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Atmospheric water transport connectivity within and between Ocean basins and land

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Abstract. The global atmospheric water transport from the net evaporation to the net precipitation regions has been traced using Lagrangian trajectories. A matrix has been constructed by selecting various group of trajectories based on their surface starting (net evaporation) and ending (net precipitation) positions to show the connectivity of the 3-D atmospheric water transport within and between the three major ocean basins and the global landmass. The analysis reveals that a major portion of the net evaporated water precipitates back into the same region, namely 67% for the Indian, 64% for the Atlantic, 85% for the Pacific Ocean and 72% for the global landmass. It has also been calculated that 58% of the net terrestrial precipitation were sourced from the land evaporation. The net evaporation from the subtropical regions of the Indian, Atlantic and Pacific Oceans is found to be the primary source of atmospheric water for precipitation over the Intertropical Convergence Zone (ITCZ) in the corresponding basins. The net evaporated waters from the subtropical and western Indian Ocean were traced as the source for precipitation over the South Asian and Eastern African landmass, while Atlantic Ocean waters are responsible for rainfall over North Asia and Western Africa. Atlantic storm tracks were identified as the carrier of atmospheric water that precipitates over Europe, while the Pacific storm tracks were responsible for North American, eastern Asian and Australian precipitation. The bulk of South and Central American precipitation is found to have its source in the tropical Atlantic Ocean. The land-to-land atmospheric water transport is pronounced over the Amazon basin, western coast of South America, Congo basin, Northeastern Asia, Canada and Greenland. The ocean-to-land and land-to-ocean water transport through the atmosphere was computed to be 2×10^9 kg s^{-1} and 1×10^9 kg s^{-1}, respectively. The difference between them (net ocean-to-land transport), i.e. 1×10^9 kg s^{-1}, is transported to land. This net transport is approximately the same as found in previous estimates which were calculated from the global surface water budget.

1 Introduction

The hydrologic cycle traces the continuous movement of the water in the Earth system. The atmospheric hydrological cycle starts from the evaporation regions and ends in the precipitation regions. Generally evaporation tends to exceed precipitation over the ocean, while for land the opposite holds true. A consequence of this excess precipitation over land is that this surplus water eventually discharges into the ocean by the rivers, completing the atmospheric branch of the water cycle. The hydrological cycle is believed to strengthen in a future warmer climate. The Clausius-Clapeyron (CC) thermodynamic relation indicates that for every 1°C temperature rise, the saturation vapour pressure will approximately increase by 7%. This implies that the vapour pressure, which is equivalent to the specific humidity or the amount of moisture in the atmosphere (Wallace and Hobbs, 2006), will also increase, as the tropospheric relative humidity is believed to remain the same in a warmer climate (Soden and Held, 2006). If the atmospheric circulation would remain unchanged, the water-vapour increase will solely act to intensify the moisture transport from the evaporation regions to the precipitation areas and help to magnify the strength of the existing global evaporation (E) - precipitation (P) patterns. This is the paradigm of "dry gets drier and wet gets wetter" or in other words "rich-get-richer mechanism" (Chou and Neelin, 2004). However, the increase of atmospheric moisture in a warmer climate does not necessarily imply that the global evaporation and precipitation will also increase by the same CC rate, as these are constrained by the surface energy budget (Held and Soden, 2006; Huntington, 2006). Analyses of future climate scenarios from Earth system models have revealed a 2-3$\%$ increase in global precipitation per 1°C temperature rise (Allan et al., 2014). The imbalance between increasing rate of moisture and precipitation ensures that the precipitation intensity will increase in the future climate, while the frequency and duration are apt to decrease (Trenberth, 1999). In addition to this, the hydrologic cycle also plays a critical role in the global energy cycle through evaporative cooling of the Earth's surface and latent heating of the atmosphere. The impact of the hydrologic cycle is not only important for the atmosphere but also for the ocean. The evaporation-dominated regions over the ocean generally leads to high salinity and the precipitation-dominated regions to low salinity. The Atlantic Ocean is e.g. a net freshwater flux surplus ($E-P>0$) region in contrast to the Pacific Ocean, where the opposite holds true. This in turn gives rise to a salinity asymmetry, which can explain the generation of deep water in the North Atlantic but not in the North Pacific Ocean (Warren, 1983; Broecker et al., 1985; Emile-Geay et al., 2003). The North Atlantic Deep Water (NADW) is an integral part of the Atlantic Meridional Overturning Circulation (AMOC), which distributes heat within the climate system (Vellinga and Wood, 2008). It is projected by many climate models that the AMOC will weaken during the 21st century, which could be linked to changes in the hydrologic cyle (Stocker et al., 2014).

Given these diverse roles of the hydrologic cycle within the Earth system, it is important to disentangle and understand its different parts. Previous studies were able to provide an estimate of the water storage in the reservoirs and also the net exchange of water between them using the surface water budgets (Chahine, 1992; Trenberth et al., 2007, 2011). The atmospheric water transport between the global ocean and land, the two dominating water reservoirs, are primarily obtained by integrating the net freshwater flux ($E-P$) over them. The integrated $E-P$ over the ocean is positive and calculated to be approximately 1 Sverdrups (1 Sv $\equiv 10^9$ kg s^{-1} $\equiv 0.031536$ km^3 year^{-1}, assuming water density is constant at 1000 kg m^{-3}), which is transported to land (Schmitt, 2008). Due to water-mass conservation this 1 Sv is equivalent to the negative $E-P$ integral over land (as $P>E$ over the land) and will return to the ocean through river discharges. The $E-P$ can either be directly obtained from the observationally based reanalysis data sets or derived from the moisture budget analysis (Trenberth et al., 2011). These kinds of studies suffer from the limitation that they can not provide information about the atmospheric water transport within and between different ocean basins and land. In addition, knowledge about how much of the ocean/land evaporated water precipitates over the ocean/land itself and is transported to the land/ocean is not achievable. However, these question will be possible to address using Eulerian/Lagrangian atmospheric water tracing schemes (Van der Ent et al., 2010; Tuinenburg et al., 2020; Stohl and James, 2004; Stein et al., 2015; Dey and Döös, 2020). A list of atmospheric water tracing models and their advantages and disadvantages has been discussed briefly in Dominguez et al. (2020). The primary objective of the present study is to link 3-D atmospheric water transports within and between different ocean basins and land using Lagrangian trajectories, which makes it possible to trace water from the net evaporation at the surface to where it precipitates. This will facilitate the construction of an atmospheric freshwater connectivity matrix, which will provide both quantitative as well as qualitative descriptions of the 3-D atmospheric water exchange.

2 Methods and data

2.1 Lagrangian model for tracing water in the atmosphere

The mass conserving Lagrangian trajectory model TRACMASS v7.0 (Aldama-Campino et al., 2020; Döös, 1995) was used in the present study to obtain a detailed understanding of the global hydrologic cycle. One of the unique characteristics of TRACMASS is that it uses mass transports through the model grid box faces instead of velocity fields (Vries and Döös, 2001). TRACMASS was employed frequently to track the oceanic water-transport pathways (Berglund et al., 2017, 2021; Döös et al., 2008) and atmospheric air-mass routes (Kjellsson and Döös, 2012). In Dey and Döös (2020) TRACMASS was updated in order to trace water instead of air in the atmosphere. The atmospheric water tracing version of TRACMASS was also implemented recently to study the seasonal and inter-annual characteristics of the South Asian summer monsoon precipitation (Dey and Döös, 2021). Note here that these trajectory calculations are based on atmospheric water-mass transport in kg s^{-1} and not transports of humid air. We are hence tracing the actual atmospheric water and not the moisture change along air-parcel trajectories. An elaborate evaluation of the atmospheric and oceanic trajectory schemes that are used in TRACMASS can be found in Döös et al. (2017).

The horizontal water transports through the model grid box faces are obtained by multiplying the air transports with its water content. The vertical water transport field is then obtained from an atmospheric water-mass conservation equation (Dey and Döös, 2019), which is zero at the top of the atmosphere and equal to $E - P$ at each model level. The calculation of the vertical water transport from the conservation equation confirms that the evaporation, precipitation, condensation and advection of moisture by the winds are all summed up as the vertical water transport and cannot be separable. Note that the diffusive water transports, specific rain water and snow water content were omitted in Dey and Döös (2019, 2020), as well as in the present study due to its unavailability from the ERA-Interim but could be included in future studies. For a detailed mathematical derivation of the atmospheric water transport see Dey and Döös (2019, 2020, 2021).

The mass conserving ability of TRACMASS (i.e. mass transport of a trajectory is conserved throughout its journey) has made it possible to compute Lagrangian stream functions from the simulated trajectories. The Lagrangian stream function is an useful tool to understand atmospheric and oceanic circulation pathways and has been used in previous studies extensively (Blanke et al., 1999; Berglund et al., 2017; Kjellsson and Döös, 2012; Döös et al., 2008). In the present study the Lagrangian meridional and zonal overturning stream functions were computed to quantify atmospheric water-mass transport pathways in the meridional-vertical and zonal-vertical coordinate system respectively. The Lagrangian meridional overturning stream function can be expressed as

$$\psi_{j,k} = \sum_{k'=k}^{kz} \sum_{i} \sum_{m} T^{y}_{i,j,k',m} \quad , \tag{1}$$

here, i,j,k' are the zonal, meridional and vertical coordinates through which the trajectory indexed m passes. $T^{y}_{i,j,k',m}$ is the atmospheric water transport (kg s^{-1}) by the trajectory indexed m through the zonal-vertical grid box. The highest vertical level of the atmosphere is at 0.1 hPa and denoted as $k' = kz$. Note that the streamlines will be open and crossing the surface due to the sources (net evaporation) and sinks (net precipitation) of atmospheric water. Similarly, the Lagrangian zonal overturning stream function was computed as:

$$\psi_{i,k} = \sum_{k'=k}^{kz} \sum_{j} \sum_{m} T^{x}_{i,j,k',m} \quad , \tag{2}$$

where $T^{x}_{i,j,k',m}$ is the Lagrangian water transport (kg s^{-1}) through the meridional-vertical grid-box face. The vertically integrated zonal ($F^{x}_{i,j}$) and meridional ($F^{y}_{i,j}$) water flux was computed from the 3-D simulated water trajectories to describe atmospheric water transport pathways in longitude-latitude framework:

$$F^{x}_{i,j} = \frac{\sum_{k'=0}^{kz} \sum_{m} T^{x}_{i,j,k',m}}{\Delta y_{i,j}} \quad , \tag{3}$$

$$F^{y}_{i,j} = \frac{\sum_{k'=0}^{kz} \sum_{m} T^{y}_{i,j,k',m}}{\Delta x_{i,j}} \quad . \tag{4}$$

The longitudinal and latitudinal grid spacing is denoted as Δx and Δy respectively. The resultant of the vertically integrated horizontal water flux is thus

$$F_{i,j} = \sqrt{(F^{x}_{i,j})^2 + (F^{y}_{i,j})^2} \quad , \tag{5}$$

which has the unit Sv m^{-1} (1 Sv $\equiv 10^9$ kg s^{-1}). The calculated water trajectories were also used to compute atmospheric water residence time ($\tau_{i,j}$) following Dey and Döös (2020, 2021)

$$\tau_{i,j} = \frac{\sum\limits_{m=1}^{M} \{(t^{P}_{m} - t^{E}_{m}) \cdot T^{z}_{i,j,m}\}}{\sum\limits_{m=1}^{M} T^{z}_{i,j,m}}, \tag{6}$$

which is the lifetime of the atmospheric water between net evaporation and net precipitation. Here $T^{z}_{i,j,m}$ is the water transport of the trajectory indexed m through the surface. M is the total number of trajectories, t^{P} and t^{E} is the time when the atmospheric water trajectories precipitate and evaporate respectively.

