The residence time of water in the atmosphere revisited

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Supplement

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– Animation 1, separate file. Daily average time-averaged age of atmospheric water as it is in the atmospheric column (WAM-2layers, 2002–2008).

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– Discussion of the disputed validity of global water balance calculations for the global average residence time of water in the atmosphere.

1 Supplementary Figures S1–S3 and short discussion of the differences in results from WAM-2layers and 3D-T

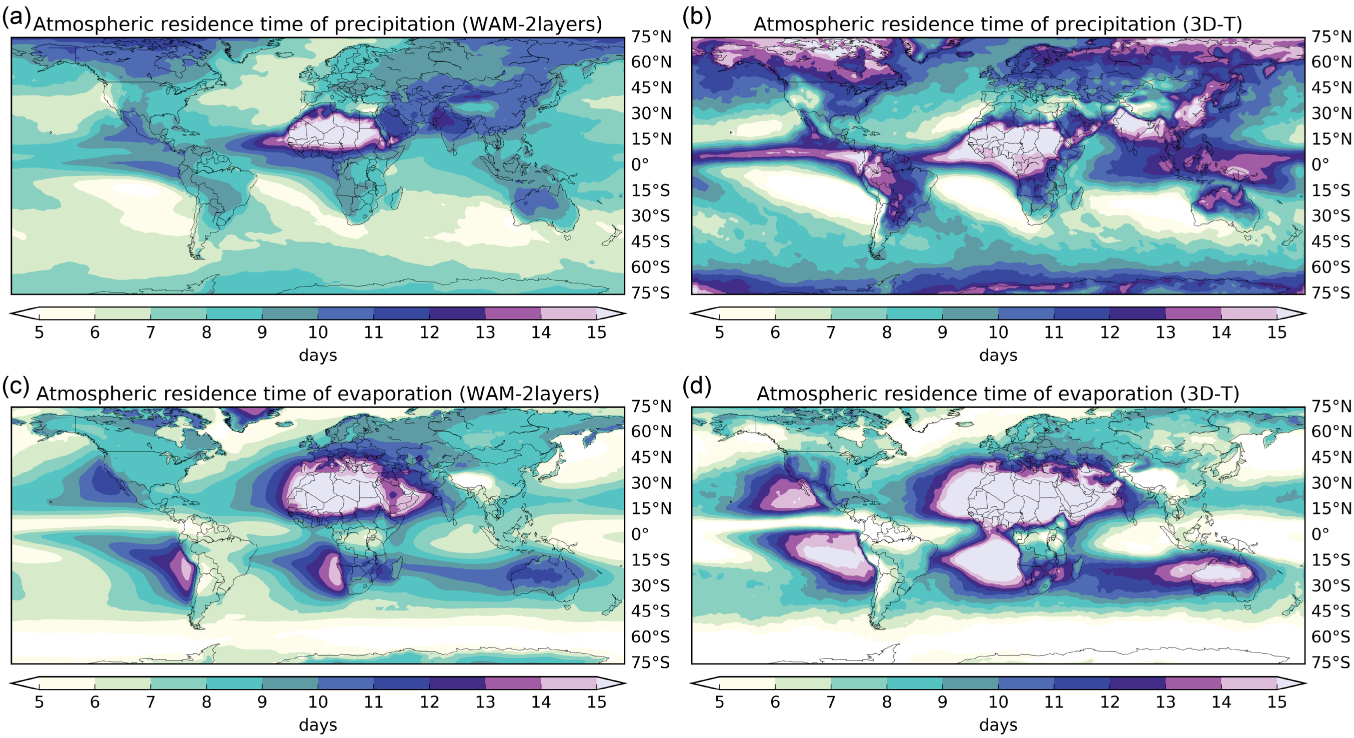

Figure S 1. Annual average atmospheric residence times for 2002–2008, based on ERA-Interim data. **(a)** Residence time of precipitation as computed by WAM-2layers. **(b)** Residence time of precipitation as computed by 3D-Trajectories. **(c)** as (a) for evaporation. **(d)** As (b) for evaporation.

