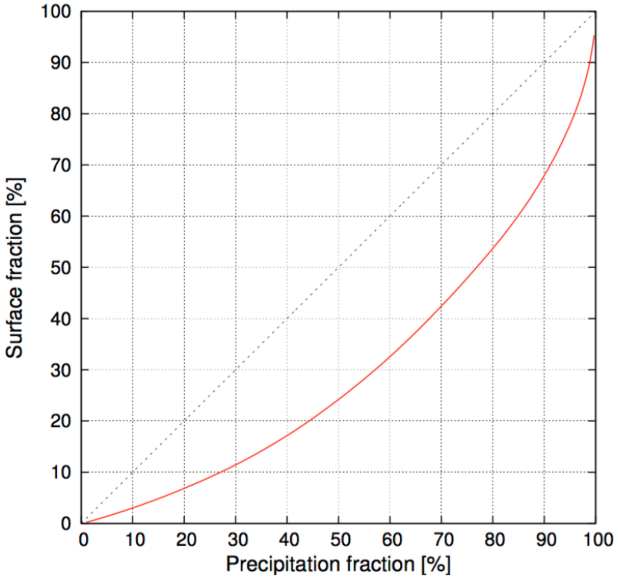

Figure C 1. Surface area fraction vs. precipitation fraction from the ERA-Interim reanalysis data (red line). The dashed line would result if precipitation were spatially homogeneous. Reproduced from Läderach and Sodemann (2016).

temporal variability of the residence time as computed by our tracking methods and still we arrive at global average residence times of 8–10 days.

As a side-note, the numeric examples provided by Sodemann are slightly different than those provided in LS16 (Supplement Section 4). In both cases, however, the spatial average calculation is not correctly executed: the units are mixed-up and the calculation itself is wrong. As shown above, the value 1.37 should have had units $10^3\,\mathrm{km}^3\,\mathrm{day}^{-1}$, of which 96 % falls over 80 % of the land surface. Thus, $1.37 * 0.96 = 1.32 \cdot 10^3\,\mathrm{km}^3\,\mathrm{day}^{-1}$. However, to be able to calculate a spatial average one should also know how much atmospheric storage (in $10^3\,\mathrm{km}^3$) resides over that 80 % land surface. Dividing that number by $1.32 \cdot 10^3\,\mathrm{km}^3\,\mathrm{day}^{-1}$ will give the spatial average residence time in days over 80 % of the land surface. We did not compute this here as it is actually irrelevant in the discussion as we have not addressed the spatial average in our manuscript anyway.

b. *Due to the prevalent atmospheric stratification, different time scales may be relevant at different atmospheric layers. For example, a lower layer of the atmosphere, representing 50 % of the column water, or integrated water vapour (IWV), may precipitate and recharge much faster with shallow weather systems. Tropical deep convection may involving the entire column water into precipitation generation, but only exist in some regions such as the ITCZ. A residence time would always consider rain to originate from the entire column, thus neclecting the existence of a faster branch. The assumption that all moisture would be depleted by a "deep" process may contribute to overly large estimates of the moisture residence time from depletion time*