2.2 Data source

The atmospheric water transports were computed using the surface pressure, specific humidity, specific cloud liquid and ice water content and horizontal wind velocities from the ERA-Interim reanalysis (Dee et al., 2011). The inclusion of the specific cloud liquid and ice water content in the water transport calculation is an update as compared to the Dey and Döös (2020, 2021). The data sets were obtained for the years 2016 and 2017 with $0.75°$ spatial resolution, 6-hourly temporal resolution and 60 hybrid vertical model levels. It is noteworthy that to satisfy the mass conservation property of the Lagrangian model TRACMASS it requires data at model levels and not at interpolated pressure levels (Dey and Döös, 2021).

2.3 Lagrangian study configuration

To understand the 3-D global atmospheric water transport the Lagrangian trajectories were started over the entire surface of the globe when evaporation exceeded precipitation and followed until they reach back to the surface, which occurs when precipitation exceeded evaporation. These water trajectories were started at the surface every 6 hours during 2016 where E > P, then advected by the 3-D mass transport of water and followed until they reached back to the surface where P > E. In total more than 89 million water trajectories were started with more than 7 million trajectories each month. The position of a given atmospheric water trajectory within a grid box is solved analytically in space and with a stepwise-stationary scheme (Döös et al., 2017) in time. The trajectories were integrated in time with six intermediate time steps between each 6-hourly output data from the ERA-Interim. The trajectories were, however, followed for a maximum of one year. Only 0.4% remained in the atmosphere after one year and were subsequently discarded. The 3-D atmospheric water transport connection within and between different ocean basins and land, which can be regarded as an atmospheric water connectivity matrix, was estimated by sorting different classes of atmospheric trajectories based on their starting (net evaporation) and ending (net precipitation) positions. In the present study, the starting and ending points of the water trajectories were classified into the global landmass and the three major ocean basins as defined in Figure 1. The ocean basins are termed the Indian, Pacific, and the Atlantic Ocean (including the Arctic ocean).

3 Results

3.1 Atmospheric water connectivity

The atmospheric water is always on the move through space and in time within the climate system. In order to grasp the full characteristics of the atmospheric water circulation, it is thus necessary to reduce its dimensionality. The geographical connection of the atmospheric water transports within and between the ocean basins and the global landmass has been established by tracing the atmospheric water from the evaporation-dominated to the precipitation-dominated regions (Fig. 2), which are the starting and ending points of the trajectories. Additionally, a quantitative view of this geographical atmospheric water transport connection is presented in Table 1 by integrating the net evaporation/precipitation transport obtained from the sorted classes of trajectories. This integration of either net evaporation or precipitation will give the same result due to the mass-conserving property of the Lagrangian model TRACMASS. The atmospheric water movement in the horizontal-vertical plane is obtained by calculating the Lagrangian overturning water-mass stream functions using equation 1 and 2 and presented in latitude-pressure and longitude-pressure coordinate systems (Fig. 3 and Fig. 4 respectively). In addition, vertically integrated horizontal water

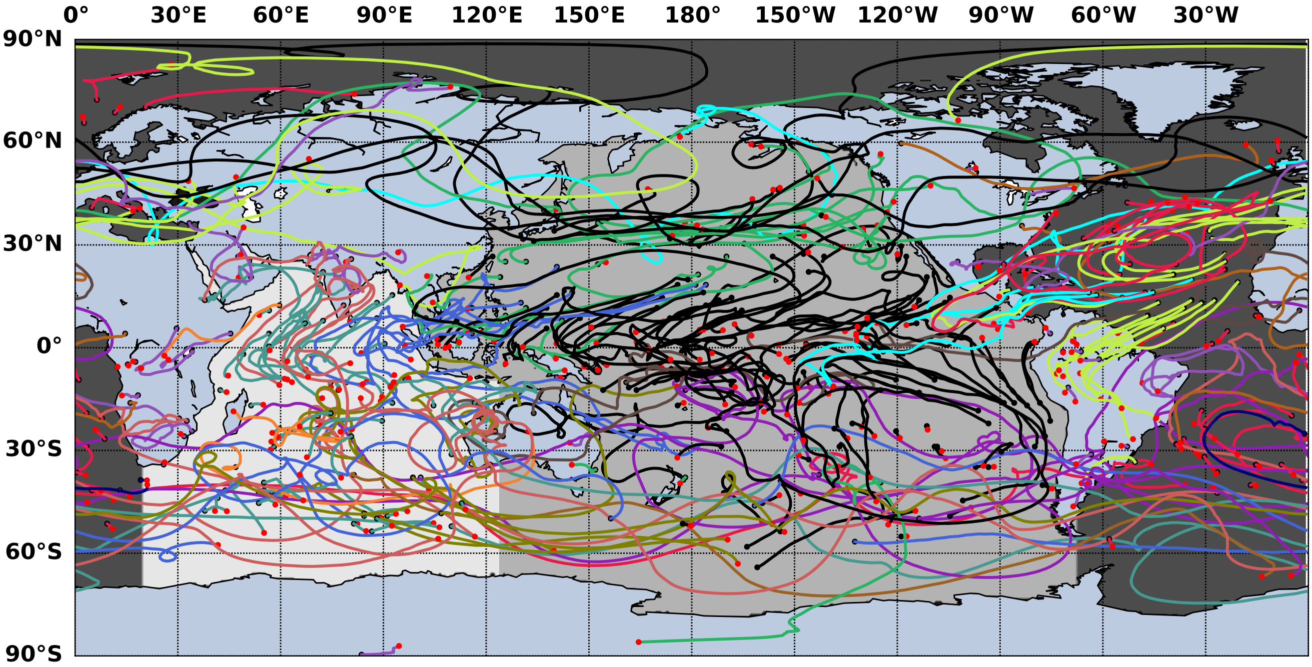

Figure 1. Spaghetti plot of few selected atmospheric water trajectories for the month of January 2016. The selected ocean basins are represented by different shadings of gray and defined as the Indian Ocean (IO), Pacific Ocean (PO) and Atlantic Ocean (AO). Note that, the Arctic Ocean is included in the Atlantic. The global landmass is taken as one single entity. The atmospheric water transport within and between the ocean basins and land has been calculated based on these defined sectors. The representative trajectories associated with these intra- and inter-basin water transport are labeled with different colors. The black dots are indicating the starting points and red points represent the ending points of the atmospheric water trajectories.

flux computation (using equation 5) is used to describe the water transport routes in longitude-latitude framework (Fig. 5). Note that the streamlines represent the integrated atmospheric water transport routes and is based on the sum of the Lagrangian trajectories, which should not be confused with the paths of the individual trajectories. Additionally, the streamlines start at the surface when E > P and terminate where the opposite holds true. While interpreting the atmospheric water pathways from the meridional and zonal overturning stream functions, it should be remembered that these are zonally and meridionally integrated pathways respectively. For instance, the atmospheric water mass crossing a longitude can be transported zonally both by the tropical easterly trade winds and by the mid-latitude westerlies. If e.g. the westerlies transport more water than the easterlies at the same longitude then the meridionally integrated zonal overturning stream function will only show the dominant westerly signal. The residence time of the atmospheric water was mapped geographically at the net evaporation points using equation (6). This mapping was split up using the connectivity matrix so that the residence times indicate the inter- and intra-basin transport time scales (Fig. 6). This residence time was calculated at the points where net evaporation exceeds a monthly mean value of 0.2 mm day^{-1} in order to focus on the main source regions of the atmospheric water.

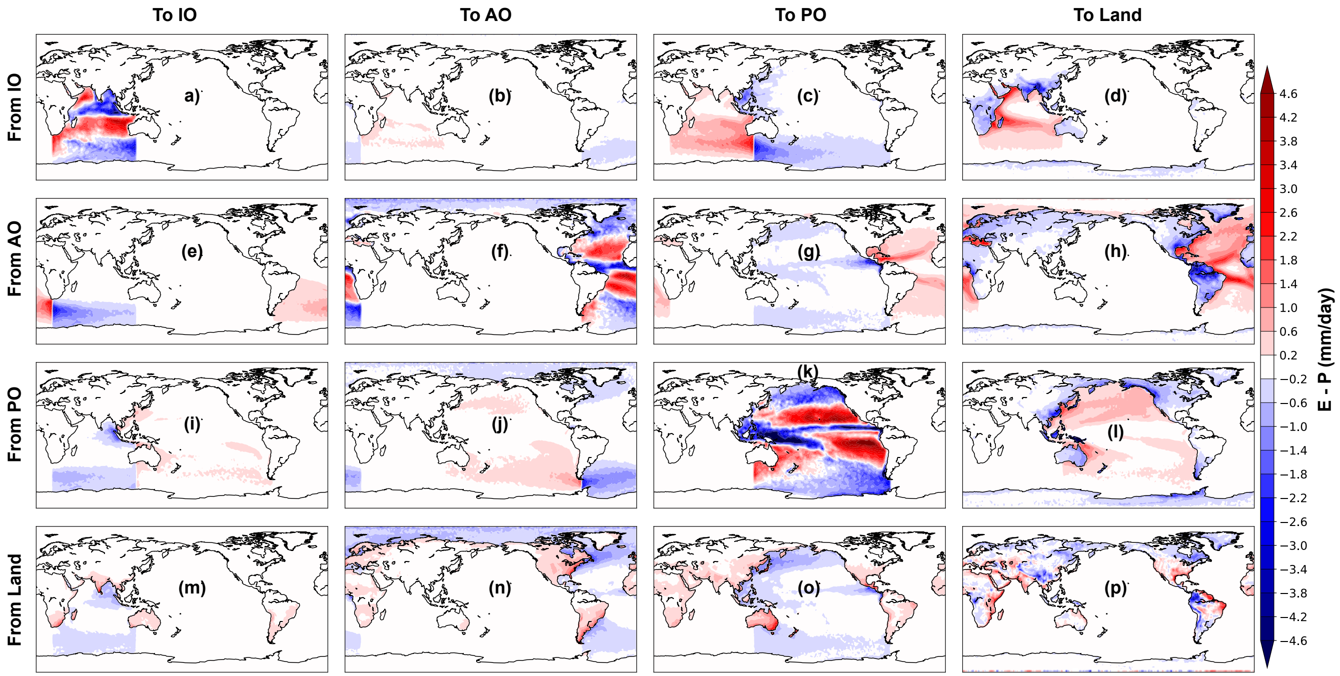

Figure 2. Annual mean $E - P$ (mm day^{-1}) inferred from the atmospheric waters travelling from the surface net evaporative regions (red contours) to the net precipitation areas (blue contours). The rows represent the net evaporative (starting points of the atmospheric water trajectories) sectors and the columns represent the net precipitation (ending points of the trajectories) regions.