Figure S1 shows the separate estimates from WAM-2layers and 3D-T, for which the merged estimates are shown in Fig. 2c+d of the main paper. Overall, the patterns are very similar, but 3D-T estimates higher residence times of about 1 day on average. Moreover, the patterns for WAM-2layers are much smoother compared to the patterns of 3D-T. We attribute this difference to the fact that WAM2-layers was run on a coarser resolution and has numerical diffusion.

In the Eulerian WAM-2layers model, we find slightly lower residence times than what would be expected from the global water balance. One reason for this is that the tagged water column in a certain grid cell could get ‘full’ due to the fact that the offline computed water balance by WAM-2layers is not necessarily equal to the ERA-Interim water balance, which is a more detailed model, but also includes data-assimilation. This leads to a well-known unphysical residual (see Dominguez et al., 2006; Bisselink and Dolman, 2008, for a more elaborate discussion). When the tagged water reservoir is ‘full’ we let this water disappear from the model, however, in the next time step this water may again be mixed with newly evaporated water. Due to the fact that some water disappeared in the previous time step, the resulting age may be biased towards lower values. Something similar happens over the northern and southern boundaries (at 80° latitudes), where water disappears over the boundaries.

In the Lagrangian 3D-T model, however, we find slightly higher residence times than what would be expected from the global water balance. The mixing in 3D-T is based on 6-hourly vertical wind speeds, but in reality there might be more turbulent vertical mixing. It is, therefore, possible that the water in 3D-T remains in the upper atmosphere for too long leading to slightly higher residence times. Moreover, in 3D-T, we have performed trajectory calculations until 90° latitude and we set back the trajectories if they ‘disappear’ over these polar boundaries, possibly leading to overestimated residence times.

All in all, we think that the merged estimate (Fig. 2 in the main paper) gives the values that are closest to the ‘true’ residence time. For reason given above, WAM2-layers can be biased to lower values, whereas 3D-T can be biased to higher values. The merged estimate compensates for assumptions made in both models.