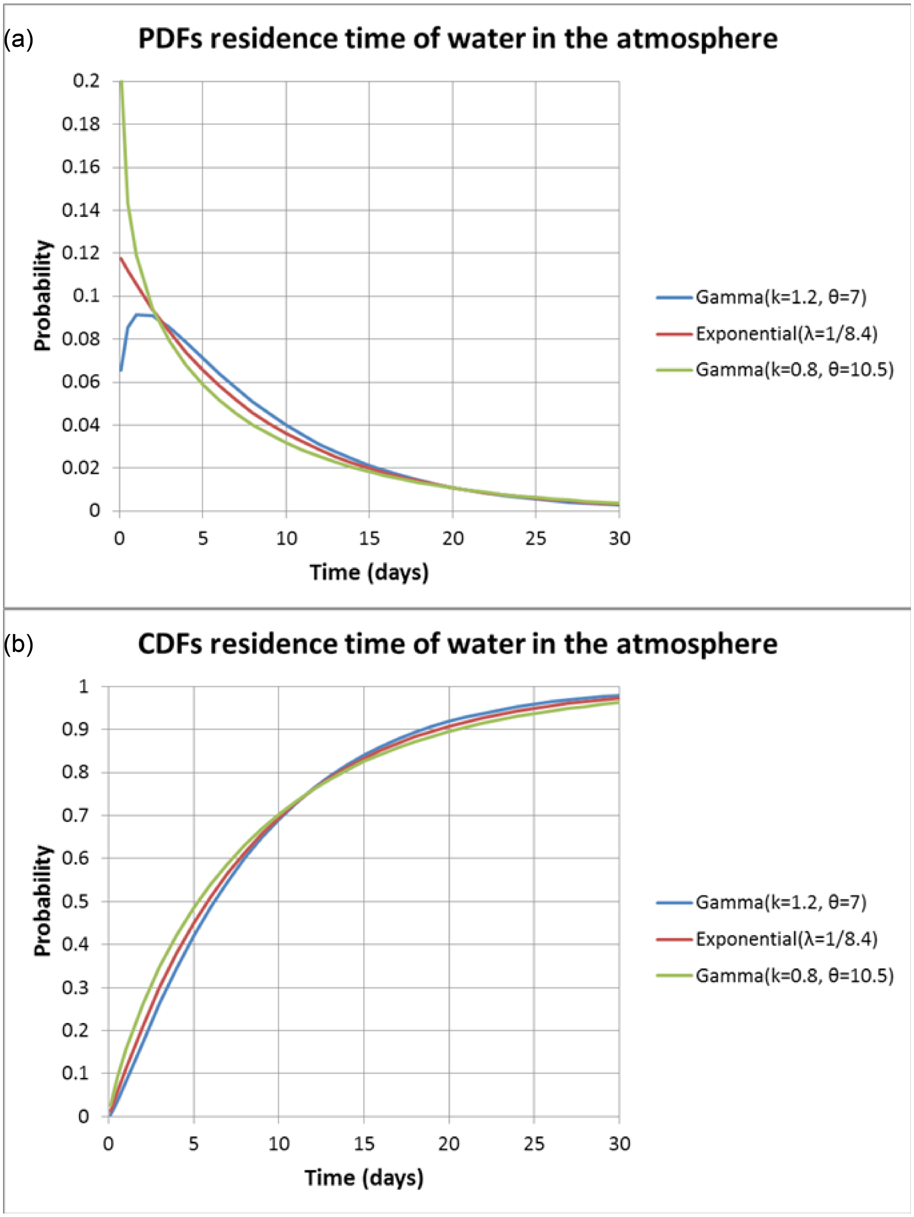

Figure C 2. Examples of different probability distributions of global atmospheric residence time, which all have a mean of 8.4 days. The “true” distribution is not exactly known, but this figure serves to illustrate that different mixing assumptions may skew the distribution without affecting the global mean. a) Probability density functions. b) Cumulative distribution functions.

constants. One may consider that a combination of several Poission processes could represent this complexity in a statistical framework.

Indeed there may very well be water particles that recycle much faster than the average particles. On the other hand, there will also be water particles that recycle much slower in the case they are found in atmospheric layers above the precipitation processes. However, wind speeds above the atmospheric boundary layer are generally quite high and these water particles will be transported, sooner or later, to places where there is deep convection or other processes that cause vertical mixing. Thus, also these water particles participate in the hydrological cycle. The argument of stratification only holds if there are water particles that never participate in precipitation processes. Even if we make the – perhaps not totally strange assumption – that water outside the troposphere (thus in the stratosphere or mesosphere) does not participate in the hydrological cycle (i.e., dead storage), the atmospheric storage is reduced by only $\approx 1\,\%$. The corresponding global average residence time of water in the troposphere then is $8.8 \pm 0.4\,\mathrm{days}$ (using the numbers from VT16, Fig 1). As we think it is important to be aware of these numbers we will add a sentence about this in Section 3 of the revised manuscript.