Table 1. Atmospheric freshwater transport within and between the ocean basins and land. The rows represent net evaporative (atmospheric water source) sectors and the columns the net precipitation (atmospheric water sink) regions. Units are in Sv ($\equiv 10^9$ kg s^{-1}). The percentages in the parentheses represent fractions of the net evaporation that are transported from the source region.

Regions	Indian Ocean	Atlantic Ocean	Pacific Ocean	Land
Indian Ocean	2.26 (67%)	0.10 (3%)	0.52 (15%)	0.52 (15%)
Atlantic Ocean	0.25 (5%)	3.07 (64%)	0.45 (9%)	1.07 (22%)
Pacific Ocean	0.23 (3%)	0.34 (4%)	7.52 (85%)	0.77 (8%)
Land	0.20 (5%)	0.48 (10%)	0.61 (13%)	3.30 (72%)

The results show that the net evaporation from the subtropical Atlantic, Pacific and Indian Ocean is the major source of water for net precipitation over the Intertropical Convergence Zone (ITCZ) in their respective basins (Fig. 2a, 2f and 2k). A major portion of the net evaporated water from the ocean basins was found to precipitate over their source sectors (Table 1). On an annual average, 67% (2.26 Sv), 64% (3.07 Sv) and 85% (7.52 Sv) of the net evaporation from the Indian, Atlantic and Pacific Ocean precipitates over the same oceanic basin (Table 1). The meridional overturning stream function and vertically

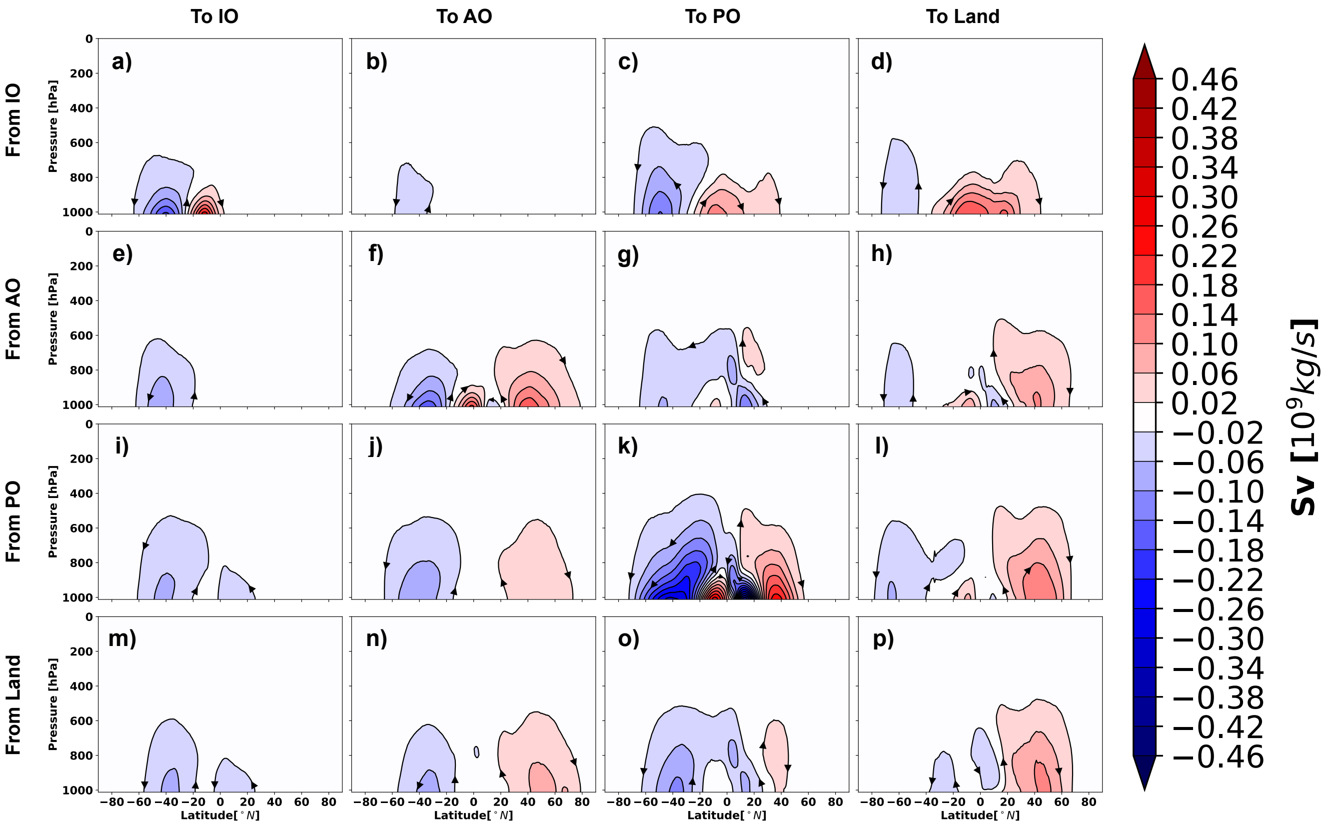

Figure 3. The Lagrangian meridional overturning stream function within and between the ocean basins and land. This has been undertaken by grouping the trajectories according to their starting and ending locations. The starting and ending points of the atmospheric trajectories are defined as per the sectors presented in Fig. 1. Note that the streamlines represent the integrated atmospheric water transport routes and is based on the sum of the Lagrangian trajectories, which should not be confused with the paths of the individual trajectories.

integrated horizontal water transport corresponding to these intra-basin atmospheric water transports (Fig. (3a; 5a), Fig. (3f; 5f) and Fig. (3k; 5k)) show that the Equatorward meridional transport in the Atlantic and the Pacific Oceans and northward transport in the Indian Ocean are dynamically responsible for most of the oceanic ITCZ rainfall. The easterly (east-to-west) water transport within the Pacific Ocean (blue cell in Fig. 4k and black lines in Fig. 5k) also plays a crucial role for the Pacific ITCZ precipitation and shows the atmospheric water movement within the Walker circulation. The evaporative waters from the Indian, Atlantic and Pacific Oceans stay on an average 4, 3 and 5 days, respectively, in the atmosphere before precipitating back into their basins of origin (Fig. 6a, 6f and 6k). Note that the residence-time map has a large spectrum of values and varies a lot within small distances in some of the defined regions, e.g. the evaporative water from the subtropical Pacific Ocean has residence time from 0 days to more than 24 days (Fig. 6k). The rainfall over the South Asian landmass and Eastern Africa is traced to originating and transporting mostly from the subtropical and Western Indian Ocean (Fig. 2d and Fig. 5d). Note that this is an annual-mean figure and consists of precipitation signals from the entire year. The atmospheric water transport from

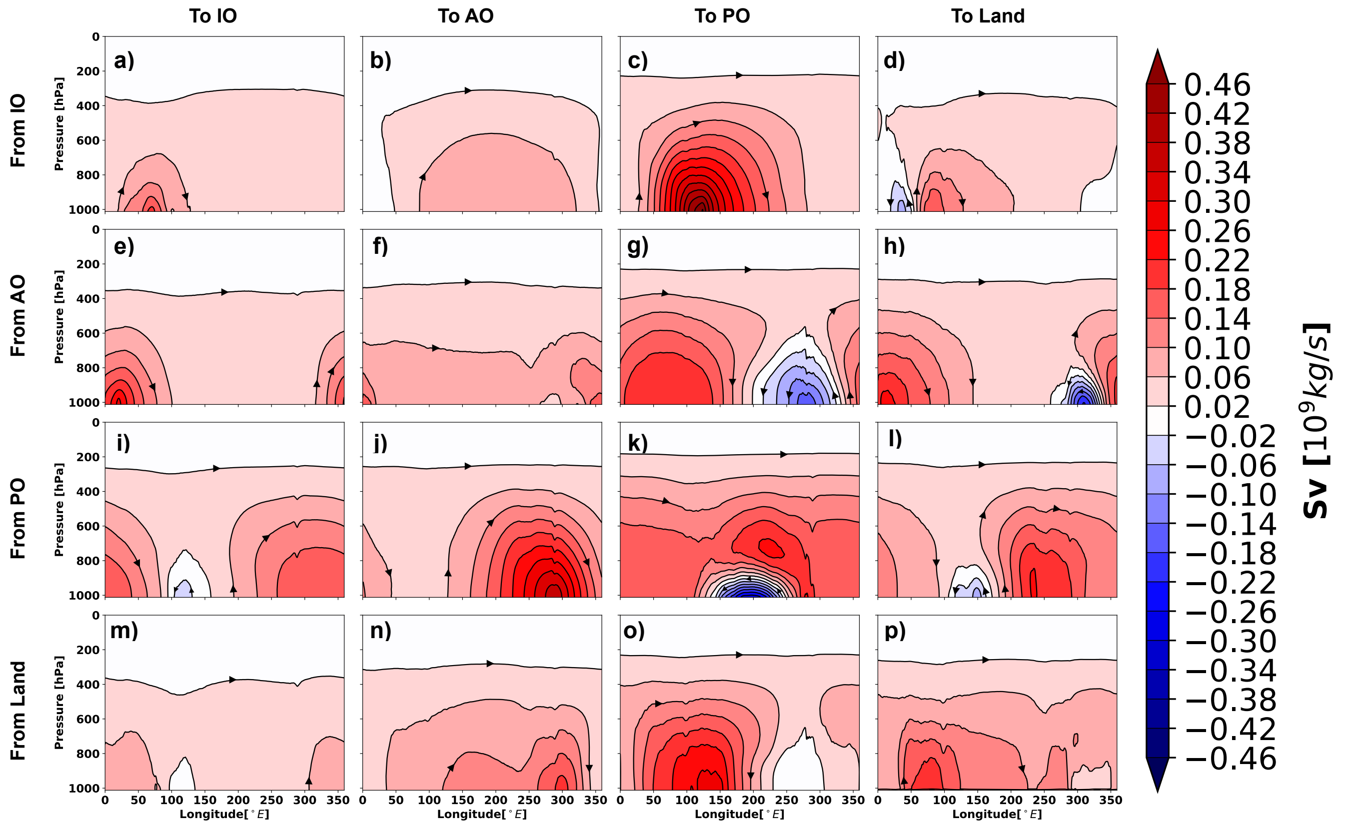

Figure 4. Same as Fig. 3 but for the zonal overturning stream function.