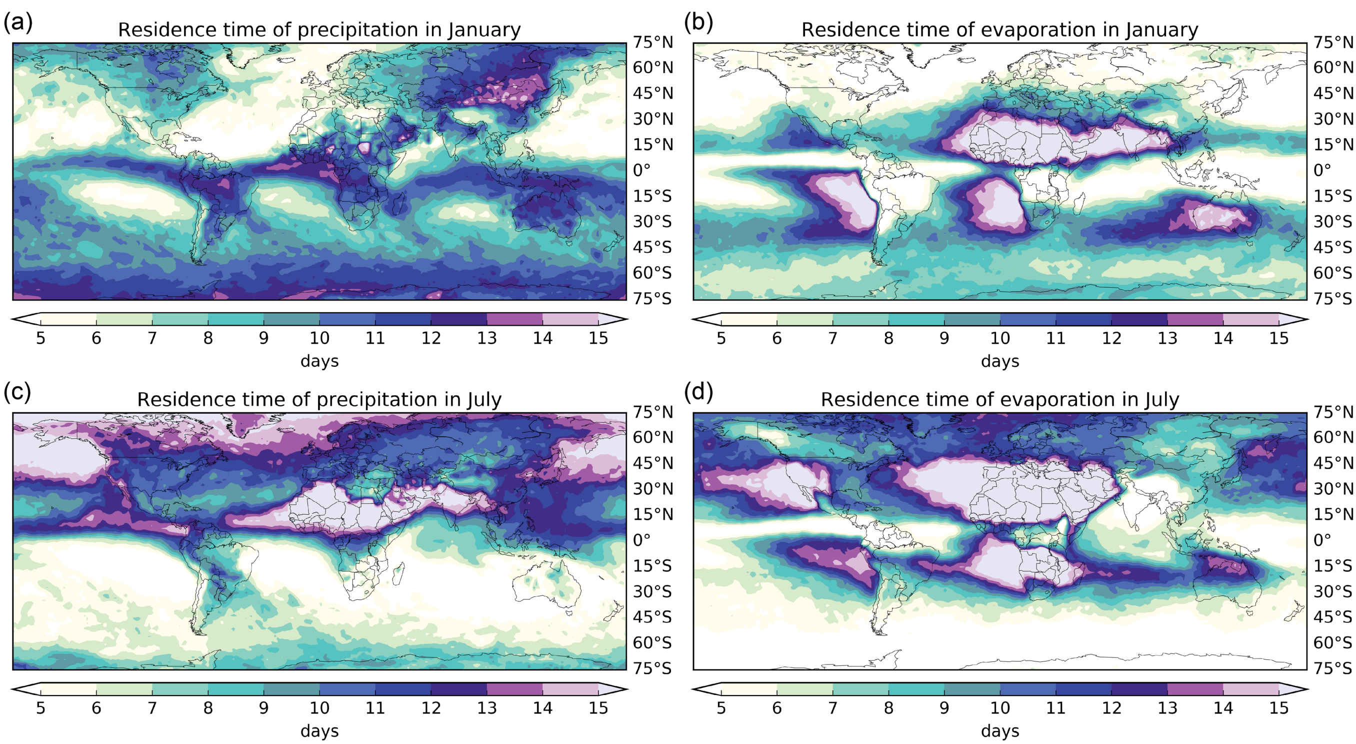

Figure S 2. Atmospheric residence times in January and July for 2002–2008, based on ERA-Interim data (averages of WAM-2layers and 3D-T).