In both WAM-2layers and 3D-Trajectories we assume evaporation to enter in the lower levels of the atmosphere, but for precipitation we have indeed assumed a well-mixed atmosphere. This may have some consequences for the probability density functions (VT16, Fig 4), but can by definition not change the global average. An example of the consequence of the well-mixed assumption for precipitation can be explained at the hand of Fig. C2. Let's assume that the true PDF of global atmospheric residence corresponds to the Gamma($k = 0.8, \theta = 10.5$). Invoking the well-mixed assumption could shift this distribution to become an Exponential($\lambda = 1/8.4$) distribution or Gamma($k = 1.2, \theta = 7$) distribution, but cannot alter the actual mean of the distribution. When more water particles undergo a faster cycle, as a logical consequence, also more water particles undergo a slower cycle.

c. *Consider two hypothetical cases of global temporal precipitation patterns. In the first case, during any given month, rain falls globally every day with an average rain rate of* $1.37\,\mathrm{mm\,day}^{-1}$*. The same amount of evaporation occurs continously and maintains an atmospheric water volume of* $12.7x10^3 km^3$*. This case will give a depletion time constant of 9.3 days. In a second case, all of the monthly evaporation happens on the first day of each month, and all of the monthly precipitation on the last day. In this second example, the average lifetime of the water vapour is obviously enhanced considerably, while the depletion time constant would still provide the same value of 9.3 days. Obviously, here the stationarity required by a Possion process is not given. Compared to the real atmosphere, both examples are artificial, but they serve to illustrate the point that the depletion time constants do not necessarily faithfully quantify the residence time of atmospheric water vapour. (This example has been modified from the one given in the Supplement to LS16 to be more to the point of the assumptions underpinning a Possion process).*

Before we show that these examples are inconsistent with themselves and that the "depletion time constant", in fact, equals residence time in both cases, we have copied below the two other hypothetical cases from LS16:

Consider two hypothetical cases of global temporal precipitation patterns. In the first case, rain falls globally every other day with an efficiency of 100 %, i.e. all atmospheric water vapor rains out. In the second case, it rains once in 30 days, again with an efficiency of 100 %. Evaporation recharges the atmospheric moisture reservoir between the precipitation events in both