the Indian Ocean to the landmass is estimated to be around 0.52 Sv, which is 15% of the total Indian Ocean net evaporation (Table 1). The evaporated water from the Indian Ocean is primarily transported by the Somali low-level jet to the South Asian landmass. This low-level jet is a southwesterly flow which is active along the Somali coast during the summer monsoon months of June to September. The atmospheric water transport pathways associated with this jet is captured by the meridional and zonal
180 overturning stream functions (Fig. 3d and Fig. 4d), in which the Northward (Fig. 3d) and Eastward (Fig. 4d) flow components carry atmospheric water to South Asia. Additionally, the horizontal water transport pathway from the Indian Ocean to the South Asian landmass by the Somali low-level jet is clearly noticeable in Fig. 5d.

The Easterly (Fig. 4d and Fig. 5d) component of the flow field transport water to Eastern Africa from the nearby Indian Ocean. The water that evaporated from the Indian Ocean and transported to land remains around 20 days in the atmosphere
185 (Fig. 6d). The transport from the subtropical Atlantic Ocean to the tropical and mid-latitude Pacific Ocean (Fig. 2g) is found to be accomplished by the Easterly and Westerly winds, respectively , (Fig. 4g and Fig. 5g) and is calculated to be approximately 0.45 Sv (Table 1). The mean residence time of the evaporated waters from the Atlantic Ocean that are transported to the Pacific Ocean is 35 days (Fig. 6g). The majority of the South and Central American precipitation is found to be transported

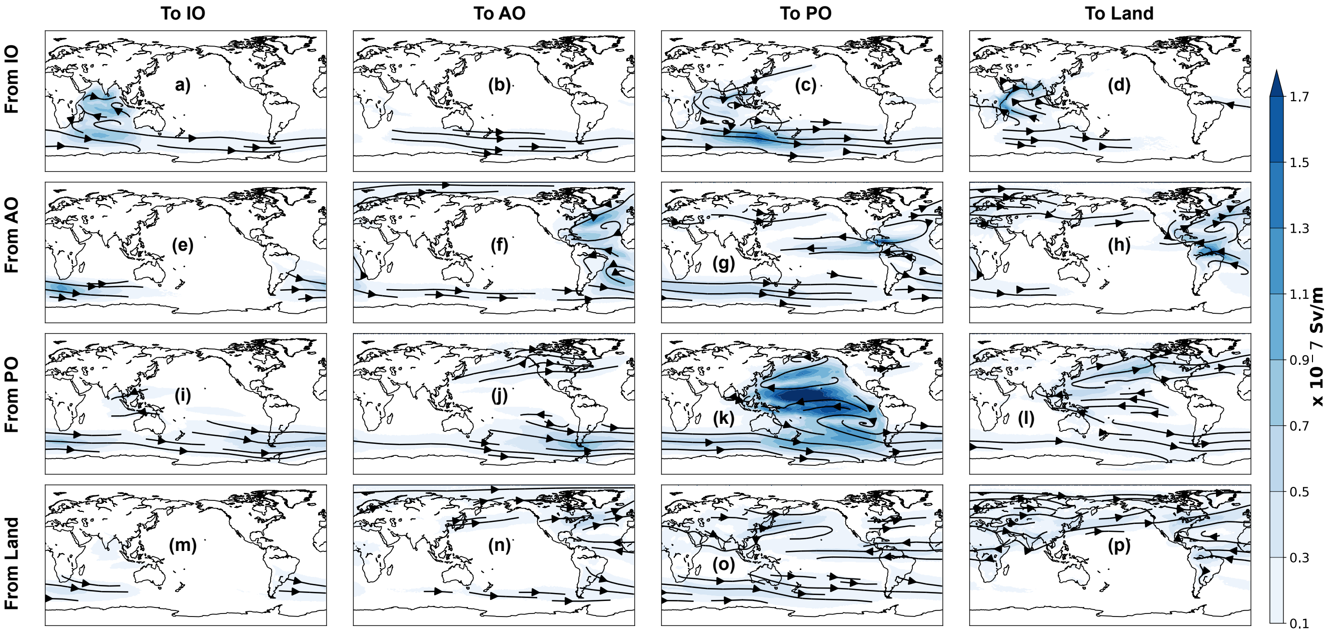

Figure 5. The vertically integrated horizontal water flux (shaded; Sv m^{-1}) within and between the ocean basins and land. This has been achieved by grouping the atmospheric water trajectories according to their starting and ending locations. The starting and ending points of the Lagrangian trajectories are defined as per the sectors presented in Fig. 1. The flux directions are given by the black lines.

from the tropical Atlantic (Fig. 2h) with the help of Easterly trade winds (blue cell in Fig. 4h and black lines in Fig. 5h). The Atlantic storm tracks, which orientated in an eastward direction, seemed to be responsible for the European and North Asian precipitation (Fig. 2h, 4h and 5h). The annual-mean Western African precipitation that is dominated by the Western African monsoon is traced to originating from the Atlantic Ocean and moves eastward (Fig. 2h and 4h). The winds over the Atlantic Ocean transport around 1.07 Sv atmospheric water to the land, which is 22% of its net evaporation (Table 1). The Atlantic Ocean evaporated waters stay in the atmosphere for 15 days before precipitating over Land (Fig. 6h). The rainfall over the west coast of North America, eastern coasts of Asia and Australia is primarily sourced from the Pacific Ocean (Fig. 2l) and its pattern closely resembles the pathways of the Pacific storm tracks. The total atmospheric water transport from the Pacific Ocean to the landmass is approximately 0.77 Sv (Table 1). The average residence time of the waters that are evaporated from the Pacific Ocean and precipitated over the landmass is found to be 21 days (Fig. 6l). The land to land atmospheric water transport is prominent over the Amazon basin, western coast of South America, Congo basin, the Northeastern sector of Asia, Canada and Greenland (Fig. 2p). The total amount of land-to-land atmospheric water transport is estimated to be around 3.30 Sv and is equal to 72% of its evapotranspiration, while 58% of the terrestrial precipitation were sourced from the land evaporation (Table 1). The evaporated water from land that falls back over the continents spends 6 days in the atmosphere (Fig. 6p). A spatial view of the global atmospheric water residence time (from both the evaporation and precipitation perspective) has been constructed from the Lagrangian water trajectories (Fig. S1) and discussed in the supplementary material (Text S1). The global average

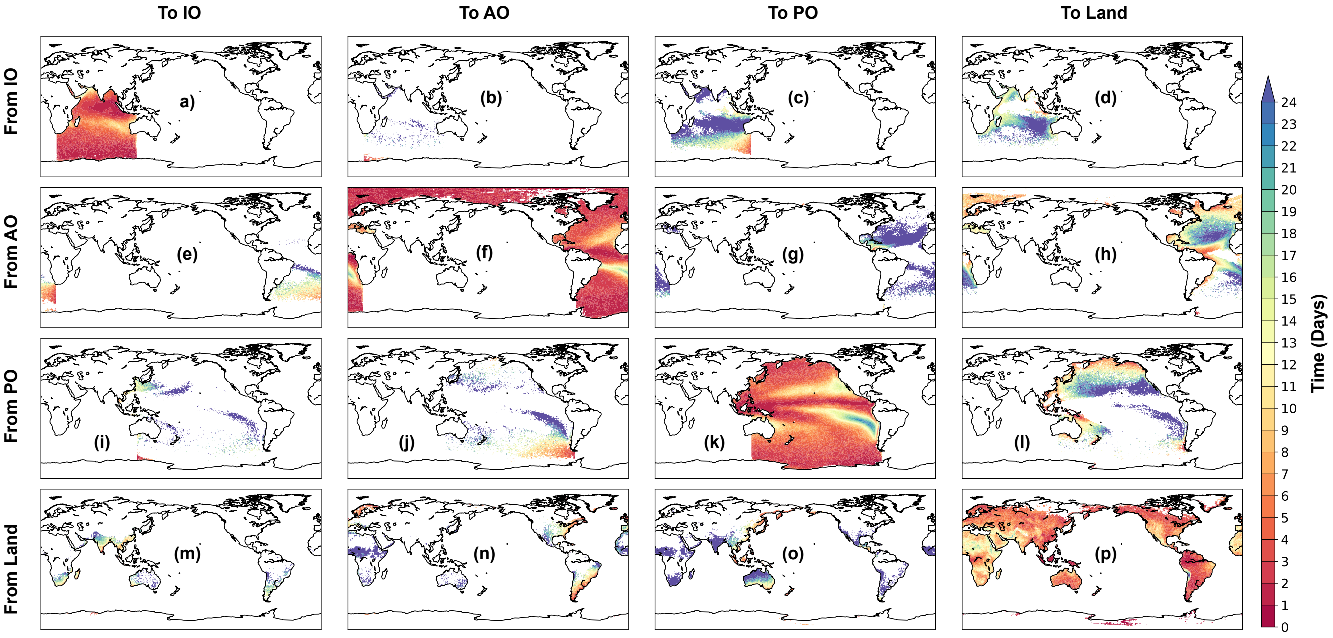

Figure 6. The average residence time (days) of the atmospheric waters mapped on their net evaporative points within and between the three ocean basins and land. Note that this has been mapped where the net evaporation exceeds a monthly mean value of 0.2 mm day^{-1}. The residence time has been calculated from the time the trajectories have spent in the atmosphere between their starting (net evaporation) and ending (net precipitation) points.

residence time of the atmospheric waters from the evaporation and precipitation point of view is calculated to be around 7.5 days and 11 days respectively, which is similar to the estimate of 8 to 10 days by Van Der Ent and Tuinenburg (2017) and the references therein.