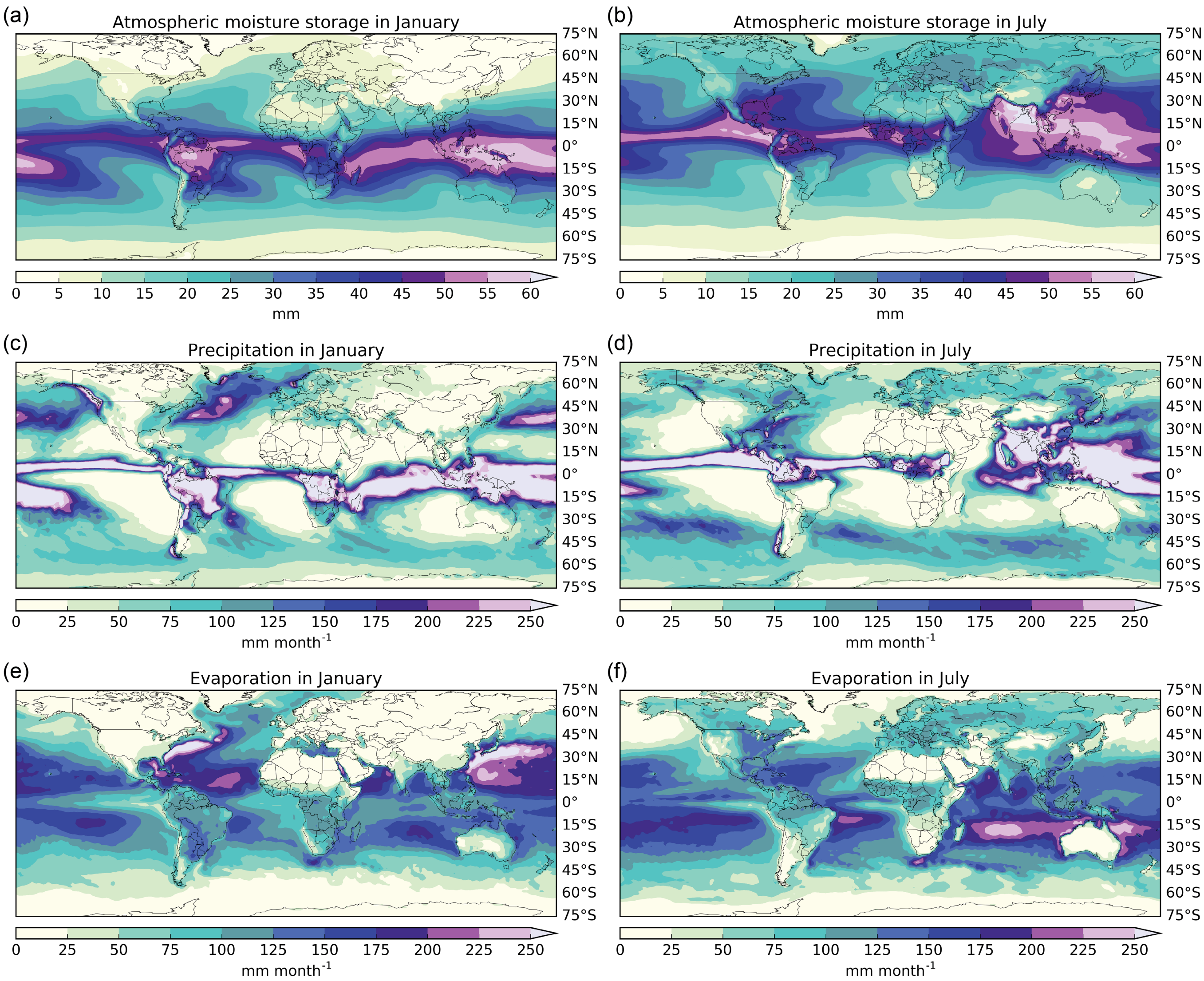

Figure S 3. Atmospheric moisture storage (i.e., precipitable water), precipitation and evaporation in January and July (2002—2008, ERA-Interim).

2 Discussion of the disputed validity of global water balance calculations for the global average residence time of water in the atmosphere

As discussed in our manuscript, the commonly accepted method to calculate the average residence time of any reservoir is to divide its mass (or volume) by the influx or outflux under the assumption that the total mass does not change over a longer time period. This was, however, challenged by Läderach and Sodemann (2016) and they provided two counter-arguments against such simple calculations in section 4 of their Supporting Information. These two arguments are iterated below, and we will argue that these counter-arguments are not valid. First, we have to introduce the global numbers, which are used in the examples by (Läderach and Sodemann, 2016). We quote these numbers below, but we took the liberty to directly 'correct' the mistakes that were made in the units. Please refer to author comment 6 (AC6) or short comment 1 (SC1) in the interactive discussion for the 'uncorrected' quotes.

Läderach and Sodemann (2016) write:
"Using a value for global precipitation (which equals global evaporation) of $500 \cdot 10^3\,\mathrm{km}^3/\mathrm{yr} = 1.37 \cdot 10^3\,\mathrm{km}^3\,\mathrm{day}^{-1} = 2.68\,\mathrm{mm}\,\mathrm{day}^{-1}$ *and a volume of the global moisture in the atmosphere of* $12.7 \cdot 10^3\,\mathrm{km}^3$ *(Trenberth et al., 2011), one obtains a global depletion time constant of* $12.7 \cdot 10^3/1.37 \cdot 10^3 = 9.3\,\mathrm{days}$*. Assuming a more extreme case within the range of uncertainty for both quantities, the numbers change to a global precipitation of* $616 \cdot 10^3\,\mathrm{km}\,\mathrm{yr}^{-1} = 1.69\,\mathrm{km}^3\,\mathrm{day}^{-1} = 3.31\,\mathrm{mm}\,\mathrm{day}^{-1}$ *and the global amount of moisture in the atmosphere of* $12.3 \cdot 10^3\,\mathrm{km}^3$*. This would result in a global average depletion time constant, assumed to be identical to the residence time of moisture, of* $12.3 \cdot 10^3/1.69 \cdot 10^3 = 7.3\,\mathrm{days}$*."*

Before we present the two counter-arguments by (Läderach and Sodemann, 2016), it should be noted that the extreme case is indeed quite extreme as it is 4 standard deviations away from the most likely value of $8.9 \pm 0.4\,\mathrm{days}$, computed by us based on the numbers provided by Rodell et al. (2015) and Trenberth et al. (2011).

