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Local moisture recycling across the globe

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Abstract. Changes in evaporation over land affect terrestrial precipitation via atmospheric moisture recycling and consequently freshwater availability. Although global moisture recycling at regional and continental scales are relatively well understood, the patterns and drivers of local moisture recycling remain unknown. For the first time, we calculate the local moisture recycling ratio (LMR), defined as the fraction of evaporated moisture that rains out within approximately 50 km from its source, and identify its drivers over land globally. We derive seasonal and annual LMR from multi-year (2008–2017) monthly averaged atmospheric moisture connections at a scale of 0.5° obtained from a Lagrangian atmospheric moisture tracking model. We find that, annually, on average 1.6% of evaporated moisture returns as rainfall locally, but with large temporal and spatial variability, where LMR peaks in summer and over wet and mountainous regions. We identify wetness, orography, latitude, and convective available potential energy as drivers of LMR, indicating a crucial role for convection. Our results can be used to study impacts of evaporation changes on local precipitation, with widespread implications for, for example, regreening and water management.

1 Introduction

Atmospheric moisture connections redistribute water from evaporation sources to sink locations, affecting climates globally, regionally, and locally. These connections are key in the global hydrological cycle and are used to understand the importance of terrestrial evaporation for water availability. More than half of terrestrial evaporated moisture rains out over land (Van der Ent et al., 2010; Tuinenburg et al., 2020). However, it is unknown which fraction of moisture recycles within its source location, and how this recycling varies across the globe. The fraction of evaporated moisture that rains out locally is referred to as the local moisture recycling ratio. This information could be crucial in understanding the local hydrological effects of land-use changes. For example, previous studies showed afforestation causes a reduction in streamflow through an increase in evaporation (Brown et al., 2005; Jackson et al., 2005). However, regional recycling enhances precipitation, minimizing a reduction in water availability (Hoek van Dijke et al., 2022). The local recycling of evaporated moisture would give novel insights into local effects of land-use changes and deepen our knowledge on local water cycles globally, which may be used to study where afforestation could enhance evaporation without drastically decreasing streamflow locally.

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The state-of-the-art high-resolution output of atmospheric moisture tracking models allows us to calculate the local evaporated moisture recycling ratio at 0.5° spatial resolution. Up until now, atmospheric moisture connections have been mainly used to study larger-scale terrestrial precipitation recycling and regional recycling (e.g. Van der Ent et al., 2010), the residence time of moisture in the atmosphere (e.g. Van der Ent & Tuinenburg, 2017), atmospheric teleconnections to understand remote land-use impacts (e.g. Bagley et al., 2012; Keys et al., 2012; Wang-Erlandsson et al., 2018) and the impact of ecosystems on other ecosystems (e.g. O'Connor et al., 2021). In this article, we aim to quantify local evaporated moisture recycling, identify its drivers and it spatial-temporal variation across the globe. We refer to local evaporated moisture recycling as the local moisture recycling ratio (LMR).

We study the relation between local moisture recycling and latitude, orography, precipitation, precipitation type, evaporation, shear, convective available potential energy, and atmospheric moisture flux. These variables relate to either convection, local wetness, or moisture transport away from the source location, which we identified as important factors for local moisture recycling.

2 Methods

We use global atmospheric moisture connections obtained from Tuinenburg et al., (2020) to calculate LMR worldwide. These moisture connections are multi-yearly (2008–2017) monthly averages and have a spatial resolution of 0.5°. These UTrack-atmospheric-moisture data are derived using a Lagrangian atmospheric moisture tracking model by Tuinenburg & Staal (2020). In this model, for each grid cell of 0.25°, each mm of evaporation is represented by one hundred released moisture parcels. The wind transports these parcels horizontally and vertically through the atmosphere. Additionally, a probabilistic scheme describes the vertical movement of the moisture parcels over 25 atmospheric layers. In this scheme, the parcels are randomly distributed across the vertical moisture profile of each grid cell. At each time step (0.1 h), the moisture budget is made using evaporation, precipitation and total precipitable water. Parcels are tracked for up to 30 days or up to the point at which only 1% of their original moisture is still present. Input data for UTrack consist of evaporation, precipitation, precipitable water, and wind speed obtained from the ERA5 dataset (Hersbach et al., 2020). We refer to Tuinenburg & Staal (2020) for a complete description of the model settings and the tests and assumptions underlying them.