3.2 A simplified quantitative view of the atmospheric water cycle

A simplified schematic of the annual mean global atmospheric water transports from both the surface water budget and Lagrangian perspectives is presented in Fig. 7. It reflects the advantage of using a Lagrangian framework, from which ocean-to-ocean, ocean-to-land, land-to-land and land-to-ocean atmospheric water transport could be and was calculated (Fig. 7, bottom). The sketch was constructed by summing and rounding off the values of Table 1. For instance, net evaporation over the entire ocean was calculated by summing all the values of the atmospheric water transports from the defined ocean basins. The net evaporative transport from all the ocean basins is around 17 Sv, of which nearly 16 Sv precipitates over the ocean itself. The net ocean-to-land transport is thus 1 Sv, which returns to the ocean as runoff from land and equals the difference between the land net evaporation ($\approx$4.6 Sv) and land net precipitation ($\approx$5.6 Sv). It is found that 88% of the oceanic net evaporation (i.e. approximately 15 Sv) transported back to the ocean through precipitation. The ocean-to-land transport is computed to be around 2 Sv, while the land-to-ocean atmospheric water transport is approximately 1 Sv. The difference between them (i.e. 1 Sv) is the same

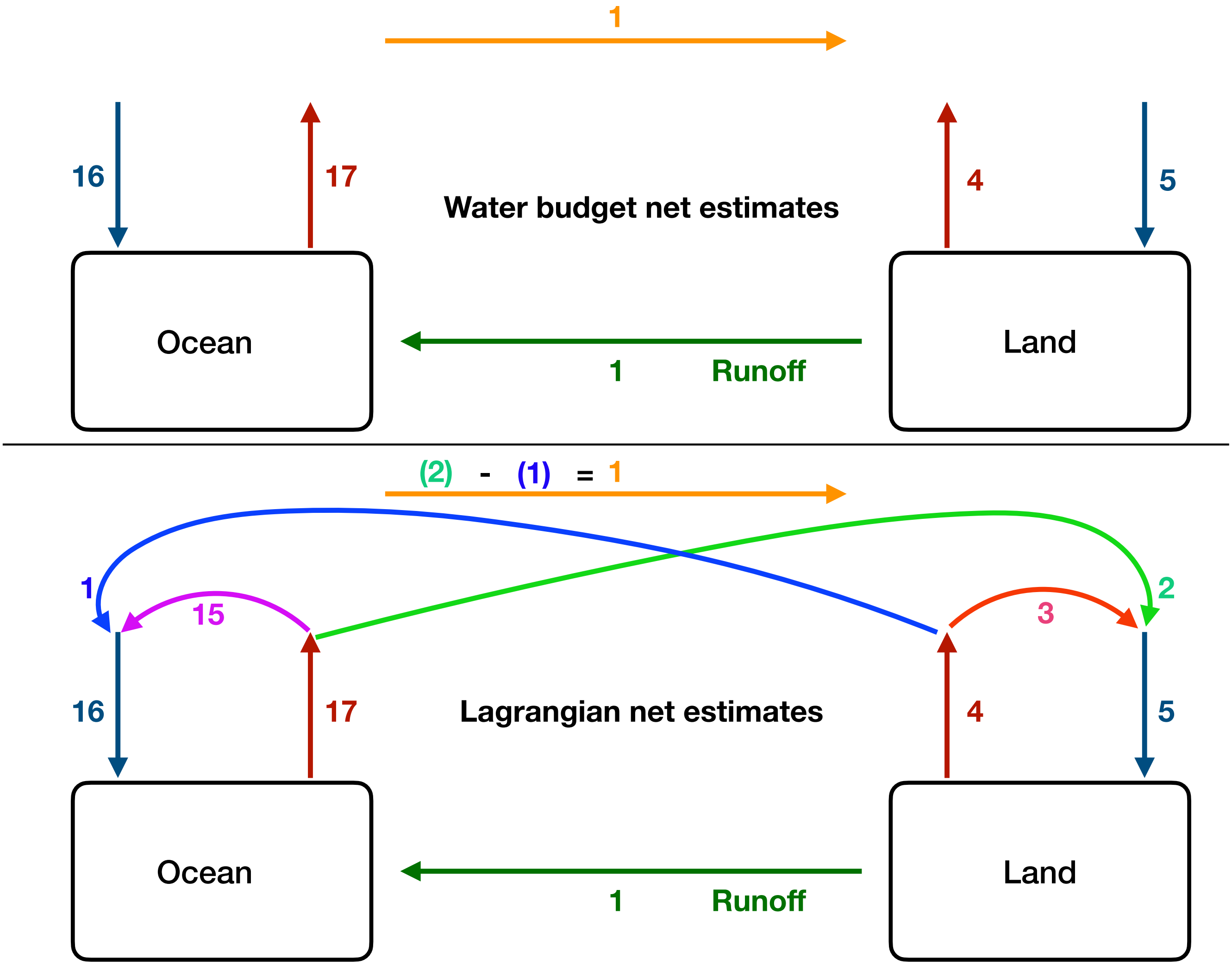

Figure 7. A sketch of the atmospheric water exchange between the Global Ocean and land. The top panel shows the surface water budget understanding of the hydrologic cycle, while the bottom panel elaborates the intricacies of the water movement that can be obtained using a Lagrangian framework. The upward and downward arrows represent net evaporation and net precipitation transport respectively. Note, the numbers presented here are the crudely estimated transports from Table 1 and have not been used for any quantification. Units are in Sverdrups (1 Sv $\equiv 10^9$ kg s^{-1}).

as the net ocean-to-land water transport through the atmosphere one might obtain from an atmospheric surface water budget point of view. The net land evapotranspiration is calculated to be around 4.6 Sv and 72% of this (i.e. around 3.3 Sv) goes into terrestrial precipitation. This estimate is similar to the estimate of 70% by Tuinenburg et al. (2020), which was based on the higher resolution ERA5 atmospheric reanalysis data during 2008 -2017 and a trajectory based moisture tracing model UTrack.

However Link et al. (2020) and Van der Ent et al. (2010) reported a lower estimate of around 59% and 57% respectively while using the Eulerian numerical moisture tracking model Water Accounting Model (WAM), coarser ERA-Interim data and different study period. The net land precipitation is estimated around 5.6 Sv and 58% of this (i.e. approximately 3.3 Sv) found to be originates from the land evaporation. This estimation is comparable with the Tuinenburg et al. (2020) study in which they noted that 51% of the global precipitation has evaporated from land. A study by Van der Ent et al. (2010) using WAM-1layer model reported that the continental precipitation recycling is 40%, an estimate lower than the present study. However using an updated moisture tracking model WAM-2layers Van der Ent et al. (2014) found that the continental precipitation recycling dropped to 36%.

The strength of the hydrological cycle in the present study is stronger than previous estimates such as Chahine (1992); Trenberth et al. (2007). This despite one might expect the opposite since in the present study the atmospheric water is traced from the net evaporation ($E - P > 0$) to the net precipitation points ($E - P < 0$) and not from the total evaporation (E) to the total precipitation (P). The reason for this could be explained by the way $E - P$ has been computed in the current study, which omits diffusive atmospheric water transports, specific rain and snow water content. Consider a hypothetical situation in which the vertical water transport computation without the diffusive water transport component leads to net precipitation and net evaporation regions adjacent to each other. Now, if we would include the diffusive water transport into the water-mass conservation equation and for simplicity assume this addition would increase only the water transport through the connecting grid box face (keeping all the other horizontal water transports constant as previous) then the vertical water transport calculation would lead to a weaker net precipitation and net evaporation estimates. Additional reason might be related to the use of 6-hourly cumulative net freshwater transport in the present study which prohibits the inclusion of processes occurring at a shorter timescale.

4 Conclusion and Discussion

One of the most striking and robust features of climate change is the acceleration of the atmospheric water cycle branch, which is associated with the temperature increase of the lower troposphere. In order to gain a detailed understanding of the future atmospheric water cycle and its importance, one should know the intricacies of the present-climate water cycle in the atmosphere. Although earlier studies were able to provide a quantification of the global atmospheric water cycle ~~but~~ they missed a lot of detailed and important information which is essential to explain variations in continental water availability and near surface ocean salinity asymmetries. For instance, the global ocean-to-ocean, total ocean-to-land, total land-to-ocean and land-to-land water transport through the atmosphere were not extensively studied previously. Thus the global picture of the atmospheric water movement was incomplete. These shortcomings were overcome in the present study using a novel Lagrangian framework and presented a complete synthesised and quantitative view of the atmospheric water cycle. This Lagrangian methodology used in the present study made it possible to trace the atmospheric water transport from the net evaporation to the net precipitation regions within and between the different ocean basins and land. Earlier studies focused more on the regional or basin-scale surface water budget analysis (Alestalo, 1983; Yoon and Chen, 2005; Shi et al., 2014; Zheng et al., 2017; Liu et al., 2018) or continental water cycle (Van der Ent et al., 2010, 2014; Tuinenburg et al., 2020; Link et al., 2020), which could be viewed as a few pieces of a big puzzle. Only a handful of studies were able to put forward a quantitative and synthesized view of the global atmospheric water cycle (Chahine, 1992; Browning and Gurney, 1999; Trenberth et al., 2007, 2011). The atmospheric water transport quantification between two primary water reservoirs, e.g. ocean and land, is a straightforward issue to address. The residual between the integrated evaporation and precipitation over the ocean should be the net ocean-to land transport and must be returned to the ocean as runoff. The water-mass conservation yields that this runoff should then be equal to the difference between the integrated evapotranspiration and precipitation over land. This concept has been elaborately demonstrated in Fig. 7 (top panel) and frequently been used previously in global quantification of the atmospheric water cycle. The surface water budget method suffers, however, from limitations as it can not provide any information about how much of the ocean/land evaporated water precipitates over the ocean/land itself and is transported to the land/ocean. However, these constraints were overcome in the present study by using Lagrangian water trajectories (Fig. 7, bottom panel). For example, in previous studies the net ocean-to-land water transport through the atmosphere was estimated to be around 1 Sv using the surface water budget method. This 1 Sv is practically the difference between the ocean-to-land (≈2 Sv) and land-to-ocean (≈1 Sv) transport, which is quantified in the present study.