The first counter-argument by Läderach and Sodemann (2016) is:
"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 example when considering that the global mean precipitation of $1.69 \cdot 10^3\,\mathrm{km}^3\,\mathrm{day}^{-1} = 3.31\,\mathrm{mm}\,\mathrm{day}^{-1}$ *assumes that all areas of the earth receive an equal amount of precipitation. According to ERA-Interim, 90 % of the global precipitation in a year fall onto less than 70 % of the global surface area (Fig. S4). 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 that 90 % of the effective global precipitation from the simple number example* $(1.37/0.7 =$

$1.95\,\mathrm{km^3\,day^{-1}}$ *and* $1.69/0.7 = 2.41\,\mathrm{km^3\,day^{-1}}$, *respectively) lead us to depletion time constants of 6.51 and 5.10* days, *respectively. This is clearly shorter than the 7–9 days obtained originally, and in fact quite close to the about 4–5 days we obtain from our method. The simple estimates rely thus on a global uniform distribution of precipitation, which is in fact not given."*

In the interactive discussion (SC1), Sodemann adds: *"In terms of a Poisson process, the spatial and temporal coherence of precipitation violates the randomness requirement."*

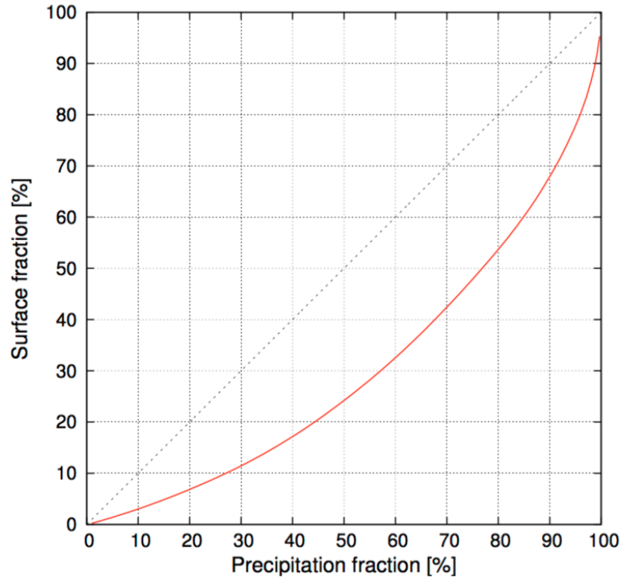

Figure S 4. Surface area fraction vs. precipitation fraction from the ERA-Interim reanalysis data (red line). The dashed line would result if precipitation were spatially homogeneous. Reproduced from Läderach and Sodemann (2016).

We disagree with this argument, because it there is no point in 'correcting' the value for the 70 % of the Earth's surface that receives most precipitation, when talking about the global average value. Recall that in the main paper (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 depletion time of precipitation for of the x % wettest regions of the Earth, which is obviously not the same as the global average residence time of water in the atmosphere. In Läderach and Sodemann (2016) it is nowhere mentioned that they understand their estimate of 4–5 days as a spatial average precipitation residence time for the 70 % 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 no effect on the global mean value, nor does a bulk estimation invoke the necessity of being uniform, constant or a Poisson process. In the main paper we clearly showed the spatial and 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 spatial average calculation is not correctly executed. The global average precipitation is $1.37 \cdot 10^3\,\mathrm{km}^3\,\mathrm{day}^{-1}$, of which 90 % falls over 70 % of the land surface. Thus, $1.37 * 0.90 = 1.23 \cdot 10^3\,\mathrm{km}^3\,\mathrm{day}^{-1}$. 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 70 % land surface. Dividing that number by $1.23 \cdot 10^3\,\mathrm{km}^3\,\mathrm{day}^{-1}$ will give the spatial average depletion time in days over 70 % of the land surface. We did not compute this here as it is actually not a pure residence time, and we have not addressed spatial averages in our main paper anyway.