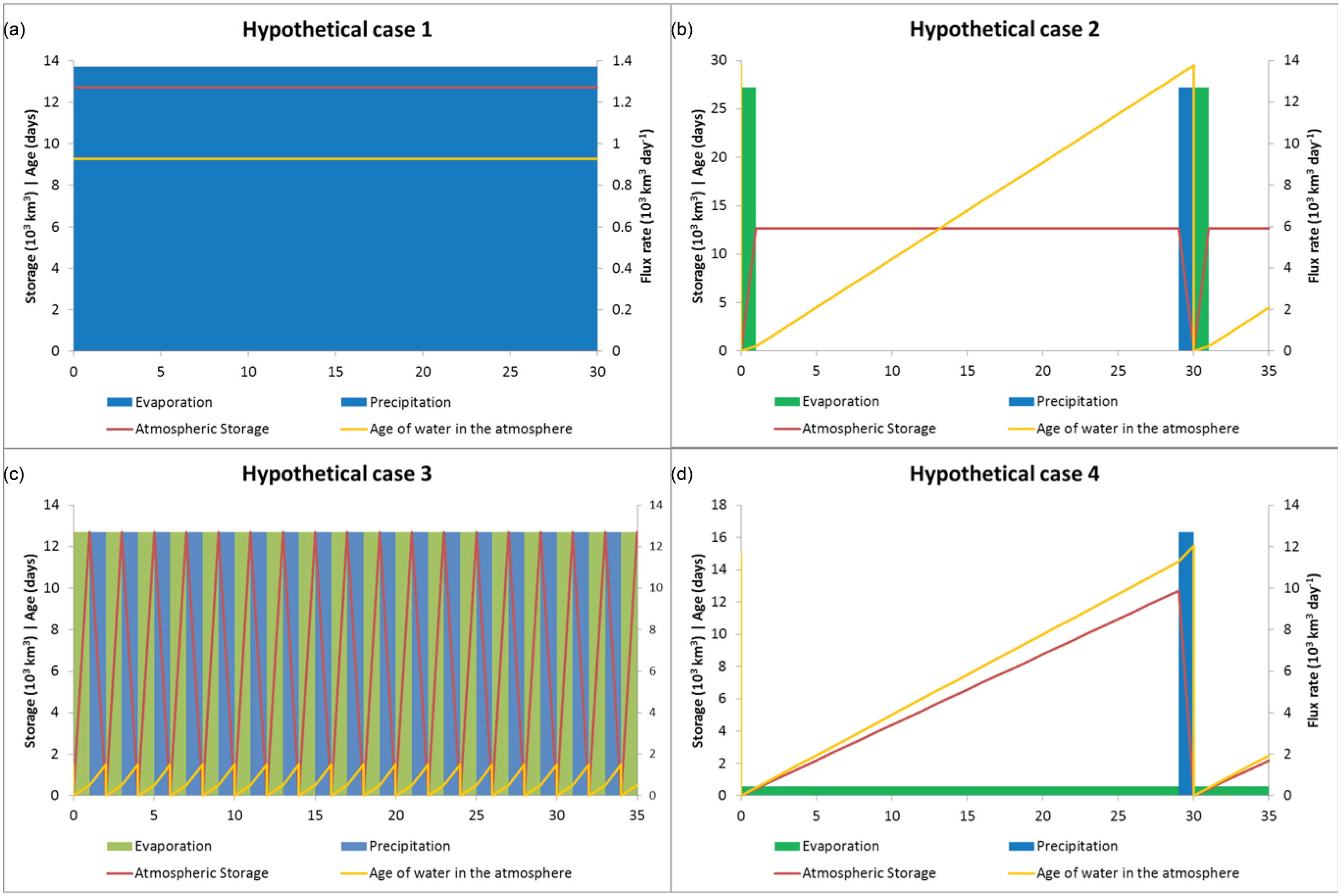

Figure C 3. Visualization of four hypothetical cases of depleting and replenishing the global atmospheric water store as described by Sodemann's comment (cases 1 and 2) and LS16 (cases 3 and 4). Note that in panel (a) precipitation and evaporation are constant, and, therefore overlap each other in the visualization.

cases. Both of these scenarios are not inconsistent with a global long-term average rain rate of 1.37 $\mathrm{mm/day}$ *and a global amount of moisture of 12.7 thousands of* km^3*, and will give a depletion time constant of 9.3* days*. Yet the actual residence time of the water vapor in the atmosphere, i.e. the time water vapor stays in the atmosphere between evaporation and precipitation, will be 1 day in the first example, and 30 days in the second. Of course both examples are artificial and unrealistic, but they serve to illustrate the point that the temporal characteristics of global precipitation are not measured by depletion time constants as provided by simple global estimates.*

In the following lines we will explore these four hypothetical cases in more depth, from which we conclude that these four cases, in fact, have very different evaporation/precipitation rates and consequently very different residence times. First, we have again to correct the units that were mixed-up by Sodemann. A global average rain rate of $500 \cdot 10^3\,\mathrm{km}^3\,\mathrm{year}^{-1} = 1.37 \cdot$

Table C 1. Summary of the four hypothetical cases brought forward by Sodemann's comment and LS16.

Case	Cumulative P or E after 30 days ($10^3\,\mathrm{km}^3$)	average P or E rate ($10^3\,\mathrm{km}^3\,\mathrm{day}^{-1}$)	Average atmospheric storage ($10^3\,\mathrm{km}^3$)	Residence time from average age of water during precipitation (days)	Residence time from stock divided by flux (depletion time constant in LS16 terminology) (days)
1	41.1	1.37	12.7	9.3	9.3
2	12.7	0.42	12.3	29.0	29.0
3	190.5	6.35	6.35	1.0	1.0
4	12.7	0.42	6.35	15.0	15.0

$10^3\,\mathrm{km}^3\,\mathrm{day}^{-1} = 2.68\,\mathrm{mm}\,\mathrm{day}^{-1}$. The corresponding global average residence time (or depletion time constant as Sodemann calls it) equals $12.7 \cdot 10^3\,\mathrm{km}^3 / 1.37 \cdot 10^3\,\mathrm{km}^3\,\mathrm{day}^{-1} = 9.3\,\mathrm{days}$.

All four cases are displayed graphically in Fig. C3. The corresponding average atmospheric storage, average precipitation rate, average evaporation rate and average residence time are given in Table C1. According to the comment by Sodemann, the residence time in case 2 should be much greater than the residence time in case 1, but case 1 and 2 would give the exact same depletion time constant. However, we can observe from Fig. C3 and Table C1 that the depletion time constant in case 2 is exactly equal to the residence time based on atmospheric water age. The simple reason for this being that the average precipitation rate in case 2 is much lower than in case 1. According to the Supplement of LS16, case 3 and 4 are both not inconsistent with a long-term average rain rate of $1.37 \cdot 10^3\,\mathrm{km}^3\,\mathrm{day}^{-1}$ and global average atmospheric water storage of $12.7 \cdot 10^3\,\mathrm{km}^3$. As can be seen from Fig. C3 and Table C1 these cases correspond with neither and the global average precipitation rate in case 1 is many times larger than the precipitation rate in case 2, hence the very different residence times.