The Eulerian/Lagrangian moisture tracking models that has been used in earlier studies were focused, in particular, on isolated aspects of the atmospheric hydrologic cycle, e.g. only ocean to river basin transport, land-to-land transport or some extreme precipitation events (Stohl and James, 2004, 2005; Stein et al., 2015; Van der Ent et al., 2010; Tuinenburg et al., 2020) and were also unable to provide the integrated water circulation pathways in the zonal-vertical or meridional-vertical framework. So, a complete 3-D picture of the atmospheric water transport connectivity within and between different ocean basins and land was missing. The sorting of the atmospheric water trajectories based on their starting and ending positions made it feasible to construct a map that shows the geographic connection of the atmospheric water transport from the net evaporative regions to the net precipitating areas (Fig. 2). It also reveals the integrated meridional, zonal and vertical transport pathways (Fig. 3, Fig. 4 and Fig. 5 respectively) of atmospheric water that travels within and between the defined ocean basins and the landmass. Further, an average atmospheric water residence time was presented (Fig. 6) which shows how long evaporated water from a particular location remains in the atmosphere before precipitating. The trajectory analysis indicates that 67% of the Indian Ocean net evaporation, 64% of the Atlantic Ocean net evaporation, 85% of the Pacific Ocean net evaporation and 72% of the land net evaporation precipitates back into the same region. The land-to-land atmospheric water transport is prominent over the Amazon basin, western coast of South America, Congo basin, Northeastern Asia, Canada and Greenland. It has also been noted that 58% of the net terrestrial precipitation were soured from the land evaporation. The net evaporation from the subtropical regions of the Indian, Atlantic and Pacific Oceans is found to be the major source of atmospheric water for ITCZ precipitation in the corresponding basins. The global average residence time of the atmospheric waters from the evaporation and precipitation perspectives was calculated to be around 7.5 days and 11 days respectively. The strength of the atmospheric hydrologic cycle in the present study is stronger than the earlier estimates and could be attributed to the omission of the diffusive water transports, specific rain and snow water content from the water-mass continuity equation and also to the processes occurring at time scale shorter than 6-hours. These limitations of the present method could be overcome by running the trajectory model on-line (i.e. calculating water trajectories simultaneously with the general circulation model run) with the inclusion of all the components of the water transport field. The present study has only used the advective fluxes of water but, if available, should also include the diffusive fluxes of water, which could still be computed off-line.

In a warmer climate the atmospheric water transport is expected to be enhanced, which has far-reaching consequences. An extension of the present study could be to repeat a similar investigative strategy for future climate scenarios and identify how the atmospheric water transport within and between ocean basins and the landmass will change with respect to the present climate. The results could provide a detailed understanding of the future ocean salinity asymmetries as the ocean salinity is closely tied to the surface evaporation and precipitation, which are the starting and ending points of the atmospheric water transport. Note that observational evidence of the oceanic salinity change already indirectly indicates a strengthening of the atmospheric branch of the water cycle (Durack and Wijffels, 2010). Additionally, future precipitation availability over the continents and the variability associated with it can also be mapped beforehand, and thus will be helpful for making strategies for the policymakers. The outcome of the present study is essential before pursuing any future climate studies regarding the global atmospheric water cycle as it provides a complete global view of water transport through the atmosphere, which was missing earlier. The present study can be used as a springboard to launch and address future water-transport issues.

Code and data availability. The Lagrangian trajectory model TRACMASS v7.0 can be freely downloaded from https://doi.org/10.5281/zenodo.4337926. The ERA-Interim data at model levels are available from the ECMWF (https://www.ecmwf.int/en/forecasts/datasets/archive-datasets/reanalysis-datasets/era-interim) The trajectory model TRACMASS outputs that are used to plot the figures are freely accessible at https://doi.org/10.5281/zenodo.5549573. The analysis scripts are available on request from the corresponding author.

Author contributions. D. Dey and K. Döös conceptualized the study. D. Dey collected all the necessary data sets and employed the trajectory model TRACMASS. The outputs from the TRACMASS were analyzed by D. Dey with the programming help from A. Aldama Campino. The results were then discussed elaborately between all the authors. The manuscript is written by D. Dey with inputs from all the co-authors. A. Aldama Campino was responsible for the inclusion of the cloud liquid and ice water into the updated version of the TRACMASS.

Competing interests. No potential conflict of interest was reported by the authors.

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March 29, 2022

Dear Dr. Wanders,

Please find our answers to the reviewers below. We have answered all questions and made all possible changes suggested by the reviewers. The revised version of the manuscript has been uploaded using the Hydrology and Earth System Sciences (HESS) online submission system.

Best regards,

Dipanjan Dey

Reply to Mr. Dominik Schumacher *Thank you for the response on our article. We are grateful for all your constructive suggestions, which have helped us improving the manuscript. Below you can see our answers. The line numbers are from the revised manuscript*

Major Comments

Based on my current understanding of this manuscript and previous publications of the authors, the mass of each water 'parcel/particle' released when E-P>0 is given by the net evaporation amount, and hence simply E-P. Such a 6-hourly net evaporation event may range from a water amount of nearly zero to 1 mm or more, especially over subtropical oceans. Is it true that for every 'water release event' (E-P>0 at the surface), this water is then advected in accordance with the Eulerian water fluxes, behaving as a coherent 'parcel' with constant mass until 'reaching the surface', that is, precipitating? Moreover, I would like to understand if the advection of water is fully independent of the mass that it represents in this framework. I suspect that for the 'regular' version of TRACMASS (tracking air or ocean water), considering that "mass transport is linearly interpolated within the grid box" (Döös et al., 2017), this is not the case. I thus wonder whether the same analysis had a different outcome if, e.g., large net evaporation events were represented by several water parcels of uniform mass, rather than a single one. To compare, in Tuinenburg & Staal (2020), each mm of evaporation corresponds to 2000 parcels, and sensitivity experiments were performed for a range of 10 to 10000 parcels.

Answer : *Thank you for raising this point. To clarify your query we have now clearly stated on line no: 124 - 129 that "These water trajectories were started at the surface every 6 hours during 2016 where E > P, then advected by the 3-D mass transport of water and followed until they reached back to the surface where P > E. In total more than 89 million water trajectories were started with more* *than 7 million trajectories each month. The position of a given atmospheric water trajectory within a grid box is solved analytically in space and with a stepwise-stationary scheme (Döös et al., 2017) in time. The trajectories were integrated in time with six intermediate time steps between each 6-hourly output data from the ERA-Interim." Note that the "mass transport is linearly interpolated within the grid box" is a part of the analytical solution which determines only the trajectory position within the grid box and nothing to do with the water trajectory itself whose mass is constant throughout the journey. The effect of the number of water-mass parcels on the existing result lies outside the scope of the current study. However, we think that increasing the number of water parcels will not significantly change the outcomes presented here. This since the validation performed by Dey and Döös (2020) used the same Lagrangian resolution i.e. one water parcel per grid box every 6-hours during 2016, which resulted in almost identical E - P patterns as one will get from the ERA-Interim E - P.*

According to Dey & Döös (2020), annual mean E-P as diagnosed here generally agrees well with ERA-Interim data. But what about, e.g., E-P>0 for a single time step - which should be roughly equal to the total E, at least if the author's assumption on E and P not coexisting holds? I would expect severe underestimations for both E and P in tropical forests, where this assumption is rather poor, and believe that this limitation should be emphasized in the manuscript. Also, a related sentence to this (L. 211) may benefit from rephrasing, which is not entirely clear to me as is.

Answer : *Yes, indeed you would expect an underestimation of evaporation and precipitation estimates. However, the present study noted a stronger hydrologic cycle than the previous estimates. The reason for this could be explained by the way E - P has been computed in the current study which omits diffusive atmospheric water transports, specific rain and snow water content. Additional reason might be related to the use of 6-hourly cumulative net freshwater transport in the* *present study which prohibits the inclusion of processes occurring at a shorter timescale. These are all now mentioned clearly in the revised manuscript between line no: 231 - 242. The global E - P computed from the atmospheric water-mass conservation equation (or commonly known as the moisture budget) and from the individual evaporation and precipitation data at different time scale (starting from 6 hr to month) has been compared in Dey & Döös (2021). Please have a look into the Figure S2 and Text S2 in supplementary material of Dey & Döös (2021).*

Subgrid-scale turbulence, and in particular vertical mixing is not considered here. It is also assumed that water fluxes are 'constant' in each 6-hourly period - a single grid box can either have a net upward or downward water flux, but not both. Therefore, processes occurring at shorter timescales than the 6-hourly model analyses, such as convective precipitation, may not be captured adequately, and the precipitation diagnosed with the presented framework is not necessarily consistent with the 'underlying' reanalysis product, i.e. ERA-Interim.
I would therefore suggest rephrasing a statement in the introduction (L.51-55), which implies that this approach enables insights into the "true" precipitation. As far as I am concerned, this would require online rather than offline tracking as performed here, because only then are the mass (or air/water) fluxes fully consistent between the calculated trajectories and the 'driving' Eulerian model data. Clearly, online tracking is not an option when it comes to such reanalysis-based analyses and I think such offline approaches are still valuable, but the reader should, in my opinion, nevertheless be informed about this limitation.

Answer : *Thank you for your suggestion. We completely agree with your views and thus removed the word "truely" from the revised manuscript. The limitations of the method are now emphasized in line no: 78 - 84. Also, the impact of the limitations on the result and how it can be overcome is now stated in line no: 231 - 242 and line no: 287 - 293.*

To enhance the comparability to other studies, recycling ratios of, e.g., Amazonia, or the Mississippi or Congo basin would be of great interest (e.g., Trenberth, 1999; Tuinenburg et al., 2020). It could also be interesting to provide a global mean (or median; see Sodemann, 2020) residence time, which has been debated in recent years (Läderach & Sodemann, 2016; van der Ent & Tuinenburg, 2017; Sodemann, 2020).

Answer : *The global atmospheric water residence time maps and global average water residence time are now included in the supplementary material and also in line no: 202 -207. The objective of the present study is to get a global picture of the atmospheric water connection between the Ocean basins and global landmass. We did not divided the global landmass into various basins or continents and thus it is not possible to compute the recycling ratios for Amazonia, or the Mississippi or Congo basin from the present study. However, we have now mentioned in the the abstract (line no: 13 -15) and also in line no: 198 -200 that the land-to-land atmospheric water transport is prominent over the Amazon basin, western coast of South America, Congo basin etc.*

Minor Comments

When used to trace atmospheric air, a time-dependent analytical or stepwise-stationary scheme can be employed in TRACMASS (Döös et al., 2017) - does this also apply to the water-tracking version used here? Since no 'substeps' are mentioned in the manuscript, I assume that the analytical solution was employed, but perhaps this should be stated explicitly.