The second counter-argument by Läderach and Sodemann (2016) involves the description of two cases that, in their words, *"criticizes the simple estimate more fundamentally and demonstrates that depletion time constants do not allow to conclude on the moisture residence time."* In the interactive discussion (SC1), Sodemann adds two different cases. Here, we explore these four hypothetical cases in more depth.

Sodemann writes in SC1:

"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 $1.37 \cdot 10^3\,\mathrm{km}^3\,\mathrm{day}^{-1}$. *The same amount of evaporation occurs continuously and maintains an atmospheric water volume of* $12.7 \cdot 10^3\,\mathrm{km}^3$. *This case will give a depletion time constant of* $9.3\,\mathrm{days}$. *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 vapor is obviously enhanced considerably, while the depletion time constant would still provide the same value of* $9.3\,\mathrm{days}$. *Obviously, here the stationarity required by a Poisson 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 vapor."*

And Läderach and Sodemann (2016) write: *"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 cases. Both of these scenarios are not inconsistent with a global long-term average rain rate of* $1.37 \cdot 10^3\,\mathrm{km}^3\,\mathrm{day}^{-1}$ *and a global amount of moisture of* $12.7 \cdot 10^3\,\mathrm{km}^3$, *and will give a depletion time constant of* $9.3\,\mathrm{days}$. *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* $1\,\mathrm{day}$ *in the first example, and* $30\,\mathrm{days}$ *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.*

All four cases are displayed graphically by us in Fig. S5. The corresponding average atmospheric storage, average precipitation rate, average evaporation rate and average residence time are given in Table S1. Note that cases 2, 3 and 4 cannot fulfill both