LMR is the fraction of evaporated moisture that rains out locally. To study the scale dependence of local moisture recycling, we examine three definitions of LMR (Fig. A1): the fraction of evaporated moisture that rains out in (1) its source grid cell, i.e., r_1, (2) its source grid cell and its eight neighbouring grid cells, i.e., r_9, and (3) its source grid cell and its 24 neighbouring grid cells, i.e., r_{25}. Equations 1-3 describe the three definitions of LMR, in which E is evaporation, P is precipitation, and i,j the index of the source grid cell and l is used to define the domain i.e. 1, 9 or 25 cells. We calculated seasonal and yearly averages of LMR for our different analyses.

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$$r_1 = \frac{P_{i,j}}{E_{i,j}} \quad (1)$$

$$r_9 = \frac{\sum_{l=-1}^{1}\sum_{k=-1}^{1} P_{i+l,j+k}}{E_{i,j}} \quad (2)$$

$$r_{25} = \frac{\sum_{l=-2}^{2}\sum_{k=-2}^{2} P_{i+l,j+k}}{E_{i,j}} \quad (3)$$

We study the relation between multiple variables and local moisture recycling to identify drivers of recycling. These drivers are variables that relate to atmospheric moisture and vertical displacement of air, as both higher atmospheric moisture content and ascending air promote rainfall. The variables that we assessed are: elevation (*z*), precipitation (*P*), evaporation (*E*), wetness (*P-E)*, convective precipitation (*cp*), fraction of convective precipitation, large-scale precipitation (*lsp*), fraction of large-scale precipitation, latitude, vertical integral of the atmospheric moisture flux (northward, eastward and total), convective available potential energy (*CAPE*) and vertical wind shear between 650 and 750 hPa of both meridional and zonal wind. We calculate shear (τ) using Equation (4).

$$\tau = \frac{ln\frac{v_2}{v_1}}{ln\frac{z_2}{z_1}} \quad (4)$$

In this equation v_1 and v_2 are the wind speed at two different heights (z_1 and z_2). We identified significant relations using Spearman rank correlations. Additionally, we used the Ecoregions 2017 data (https://ecoregions.appspot.com/) to study the spatially averaged local moisture recycling of 14 biomes across the globe (Fig. A2). We study variation amongst biomes, as biomes include information both biotic and abiotic factors such as climate.

3 Results

We find differences across the globe for the three different definitions of local moisture recycling (r_1, r_9 and r_{25}) (Fig. 1). For r_1, we find maxima over the oceans in areas where precipitation is relatively low, unlike evaporation (Fig. A3), which results in relatively high recycling ratios (Fig. 1). However, for r_9 and r_{25} we find maxima over land suggesting recycling over nine and 25 grid cells better captures relatively large moisture transport over the oceans than recycling over one grid cell does. Furthermore, for r_1, we find low values over elevated areas (e.g., the Andes mountains) compared to r_9 and r_{25}, which show maxima over elevated regions. Hence, there is no clear relation between r_1 and either r_9 or r_{25}. These results seem to indicate that the tracking method we use is not sufficient to define recycling within one grid cell. Finally, scaling recycling to the number of grid cells, we find r_9 and r_{25} do not relate linearly. For lower recycling, r_9 exceeds r_{25} and for higher recycling, r_{25} exceeds r_9 (Fig. 1 and Fig. A4). In the following, we define local moisture recycling (LMR) as r_9 to keep the spatial scale as small as possible but to still have a spatial pattern that we can explain physically.