Answer : *Thank you for raising this point. We have now mentioned in line no: 126 -129 that "The position of a given atmospheric water trajectory within a grid box is solved analytically in space and with a stepwise-stationary scheme (Döös et al., 2017) in time. The trajectories were integrated in time with six intermediate time steps between each 6-hourly output data from the ERA-Interim".*

Cloud liquid & ice water: Is this treated differently with respect to Dey

& Döös (2020)? If so, where is this described? To me, the ability to include not only water vapor but also liquid and frozen water is an advantage of this approach, and deserves to be mentioned.

Answer : *In line no: 116 -117 it is now mentioned that "The inclusion of the specific cloud liquid and ice water content in the water transport calculation is an update as compared to the Dey and Döös (2020, 2021)."*

The global land recycling estimates are remarkably similar to the numbers presented by Tuinenburg et al. (2020), yet their approach is notably different despite also tracking water through the atmosphere. Perhaps this agreement could be mentioned; unfortunately, most other studies I am aware of only provide numbers at much smaller spatial scales, or for specific 'sink' and/or source regions and sometimes individual seasons (e.g., DomÃnguez et al., 2006; Dirmeyer & Brubaker, 2007; Keys et al., 2012; Keune & Miralles, 2019), and not the entire land mass.

Answer : *Thank you for your suggestion. We have now compared our global land recycling estimates with the previous studies and discussed it in line no: 220 - 230.*

I am not sure if the data employed (2016 & 2017) warrant the use of 'complete' in the title. After all, there appears to be considerable interannual variability when it comes to atmospheric moisture advection, even at large spatial scales such as for (tropical) Atlantic-to-Pacific moisture transports (Yang et al., 2021). I do not think that an extension of the analysis period is crucial for the outcome of the study, but a brief discussion could still be appropriate. Similarly, I was a bit surprised to see that ERA-Interim - and not ERA5 -data are used for this study.

Answer : *Thank you for raising this point. The title has now been changed to 'Atmospheric water transport connectivity within and between Ocean basins and land'. As mentioned on line no: 119 -120 "It is noteworthy that to satisfy the mass* *conservation property of the Lagrangian model TRACMASS it requires data at model levels and not at interpolated pressure levels". The requirement of data on model levels restricts our ability to use the ERA5 data. This is since the ERA5 data on model levels are vast in volume and slow to access due to higher spatial and temporal resolution than its precursor ERA-Interim. However, it has been found that our estimates are similar to the estimates provided by the earlier studies where they have used the ERA5 data (line no: 220 - 222). So we think changing the reanalysis product will not severely impact the outcomes of the study.*

L206: I struggle a bit with this sentence - the transports presented here should be lower than Eulerian estimates such as Trenberth et al. (2007) due to relying on net evaporation and precipitation events, is this what is meant? If so, stating clearly whether these estimates are actually lower (or only should be, but aren't) would be helpful.

Answer : *Yes, it was not written clearly. We have now modified the sentence in line 231 - 235 by stating "The strength of the hydrological cycle in the present study is stronger than previous estimates such as Chahine (1992); Trenberth et al. (2007). This despite one should expect the opposite since in the present study the atmospheric water is traced from the net evaporation ($E - P > 0$) to the net precipitation points ($E - P < 0$) and not from the total evaporation (E) to the total precipitation (P). The reason for this could be explained by the way $E - P$ has been computed in the current study which omits diffusive atmospheric water transports, specific rain and snow water content".*

Also, I am not convinced if the conceptualization of 'evaporation' and 'precipitation regions' employed throughout the manuscript is justified, since most regions are clearly both (and some even within 6 hours, as commented above).

Answer : *We have now changed the 'evaporation' and 'precipitation regions' to net evaporation and net precipitation regions or evaporation-dominated and* *precipitation-dominated regions wherever applicable.*

Further Comments

L. 18: "[...] coupled ocean-atmosphere system [...]"; I would strongly prefer the inclusion of land here, and since this would make the sentence harder to read, perhaps it is better to refer to the "climate" or "Earth system" as a whole?

Answer : *Changed it to "Earth System (line no: 20)".*

L. 69: "[...] this trajectory calculations [...]"

Answer : *Removed "this" and replaced with "these" (line no: 73).*

L. 184: "[...] waters are stay in [...]"

Answer : *Removed "are" (line no: 194).*

L. 207: "This since in the present study, [...]";

Answer : *The whole paragraph has now been modified (line no: 231 - 242). Thank you.*

Reply to Dr. Ruud van der Ent *Thank you for the response on our article. We are grateful for all your constructive suggestions, which have helped us improving the manuscript. Below you can see our answers. The line numbers are from the revised manuscript*

Major Comments

My first major comment is that the authors tend to overstate the novelty of their results and I found that a lot of relevant literature is not taken into consideration when putting their own results into context.

Answer : *We have now modified the sentences that might be overstating the novelty of our results and compared the results with previous literature wherever applicable (e.g., line no: 220 - 230). However, we still thinks most of the results presented here are novel to some extent. This since no previous studies have constructed an atmospheric water transport connectivity within and between ocean basins and land. We have also changed the title of the manuscript to "Atmospheric water transport connectivity within and between Ocean basins and land" in order to emphasize on the actual contribution of the present study.*

My second major comment refers to Figure 7, Table 1 and L207-214: "Note that this net evaporative and precipitating transports should underestimate the earlier Eulerian estimates (Trenberth et al., 2007). This since in the present study, atmospheric water is traced from the net evaporation (E - P >0) to the net precipitation points (E - P <0) and not from the total evaporation (E) to the total precipitation (P). The computation of the vertical mass transport of atmospheric water in the present study omits diffusive atmospheric water transport, specific rain and snow water content and thus leading towards an overestimate of the net evaporative and precipitating transports as compared to the total evaporation and precipitation estimates from previous studies, e.g. Trenberth et al. (2007). At any given time, the instantaneous net evaporation (E

- P > 0) and total evaporation might roughly be the same, if assuming that evaporation and precipitation cannot coexist at the same time but the present study uses 6-hourly cumulative net freshwater transport." If you do the conversion for example for land evaporation using the numbers from Table 1 (0.20+0.48+0.61+3.30 =4.59 $\times$ 10^9 kg s^{-1}) this equals 146 $\times$ 10^3 km^3 $year^{-1}$ if I haven't made any calculation mistake. Comparing this to generally accepted values of land evaporation of around 70 $\times$ 10^3 km^3 $year^{-1}$ (Rodell et al., 2015) or 81 $\times 10^3$ km^3 $year^{-1}$ for ERA-Interim evaporation fields directly (I used the values from van der Ent and Tuinenburg, 2017, Figure 1) one can easily see that the method in fact does not lead to underestimation, but rather a huge overestimation, which I would say cannot be assigned only to missing diffusive atmospheric transport, specific rain and snow water content. So this tells us that much bigger problems exist with the Lagrangian scheme presented here especially when applied to reanalysis data that normally does not close the water balance by design. One would expect such a striking problem of severely overestimating the intensity of the hydrological cycle to be investigated and discussed at great length in the context of the assumptions made by the applied method and a strong warning in the abstract, captions of all tables and figures and not just in the final sentences of the results (L207-2013).

Answer : *Thank you for the math and you are right that the net evaporative transports obtained in the present study are higher than the actual evaporation estimates. The reason for this could be explained by the way E - P has been computed in the current study which omits diffusive atmospheric water transports, specific rain and snow water content. Additional reason might be related to the use of 6-hourly cumulative net freshwater transport in the present study which prohibits the inclusion of processes occurring at a shorter timescale. These are now mentioned clearly in the revised manuscript between line no: 231 - 242, including a hypothetical situation explaining how the diffusive fluxes of water could modify* *the results. Note that this overestimation is nothing to do with the Lagrangian method presented here but associated with the way E - P has been computed in the present study. This since the net evaporative transports in the present study were calculated from the 6-hourly E - P dataset whenever E > P (E - P has been calculated using the water-mass conservation equation) and were only the starting points of the Lagrangian trajectories. This has been now repeatedly mentioned in the revised manuscript (e.g., line no: 131 -132, line no: 141 - 142, caption of Fig.2 , line no: 298 etc.). In the revised manuscript we have now stated clearly the limitations of the present study, its effects on the results and how we could overcome it in line no: 78 - 84, line no: 231 - 242 and line no: 287 - 293. The way we have stated the limitations of the present study in the revised manuscript should now be clear to the reader. However, we think it would be unreadable to put the limitations everywhere. Every study has its own limitations and it should be mentioned and discussed, which we have done in the present study now.*

Specific Comments

Lagrangian and Eulerian: I'd say the use of these terms is somewhat incorrect. It might be more intuitive to talk about the hydrological cycle with and without moisture tracking. See for example Figure 1 in Dominguez et al. (2020) for an overview of tracking scheme differences where Eulerian can also include moisture tracking and note that the online methods are also Eulerian tracking schemes.

Answer : *Thank you for raising this important point. We agree with your views and thus discarded the word "Eulerian" wherever it is not valid.*

Title: I think 'complete' is overstated, but one could say it is more complete than the view presented by, for example, Trenberth et al. (2011). Yet, one could also easily argue that other studies contained more aspects of the hydrologic cycle and as such make this study of Dey et al. less complete regarding those aspects. For example, Van der Ent et al.

(2014) and Tuinenburg and van der Ent (2019) showed atmospheric transit times and separated into evaporation from interception or transpiration, or yet others studied much more detailed, e.g., grid cell by grid cell (Link et al., 2020; Tuinenburg et al., 2020) or region by region (Singh et al., 2016) import and export matrices of atmospheric water. Yet other studies looked at the atmospheric water cycle in much greater temporal or spatial detail (too many references available to even start listing them). My suggestion is to be more specific in the title what the contribution of this study is.

Answer : *Thank you for your suggestion. The title has now been changed to 'Atmospheric water transport connectivity within and between Ocean basins and land'.*

L12: "recycling" I think this refers to recycling from land to land, but this is not obvious

Answer : *The word "recycling" has now been removed and replaced with "land-to-land" (line no: 13).*

L55: "In addition, knowledge about how much of the ocean/land evaporated water truly precipitates over the ocean/land itself and is transported to the land/ocean is not achievable. In the present study, these questions will be possible to address using a new Lagrangian framework." There are literally dozens of other moisture tracking methods with which it would be possible to address these questions or even have already addressed those questions. See for example Figure 1 in Dominguez et al. (2020) to start a more extensive literature study.