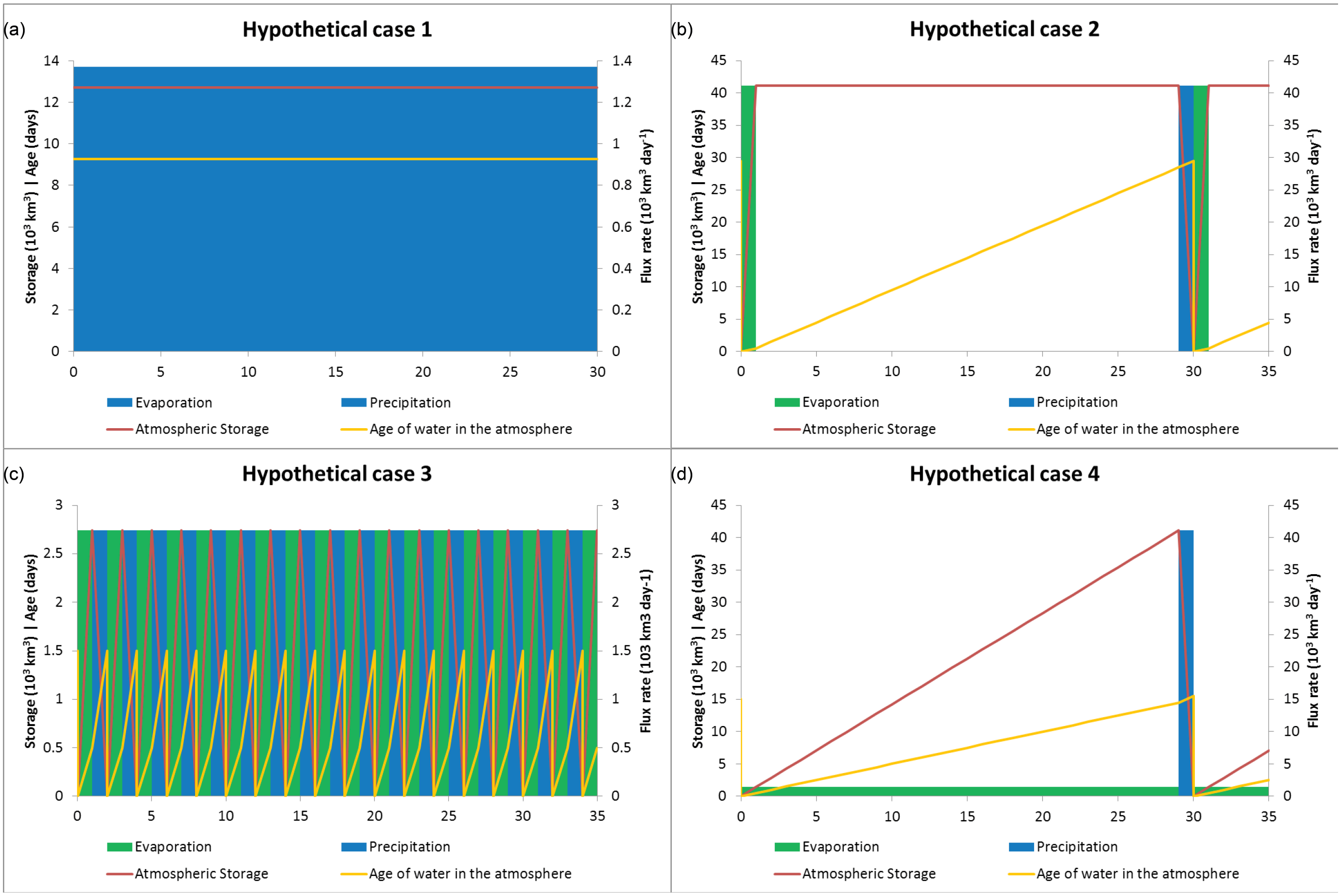

Figure S 5. Visualization of four hypothetical cases of depleting and replenishing the global atmospheric water store as described by Sodemann's comment (cases 1 and 2) and LS16 (cases 3 and 4). Note that in panel (a) precipitation and evaporation are constant, and, therefore overlap each other in the visualization.

a global average precipitation rate of $1.37 \cdot 10^3\,\mathrm{km}^3\,\mathrm{day}^{-1}$ and an average atmospheric water volume of $12.7 \cdot 10^3\,\mathrm{km}^3$. How to present these cases is thus open to interpretation, but we chose here to assume the same global average precipitation rate for all four cases as a starting point for the calculations. Alternatively, one could consider to assume the same global average atmospheric water volume. Then, the precipitation rates would greatly differ between the cases. According to Sodemann (SC1), 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. S5 and Table S1 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 atmospheric storage in case 2 is much higher than in case 1. According to the Supplement of Läderach and Sodemann (2016), 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*

Table 1. Summary of the four hypothetical cases brought forward by Sodemann (SC1) and Läderach and Sodemann (2016).

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 Läderach and Sodemann's terminology) (days)
1	41.1	1.37	12.70	9.3	9.3
2	41.1	1.37	39.73	29.0	29.0
3	41.1	1.37	1.37	1.0	1.0
4	41.1	1.37	20.55	15.0	15.0

atmospheric water storage of $12.7\cdot10^3\,\mathrm{km}^3$*"*. As can be seen from Fig. S5 and Table S1, however, case 3 and 4 yield very different values for global average atmospheric water storage, hence the very different residence times.

According to Sodemann (SC1) these hypothetical cases were supposed to *"demonstrate that for systems where the assumptions of a Poisson 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, in fact, be accurately calculated by dividing a stock by its flux (compare last two columns of Table S1). We conclude that the examples provided by Läderach and Sodemann (2016) and SC1 are inconsistent with themselves and do not show that the 'depletion time constant' is different from the residence time, as, in fact, these equal each other in all four cases (Table S1, last two columns).

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