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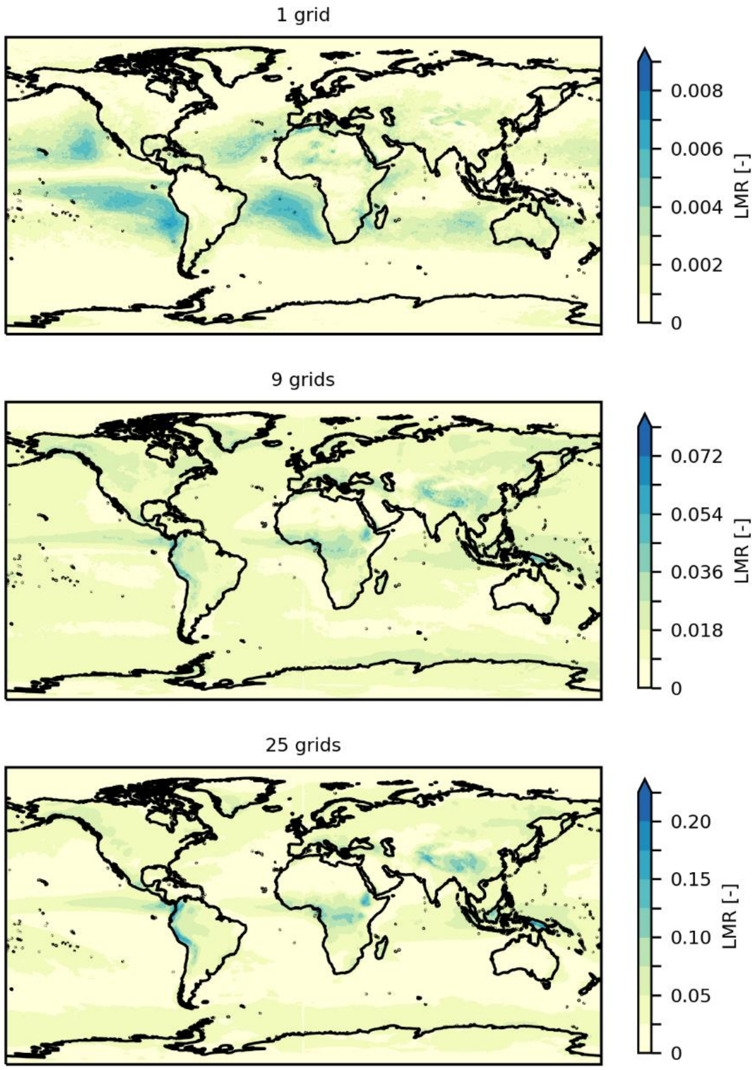

Figure 1. Multi-year (2008–2017) average of three definitions of the local moisture recycling ratio (LMR). The top panel indicates the fraction of evaporated moisture that rains out within its source grid cell (r_1), the middle panel shows the fraction of evaporated moisture that rains out within its source grid cell and its 8 neighbouring grid cells (r_9), and the lower panel shows the fraction of evaporated moisture that rains out within its source grid cell and its 24 neighbouring grid cells (r_{25}).

Annually, on average about 1.6% of terrestrial evaporated moisture recycles locally. LMR shows spatio-temporal variation (Fig. 2) with peaks over elevated (e.g., the Atlas Mountains and Ethiopian Highlands) and wet areas (e.g., Congo Basin and Southeast Asia) and minima over arid regions (e.g., Australia and the Sahara Desert). Additionally, we find peaks in LMR during summer (i.e., during DJF for the Southern Hemisphere and during JJA for the Northern Hemisphere). This seasonality is especially strong over mountainous and wet areas. For the mid-latitudes, especially the Mediterranean Basin shows

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seasonality with peaks in summer (JJA). Seasonality is largest at low latitudes. Within the tropics we find some spatial differences. First, LMR in the Congo Basin and Southeast Asia exceed LMR in the Amazon Basin. Second, recycling in the Congo Basin and Southeast Asia peaks in JJA and recycling in the Amazon Basin peaks in DJF, which is a wet season for a large part of the Amazon.