Answer : *We have now modified the sentences on line no: 56 - 60 as " In addition, knowledge about how much of the ocean/land evaporated water precipitates over the ocean/land itself and is transported to the land/ocean is not achievable. However, these question will be possible to address using Eulerian/Lagrangian* *atmospheric water tracing schemes (Van der Ent et al., 2010; Tuinenburg et al., 2020; Stohl and James, 2004; Stein et al., 2015; Dey and Döös, 2020). A list of atmospheric water tracing models and their advantages and disadvantages has been discussed briefly in Dominguez et al. (2020)".*

L69-70: "Note here that this trajectory calculations are based on atmospheric water-mass transport in kg/s and not transports of humid air." When the authors refer to transports of humid air I think they refer to the FLEXPART methodology (Stohl et al., 2015) or HYSPLIT (Stein et al., 2015) that track (E-P). However, there so many methods that track actual water mass (irrespective of the units) from evaporation to precipitation or backward. I again refer to Dominguez et al. (2020, Figure 1), but this is not even an exhaustive overview.

Answer : *The objective of this sentence is to state clearly what the present Lagrangian method is actually capable of doing and not to compare with other studies (this is also not the objective of the current study). The capabilities of the Eulerian/Lagrangian moisture tracing models are now mentioned in line no: 56 - 60.*

L95-96: "The vertically integrated zonal (Fx,i,j) and meridional (Fy,i,j) water flux was computed from the simulated water trajectories to describe atmospheric water transport pathways in longitude-latitude framework" Did I correctly interpret that the tracking scheme uses the vertically integrated fluxes only? It has been noted before that this may lead to significant errors, especially in some regions with a lot of wind shear such as West Africa (e.g., Goessling and Reick, 2013; van der Ent et al., 2013; Dominguez et al., 2020; Tuinenburg and Staal, 2020).

Answer : *No, we have used a 3-D atmospheric water transport field to compute the trajectories and the vertically integrated zonal and meridional fluxes of water were computed from those trajectories. This is now clearly stated on line no: 124*

- 129 and line no: 100 -102.

Figure 7 bottom: Note that a very similar figure was presented by Van der Ent et al. (2014, Figure 1) though only for the land, however, one can easily argue that the only unknowns in their figure are the oceanic arrows (evaporation, precipitation and oceanic recycling). However, oceanic evaporation and precipitation can easily be obtained from other data sources (e.g., Trenberth et al, 2011; Rodell et al., 2015) and oceanic recycling then follows from a simple water balance. Moreover, several others (up to Dey and co-authors to more thoroughly search the literature) have presented land recycling estimates and following the same logic using simple water balance and oceanic evaporation and precipitation estimates it would be quite simple to re-construct this figure with other numbers.

Answer : *Yes, we agree. The objective of inserting Fig.7 is to report a quantitative view (achieved from the present study) of the atmospheric water transport connectivity within and between the global ocean and land, which is not possible to obtain from the surface water budget estimates. We have therefore updated Fig.7 and its caption in order to avoid the impression that these can only be achieved with the Lagrangian method.*

L110: The atmospheric water transports were computed using the surface pressure, specific humidity, specific cloud liquid and ice water content and horizontal wind velocities from the ERA-Interim reanalysis (Dee et al., 2011). So, the method does not use evaporation and precipitation fields directly, yet infers them from the water balance. The advantage is that the water balance remains closed, but the disadvantage is that this could lead to unrealistic evaporation and precipitation estimates that compensate for atmospheric errors. This should be acknowledged, analyzed and discussed.

Answer : *In the revised manuscript we have now mentioned clearly the limitations of the present study, its effects on the results and how we could overcome it in line no: 78 - 84, line no: 231 - 242 and line no: 287 - 293.*

L118-119: These water trajectories were started at the surface every 6 hours during 2016 where E > P and followed until they reached back the surface where P > E. It should be noted that E and P occur concurrent using 6-hourly data, which is seemingly then ignored by the model setup. See `https://doi.org/10.5194/hess-2020-651-RC2` for a similar discussion. Also, it should be noted that convergence and divergence could be an issue when assigning E and P along a Lagrangian pathway. See `https://doi.org/10.5194/hess-2020-651-CC1` for a similar discussion. See Cloux et al. (2021) and associated public peer review for further details.

Answer : *Thank you for the links. We are aware of these limitations which has now been addressed on line no: 78 - 84 and line no: 231 - 242.*
We are not assigning E and P along the trajectories. We have clarified this on line no: 75 - 76 by stating "We are hence tracing the actual atmospheric water and not the moisture change along air-parcel trajectories". A brief description of the trajectory computation is also provided in line no: 124 - 129.

L138-140: "Note that the streamlines represent the integrated atmospheric water transport routes and is based on the sum of the Lagrangian trajectories, which should not be confused with the paths of the individual trajectories." This information would be more logical to put in the caption of the respective figures.

Answer : *Added in the Fig. 3 caption.*

Figure 6: I do not see any red contours as stated in the caption. Quite often white (0 days) is right next to blue (>24 days). It seems to me that white sometimes means that E-P < 0 and hence there is no data. Not

only should this then be given another color it illustrates the unrealistic consequences of assigning E only to regions where E-P > 0. In fact this is acknowledged in lines 207-214, but I then keep wondering what then the physical meaning and usefulness of these results are.

Answer : *We have realized that the Fig. 6 caption was confusing and is now rephrased as "The average residence time (days) of the atmospheric waters mapped on their net evaporative points within and between the three ocean basins and land. Note that this has been mapped where the net evaporation exceeds a monthly mean value of 0.2 mm day*$^{-1}$*. The residence time has been calculated from the time the trajectories have spent in the atmosphere between their starting (net evaporation) and ending (net precipitation) points."*
The choice of the colormap was clearly misleading and we have now opted for a different colormap. Now white regions only means where we have not calculated the residence time.

Figure 7: Units are missing

Answer : *Added.*

L240-254: Rather than discussing shortcomings of the studies by Stohl and James (2004, 2005) I think the authors should discuss the shortcomings of their own method with some priority. Moreover, the method by van der Ent et al. (2010) is neither Langrangian nor traces humidity changes, but looks at actual water transport.

Answer : *The whole paragraph has now been modified (line no: 270 - 293), which should serve the purpose. Additionally, we have now stated the limitations of the present study, its effects on the results and how we could overcome it in line no: 78 - 84, line no: 231 - 242 and line no: 287 - 293.*

Conclusions: absent (see `https://www.hydrology-and-earth-system-sciences.net/submission.html`)

Answer : *Added.*

Technical Corrections

Sv: Throughout the paper Sv is used to present 1×10^9 kg s^{-1}. However, 'Sv' in the SI system already stands for Sievert (which is something completely different). I never saw this notation before, but after some searching I did find that 'Sv'. (with period) is used in oceanic flow and known as the Sverdrups current. In hydrology this notation is, however, very uncommon and will thus be quite confusing to HESS readers and not only that it makes comparison to other studies which tend to most often present their results in km^3 year^{-1} quite cumbersome.

Answer : *We have now presented a conversion from kg s^{-1} to km^3 year^{-1} on line no: 51. The Sverdrups (Sv) unit has been used in many atmospheric studies before such as Craig et al. 2017, Craig et al. 2020, Sabin et al. 2020, Schmitt 2008 etc. Note that the present study uses units that are based on the mass transport (i.e. kg s^{-1}) and not on volume transport (i.e. m^3 s^{-1} or km^3 year^{-1}). This requires information of the water density, which is not necessarily exactly equal to 1000 kg m^{-3} .*

L13 "evapotranspirated": Evapotranspiration is already a somewhat redundant word (Miralles et al., 2020), but constructing a verb out of it always sounds even stranger. This is my personal opinion (for similar reasons as indicated in Miralles et al) and I do not want to impose it, but if the authors insist on keeping evapotranspiration they may at least consider changing the verb simply into evaporated.

Answer : *Thank you for the suggestion. We have now replaced the word "evapotranspirated" with "evaporated".*

Unit notation: Throughout the manuscript physical quantities (P and E) are often in roman font and units in italic (kg/s) which should be exactly opposite following commonly accepted notation: `https://www.`

`hydrology-and-earth-system-sciences.net/submission.html`

Answer : *Done. Thank you.*

References

Craig, P. M., Ferreira, D., & Methven, J. (2017). The contrast between Atlantic and Pacific surface water fluxes. Tellus A: Dynamic Meteorology and Oceanography, 69(1), 1330454.

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Sabin, T. P., & Pauluis, O. M. (2020). The South Asian monsoon circulation in moist isentropic coordinates. Journal of Climate, 33(12), 5253-5270.

Schmitt, R. W.: Salinity and the global water cycle, Oceanography, 21, 12-19, 2008.

Reply to Mr. Andreas Link *Thank you for the response on our article. We are grateful for all your constructive suggestions, which have helped us improving the manuscript. Below you can see our answers. The line numbers are from the revised manuscript*

Comments

The authors wrote that earlier studies focused more on the regional or basin-scale water budget analysis and perhaps miss two studies within this field, which were conducted on a global scale: One of these studies refers to a publication at which I worked with other researcher on the global fate of land evaporation ("The fate of land evaporation - A global dataset"): ESSD - The fate of land evaporation - a global dataset (copernicus.org). The other one, in turn, refers to the following publication: "High-resolution global atmospheric moisture connections from evaporation to precipitation" ESSD - High-resolution global atmospheric moisture connections from evaporation to precipitation (copernicus.org) While other global studies are available, one point of improvement could be to put the determined results into the context of those. Some of the determined patterns/ key numbers could, for instance, directly be compared and discussed to those studies. The work of Tuinenburg et al., for instance, determined that 70% of global land evaporation rains down over land, which is the range of the author's work. Our work, however, determined a recycling ratio over land of appr. 59%. Perhaps, a comparison of some key numbers would generally be interesting.

Answer : *Thank you for your input. We have now modified the sentences and included the suggested references in line no: 254- 257. The global land recycling estimates achieved in the present study has now been compared with the previous studies and discussed in line no: 220 - 230.*

Figure 6 of the work provides the average residence time in days for

water travelling from specific types of source to receptor regions. Is it perhaps possible to put them into context of resident times which have been determined in previous studies (e.g. overall residence time in atmosphere independent from its source: 8 days as estimated by Shiklomanov and Rodda; Shiklomanov, I. A.; Rodda, J. C. World Water Resources at the Beginning of the Twenty-First Century. International Hydrology Series; Cambridge University of Press, 2004.).

Answer : *Thank you for your suggestion. The global atmospheric water residence time maps and global average water residence time are now included in the supplementary material and also in line no: 202 -207.*