According to Sodemann these hypothetical cases were supposed to "demonstrate that for systems where the assumptions of a Poission process are violated, depletion time constants do not allow to conclude on the moisture residence time". By exploring these cases in depth we have clearly shown that residence time can be accurately calculated by dividing a stock by its flux (compare last two columns of Table C1). In our opinion this is actually quite basic knowledge and we feel that for most readers Section 3 of our manuscript will be clear already as it is. Therefore, we intend to add the exploration of these four cases in a Supplement only, rather than adding it to the paper itself.

3. The lake analogy

In the introduction to their Section 3 (pg. 5, L. 24-27), the authors explain some of the reasoning behind a depletion time constant approach:

"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)."

The lake analogy serves to illustrate some of the main problems when considering the atmosphere as a hydrological reservoir. For a lake, it may be safe to assume some kind of well-mixed behaviour (or participation) on long time scales. Water vapour is however not well-mixed throughout the atmosphere, most water vapour resides close to the surface, and it travels horizontally over limited distances because of precipitation processes. For the lake, water is the medium, in the atmosphere, air is the medium and water is a trace substance. Following the lake analogy strictly, one should rather compare water vapour in the atmosphere to a tracer that is dissolved in the lake water and has source and removal processes at the surface.

We have nowhere in our manuscript assumed that the entire Earth's atmosphere is well-mixed, we only write that all water in the atmosphere participates in the hydrological cycle. As well as for lakes or the Earth's atmosphere it is completely logical to have spatial variations, but the average can still be calculated by Eq. (2).

In terms of a Poission process, it may simply be the case that a single random Poisson process does not represent global precipitation adequately. Maybe if one were to use a more realistic representation using several combined Poission processes, or a non-homogeneous Poission process, it may be feasible to obtain a realistic residence time estimate from depletion time constants. While it could be interesting to attempt to represent the atmosphere by a more complex statistical process, we argue that our Lagrangian approach already takes the complexity of the atmosphere into account more realistically that other current approaches.

We repeat that our methods do not assume Poisson processes, nor constant fluxes. As the spatial patterns observed by LS16 and VT16 are not very different, the transport in the method used by LS16 is comparable in realism to the methods used in VT16. The difference being that the absolute results of LS16 show physically impossible values.

There are different reservoirs or 'lakes', so to speak, in the atmosphere, some close to the surface that are continuously depleted and replenished by weather systems, and several higher above that only occasionally participate in the atmospheric water cycle, for example during deep convection. The situation varies with latitude and season. If one considers total column water, such as for the global residence time estimate, and as used in the methods of VT16, one implicitly assumes that precipitation extracts water vapour from all atmospheric layers, an assumption that induces large uncertainties in many regions of the world that are dominated by shallower precipitation processes. One consequence of the non-well mixed state of the atmosphere is that one should effectively reduce the IWV in the global average calculation, lowering the residence time. Remaining in the thought framework of a Poission process: If on average 80 % of the column water contribute to precipitation processes, IWV would be again be multiplied by a factor of 0.8, resulting in a 1.5–2 day lower residence time in the two examples above, and thus closely approaching the numbers of the Lagrangian residence time estimate of LS16.

The statement by Sodemann that if on average 80 % of the column water contributes to precipitation processes yield 1.5–2 days lower residence times is incorrect. You cannot simply neglect 20 % of the water when that on average does not rain out. When that water does not rain out during a particular storm it continues to "age" and sooner or later that water finds itself travelling vertically due to convection or orography, is caught in a katabatic wind, mixes turbulently for whatever reason, or simply finds itself being part of another precipitation event where 90–100 %, of the column participates. The only possible consequence of the well-mixed assumption for precipitation is that you find somewhat different distributions (see Fig. C2), but it can by definition not affect the average.

A possibly important issue is the question whether some moisture at high elevation resides in the troposphere for very long times, even months. Of course there is very little total water at these elevations, and one can ask the question whether that moisture should be considered for a residence time estimate if it does not actively take part in the atmospheric water cycle? A meaningful working definition of the residence time of water vapour in the atmosphere could then be more specifically identified as "water vapour in the troposphere that participates in the hydrological cycle on a monthly time scale". Very long-lived water vapour may require different methodological approaches that do not suffer from the accumulation of numerical errors with time.