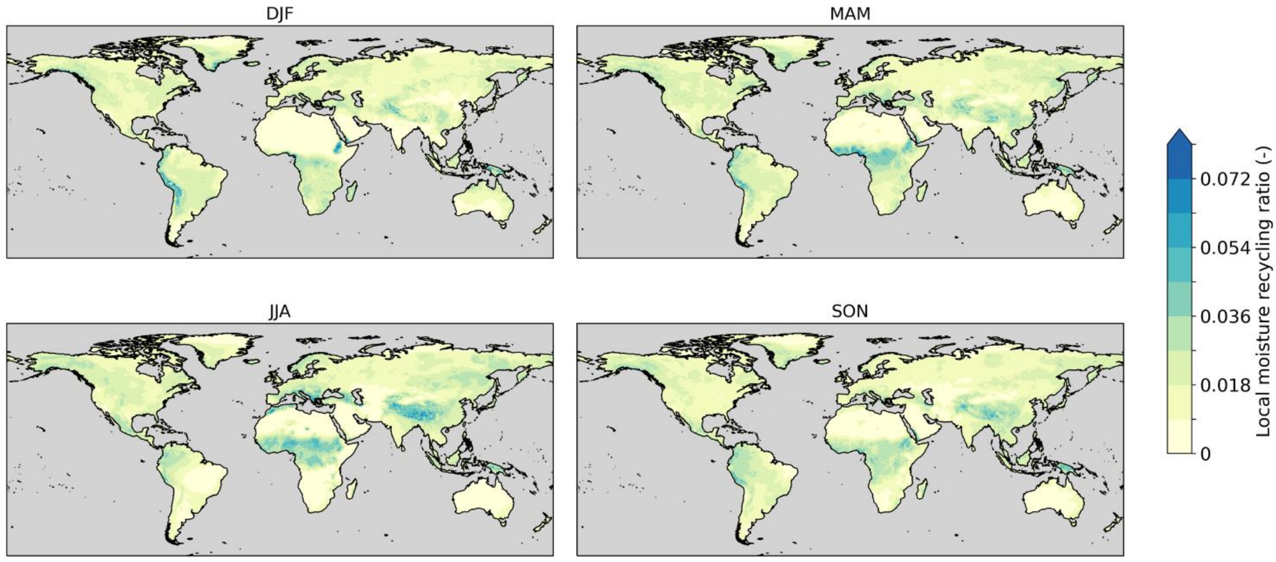

Figure 2. Multi-year (2008–2017), seasonal averages of local moisture recycling across the global land surface. Here, local moisture recycling is defined as the fraction of evaporated moisture that rains out in its source grid cell and its eight neighbouring grid cells (r9). Different seasons are DJF: December–February, MAM: March–May, JJA: June–August, and SON: September–November.

We find a statistically significant ($p < 0.01$) rank correlation between LMR and orography (weak), precipitation (*tP*, *cp*, *lsp*), evaporation, *E-P*, some latitude ranges, and *CAPE* (weak) (Table 1). All other tested variables show no clear rank correlation with LMR (Table 1). The correlation coefficient for orography indicates a weak correlation. However, for high elevation LMR is always relatively high (Fig. 2 and Fig. A5). Both convective and large-scale precipitation correlate with LMR (Table 1), however neither the fraction of convective precipitation nor the fraction of large-scale precipitation correlates with LMR (Table 1). Furthermore, evaporation correlates positively with LMR (Table 1, Fig. 3) indicating that the strong relation between *P* and LMR is not the only factor that causes a correlation between wetness and LMR. Surprisingly, the atmospheric moisture flux does not correlate with LMR (Table 1 and Fig. A5). The relation between latitude and LMR oscillates. The highest peak occurs over the equator and there is a peak around 60° north and valleys around 30° north and south (Fig. 3). Orography seems to disrupt the relation between latitude and LMR, resulting in peaks in LMR around 35° north and 20° south. Finally, the energy driving convection, e.g., convective available potential energy, weakly correlates to LMR. However, high CAPE clearly relates to LMR, as the skewed profile in the scatter density plot indicates that only a small amount of the grid cells with a relatively high CAPE have a low LMR (Fig. 3).

