Comment on van der Ent and Tuinenburg, "The residence time of water in the atmosphere revisited"
Harald Sodemann, 20.10.2016

Until recently, it was commonly accepted knowledge that the residence time of water vapour 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 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.

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 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. Bosliovich et al. (2002) by the way even state that “actual residence times should be calculated by taking a Lagrangian approach.”

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 an 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.

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.

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.

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.

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 (Fig. 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.

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 km^3/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 days. Assuming a more extreme case within the range of uncertainty for both quantities, the numbers change to a global precipitation of 616 km yr^{-1} = 1.69 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 days.

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.

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. 1). 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.

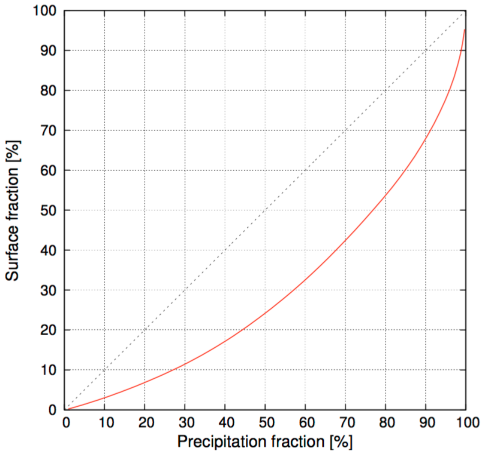

Figure 1: Surface area fraction vs. precipitation fraction from the ERA-Interim reanalysis data (red line). The dashed line would result if precipitation were spatially homogeneous. Reproduced from Läderach and Sodemann (2016).

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

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 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).

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.

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.

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.

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.

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. 2 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 m s^{-1} in the mid-latitudes, lower in the subtropics (4-8 m s^{-1}) and 8-12 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.

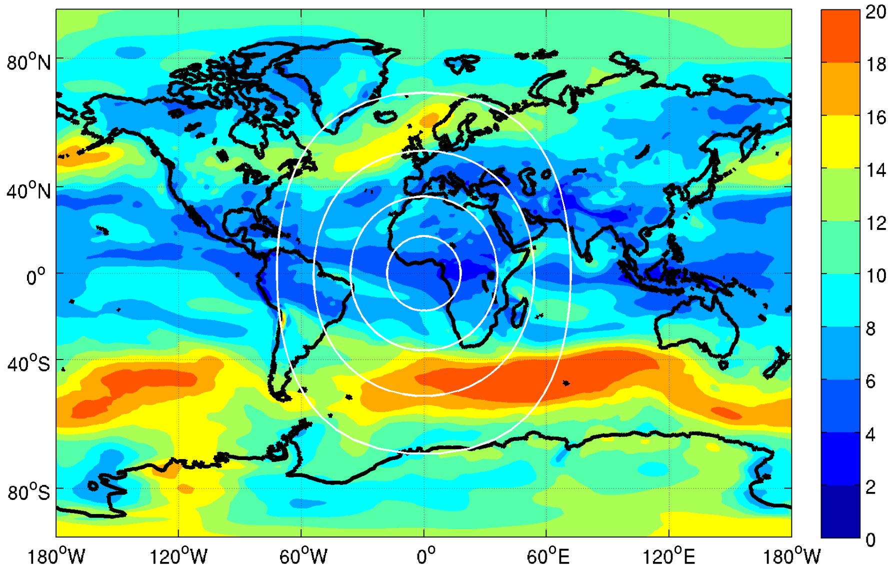

Figure 2: Humidity weighted horizontal wind velocity (for the entire column, layer by layer) during September 2005 from ERA-Interim reanalyses. Unit is m s^{-1}. Range rings around the equator indicate distances of 2000 to 8000 km from the point N0 W0.

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.

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).

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.

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.

References

Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M. A., Balsamo, G., Bauer, P., Bechtold, P., Beljaars, A. C. M., van de Berg, L., Bidlot, J., Bormann, N., Delsol, C., Dragani, R., Fuentes, M., Geer, A. J., Haimberger, L., Healy, S. B., Hersbach, H., Hólm, E. V., Isaksen, L., Kållberg, P., Köhler, M., Matricardi, M., McNally, A. P., Monge-Sanz, B. M., Mor- crette, J. J., Park, B. K., Peubey, C., de Rosnay, P., Tavolato, C., Thépaut, J. N., and Vitart, F.: The ERA-Interim reanalysis: Configuration and performance of the data assimilation system, Q. J. R. Meteorol. Soc., 137, 553–597, doi:10.1002/qj.828, 2011.

Dirmeyer, P. A., and K. L. Brubaker (1999), Contrasting evaporative moisture sources during the drought of 1988 and the flood of 1993, J. Geophys. Res., 104(D16), 19,383–19,397.

Läderach, A. and Sodemann, H.: A revised picture of the atmospheric moisture residence time, Geophys. Res. Lett., 43, 924–933, doi:10.1002/2015GL067449, 2016.

Rodell, M., Beaudoing, H. K., L'Ecuyer, T. S., Olson, W. S., Famiglietti, J. S., Houser, P. R., Adler, R., Bosilovich, M. G., Clayson, C. A., Chambers, D., Clark, E., Fetzer, E. J., Gao, X., Gu, G., Hilburn, K., Huffman, G. J., Lettenmaier, D. P., Liu, W. T., Robertson, F. R., Schlosser, C. A., Sheffield, J., and Wood, E. F.: The observed state of the water cycle in the early twenty-first century, J. Clim., 28, 8289–8318, doi:10.1175/JCLI-D-14-00555.1, 2015.

Sodemann, H., C. Schwierz, and H. Wernli (2008), Interannual variability of Greenland winter precipitation sources: Lagrangian moisture diagnostic and North Atlantic Oscillation influence, J. Geophys. Res., 113, D03107, doi: 10.1029/2007JD008503.

van der Ent, R. and Tuinenburg, O.: The residence time of water in the atmosphere revisited, Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2016-431, 2016.