The definition used in our manuscript (VT16) is the residence time of all water in the atmosphere. If Sodemann is more interested in the rather vague definition of "water vapor in the troposphere that participates in the hydrological cycle on a monthly time scale", then he should have clearly stated this in LS16, but this is not the definition we would like to use. Nonetheless, our Fig. 4 shows that these definitions are not that far apart from each other.

4. Simple estimate of the moisture transport distance

Looking at the problem from another direction, one can ask the question, what are the physical consequences of a moisture residence time of 8–10 days? Fig. C4 depicts the global mean humidity-weighted wind velocity over the entire atmospheric column for September 2005 from ERA-Interim reanalyses. Humidity-weighted wind speeds emphasize lower regions of the atmosphere, where most humidity resides, and gives an indication at what speed most of the humidity in the atmospheric column moves during that month. Values are 10–20 $\mathrm{m\,s^{-1}}$ *in the mid-latitudes, lower in the subtropics (4–8* $\mathrm{m\,s^{-1}}$*) and 8–12* $\mathrm{m\,s^{-1}}$ *at high latitudes. The implication of this is that moisture would travel on average more than 8000* km *before precipitating in the extratropics, and more than 4000* km *in the subtropics and tropics. Since the 8–10 days is an average value, individual cases will have substantially longer transport distances associated. Considering for example that mid-latitude weather systems develop and intensify, and thereby readily condense large amounts of water vapour along their fronts during 2–3 days, it is difficult to conceive how that corresponds to a 8–10 day time scale and 8000* km *length scale of the water transport. In the subtropics, the distance between the evaporation maxima and the ITCZ is only some 15–20 deg in latitude, and also there it is difficult to understand how the moisture can travel for 4000* km *on average before precipitating. Values closer to one half of these would be more consistent with expectations from the weather system characteristics in the respective latitudes. While this is not a proof for a shorter residence time, this argument points out that the 8–10 days are not easily explained, even in light of equally simple metrics of moisture lifetime and transport in the atmosphere as the global depletion time estimate.*

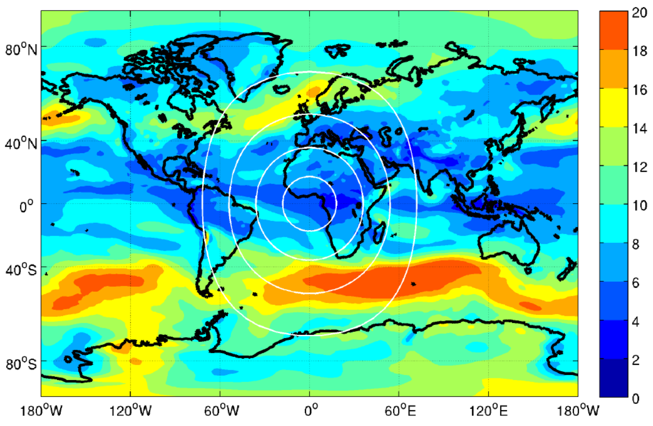

Figure C 4. Humidity weighted horizontal wind velocity (for the entire column, layer by layer) during September 2005 from ERA-Interim reanalyses. Unit is $\mathrm{m\,s^{-1}}$. Range rings around the equator indicate distances of 2000 to 8000 km from the point N0 W0. Reproduced from Sodemann's comment

These transport distances are actually quite reasonable and fit very well with the findings of global moisture recycling/transport and isotope studies (e.g., Bosilovich and Schubert 2002; Dirmeyer et al., 2009, 2014; Goessling and Reick 2011; Risi et al., 2013; van der Ent et al., 2014; Yoshimura et al., 2003, 2004a, 2004b). What Sodemann seems to be overlooking is that atmospheric water is most of the time not part of an active storm and may travel quite far during that time. Most particles will not, however, and therefore we also find a median of around 5 days (see VT16, Fig. 4). You can also turn this question around and ask what the consequence is of a 4–5 day residence time? The answer is unrealistically high precipitation rates or unrealistically low atmospheric water storage (see Fig. C3 and Table C1).