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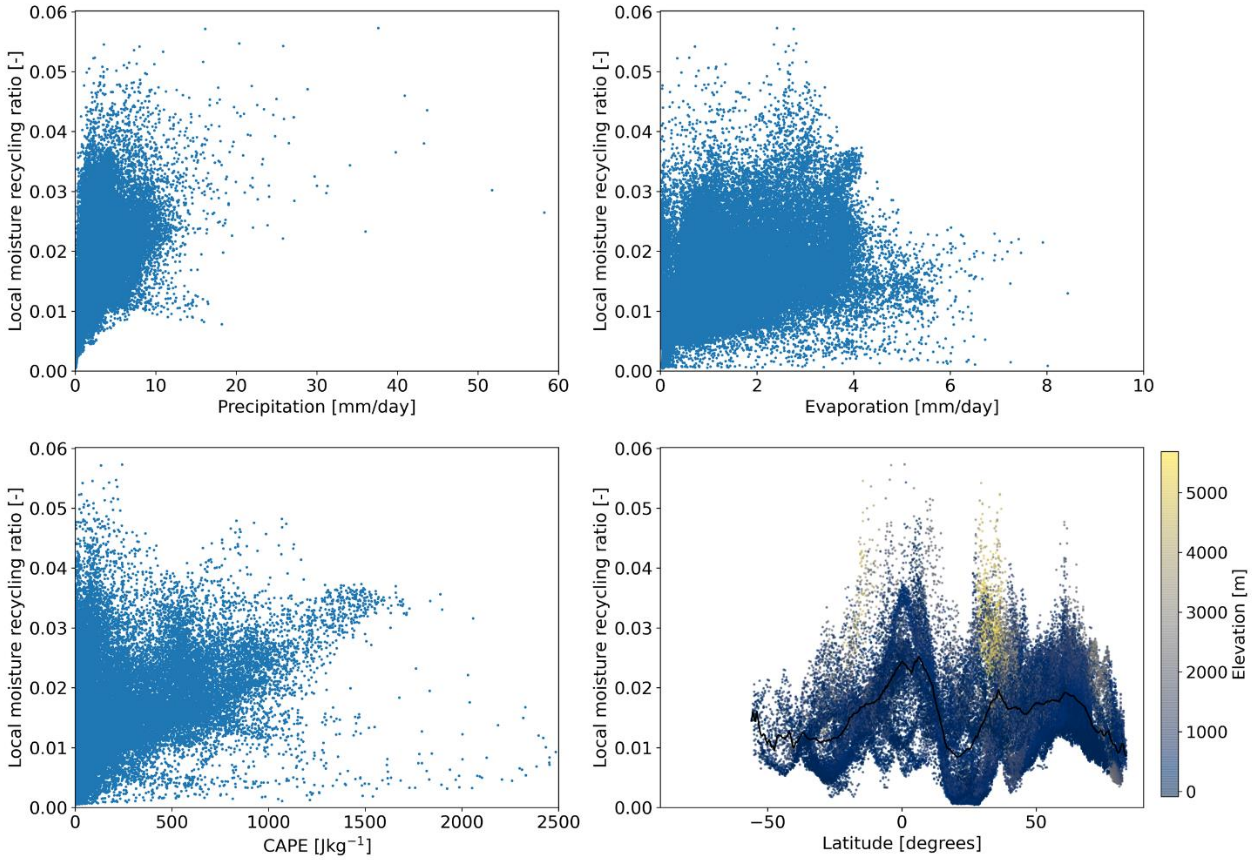

125 **Figure 3: Scatter plots of multi-year (2008–2017) annual averages of local moisture recycling over land and precipitation (top left), evaporation (top right), convective available potential energy (CAPE) (bottom left), and latitude (bottom right). For the latter the colour scale indicates elevation, with blue being low elevation and yellow being high elevation, and a black line is plotted to show the zonal average of local moisture recycling over land at 0.5° resolution. Each scatter represents one grid cell.**

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Table 1. Spearman rank correlation coefficients between LMR and all tested variables. All coefficients are significant (p<0.01).

Variable	Correlation coefficient
Precipitation	0.63
Evaporation	0.38
Wetness (P-E)	0.57
Convective precipitation	0.51
Fraction of convective precipitation	-0.07
Large scale precipitation	0.55
Fraction of large scale precipitation	0.07
Latitude	0.04
-60°:-30°	-0.12
-30°:0°	0.53
0°:30°	-0.49
30°:60°	0.09
60°:90°	-0.55
Eastward moisture flux	-0.12
Northward moisture flux	0.20
Total moisture flux	0.07
CAPE	0.28
Zonal shear	-0.12
Meridional shear	-0.02
Orography	0.30

4 Discussion

Moisture recycling affects humanity by influencing water security, agriculture, forestry, regional climate stability and earth system resilience (Keys et al., 2019; Wang-Erlandsson et al., 2022). Different types of moisture recycling were subject to research used for different applications (e.g., Bagley et al., 2012; Pranindita et al., 2022; Van der Ent et al., 2010), but for the first time, we analysed local moisture recycling ratio (LMR) and its drivers across the globe. We find that LMR, defined as the fraction of evaporated moisture that rains out within approximately 50 km of its source location, varies over time and space, peaking in summer and over elevated and wet regions. First, we identified latitude, elevation, and Convective Available Potential Energy (CAPE) as important drivers of LMR (Fig. 4). These variables all promote convection (Roe, 2005; Scheff &

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Frierson, 2012; Wallace & Hobbs, 2006), strongly suggesting a dependence of LMR on convection. The pattern of LMR across latitudes also coincides with updraft and downdraft of air caused by the Hadley cell circulation (Wallace & Hobbs, 2006). Around the equator and 60° north and south, air ascends, and we find a high LMR. Additionally, air descends around 30° north and south, where we find low LMR. Deviations from this pattern correspond to higher elevations promoting LMR through orographic lift. Overall, our results suggest a positive relation between convection and LMR.