5. There are further important points in VT16 that would merit further explanation or discussion:

***a.** The authors consider 3 variants of the residence time of moisture, termed residence time of precipitation, residence time of evaporation, and age of water vapour. No explanation is given on how the age has been calculated. I assume all of these are different projections of the same quantity (precipitation RT projects forward, evaporation RT projects backward), and should have the same mean value. The relation and difference between each way of presenting the residence time could be stated more clearly to avoid confusion of the readers.*

As mentioned in our response to Jiangfeng Wei (AC3), we will use a shortened version of the Portugal example given in our response to Jiangfeng Wei to clarify the differences between the three metrics displayed in VT16 Figs. 2c-e. The calculation of the age is quite difficult with a Lagrangian method, but very easy with an Eulerian method, thus has been performed for WAM-2layers, and the formula is given in VT16 Eq. (1).

b. *The Tuinenburg method is based on the Dirmeyer and Brubaker (1999) approach (a corresponding reference is missing in the manuscript). As I understand that method, several isentropic trajectories are calculated from every 0.5x0.5deg grid point at several elevations, then surface evaporation is accumulated along these trajectories at every time step. Essentially, that method thereby assumes a well-mixed atmosphere at every time step and grid point - because the vertical position of the trajectory does not matter. Moreover, water vapour is assumed to be a conserved quantity once it is mixed into the air parcel (i.e. precipitation does not remove earlier moisture contributions). The method is furthermore sensitive to the reliability of the evaporation data set. This method clearly relies on strong assumptions, in particular compared to our Lagrangian method (Sodemann et al., 2008) which was applied in LS16 and neither assumes well-mixed conditions nor relies on evaporation, which is a difficult variable to observe and has large local uncertainties, in particular when derived from satellite observations (Rodell et al., 2015).*

Indeed, we should have given reference to Dirmeyer and Brubaker (1999), and we will do so in the revised version of our manuscript. The consequence of the well-mixed assumption for precipitation was already discussed under Section 2b of this response. There is definitely uncertainty in evaporation, and, therefore, we have checked how ERA-Interim evaporation compares to the state-of-the-art estimates from Rodell et al., (2015). This falls within the uncertainty ranges (VT16, Fig. 1). Not making use of evaporation data at all comes at the risk of highly overestimating it (Stohl and James, 2004), and should in our opinion, therefore, not be preferred.

Interestingly however, the median of the residence time with VT16's Lagrangian method 3D-T are with 5.7 and 4.6 days clearly lower than 8–10 days. There is a lot of very short-lived water vapour identified by this method. VT16 state that the very long tail leads to a mean to 8–10 days. Taken at face value, the low median argues for a residence time of the bulk of the water vapour of much less than 8–10 days. With trajectory calculation times exceeding 10–15 days, the tail gets more and more uncertain, in particular if few trajectories per grid point are considered. What would be the residence time if evaluation was not cut off at 30 (pg. 5 L. 10), but at 20 or, say, 50 days? Would it still be possible to argue that the mean is representative of the distribution? One consequence of this difference between the mean and the median is that the results in Figure 2 of VT16 should be shown separately for the WAM and the 3D-T method.

The fact that the median is about 5 days has nothing to do with the mean, but only with the distribution. The consequence of 20-day trajectories can easily be read from the PDFs (VT16, Fig. 4). The consequence of 50-day trajectories is not likely to influence the results much as 30-day trajectories already accounted for 95 % of the initial moisture. The location of an individual parcel may be uncertain of 30 days, but all parcels together yield a very smooth shape of the tail of the PDFs. We assumed a 30 day residence for the remaining 5 % of the parcels, and what we can say with certainty is that the mean can impossibly become lower by other assumptions about the shape of the tail.

Figure 2 is already shown separately in the Supplement (Fig. S1).

c. *A particularly puzzling result is shown in Fig. 3 of VT16. The patterns of the seasonal residence time appear difficult to interpret physically. Residence times increase from about 5 days to more than 15 days during northern hemisphere winter* *over the North Pacific, and the reverse applies to the southern hemisphere. In the current version, VT16 do not provide further explanation on what could cause this result, and how it relates to observed seasonal changes in the climate system. It would be interesting to learn about a corresponding strong change in the climate system that would explain such a drastic seasonal change.*

See our response to Kevin Trenberth AC1 P5:L29–P6:L9.

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