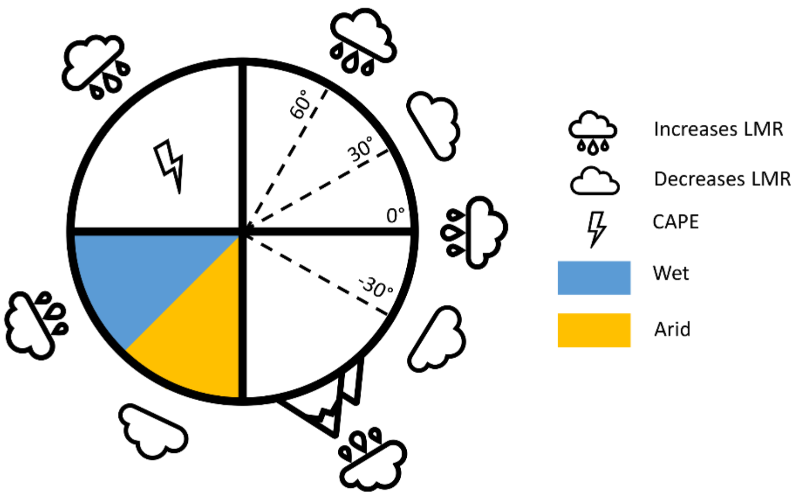

Figure 4. Conceptual model of the most important drivers of local moisture recycling around the globe. Rainy clouds indicate variables that increase LMR and clouds without raindrops indicate variables that decrease LMR. Blue indicates wet regions, yellow indicates arid regions.

Second, we find that wetness is an important driver of LMR as LMR significantly correlates with precipitation (*P*) and *P-E* (precipitation minus evaporation). Furthermore, both large-scale and convective precipitation significantly correlate with LMR. This is surprising, as convection promotes precipitation locally; therefore, we expected a stronger correlation between LMR and convective precipitation than between LMR and large-scale precipitation. This suggests that the type of precipitation does not affect LMR. Although convection is a local-scale process (i.e., spatial scale of 100 km) (Miyamoto et al., 2013), remotely evaporated moisture can be transported to a region with high convective activity and then rains out as convective precipitation. In that way, the precipitation type is independent of the distance between moisture source and target location and therefore does not relate to LMR. However, unexpectedly we do not identify a relation between the vertical integral of the atmospheric moisture flux and LMR. Overall, we find that wetness enhances LMR independent of the precipitation type.

To zoom in on the importance of each of the different drivers of LMR for various areas across the globe, we determined LMR for the major global biomes (Fig. A6). LMR is highest for the wet tropics and montane grassland and lowest for desert-like biomes in both the Northern and Southern Hemisphere, confirming the importance of wetness, orography, and latitude. However, differences between both hemispheres indicate some drivers are more robust than other ones for some biomes. In the Mediterranean biomes, located between 30–40° north and south, air descends due to the Hadley cell circulation. As a result, these biomes are expected to have low LMR. Although we find a low LMR for the Mediterranean biomes in the Southern Hemisphere, we find a relatively high LMR for the Mediterranean biomes in the Northern Hemisphere. This is a surprising result, which does not overlap with the different Mediterranean climate subclasses (i.e., hot-summer Mediterranean climate and warm-summer Mediterranean climate)(Peel et al., 2007). More research is needed to understand this difference better.

Although LMR is the highest in the wet tropics, we find different results among the various tropical regions (Amazon Basin, Congo Basin & Southeast Asia). LMR in the Congo Basin exceeds LMR in the Amazon Basin (Fig. 2), despite larger amounts of rainfall in the Amazon Basin (Hersbach et al., 2020). In the tropics, current deforestation results in drying (Bagley et al., 2014; Staal et al., 2020), reducing evaporation. For the Amazon Basin, drought is related to higher deforestation rates (Staal et al., 2020). As LMR in the Congo Basin exceeds LMR in the Amazon Basin, deforestation has a relatively large impact on local precipitation in the Congo Basin, suggesting a higher impact on droughts and deforestation locally. The latter is true when assuming drought also enhances deforestation in the Congo Basin. Unlike LMR, basin recycling is similar for both basins (Tuinenburg et al., 2020). Thus, the impact of deforestation on precipitation in the entire basin is similar for both basins, indicating both basins would experience similar overall drying. However, drought conditions can also enhance recycling ratios (Bagley et al., 2014), thus promoting LMR. Further research is necessary to understand the impact of deforestation on LMR in the tropics.

Besides atmospheric moisture tracking (e.g., Bagley et al., 2014; Keys et al., 2014;Van der Ent et al., 2010), previous studies used different methods to calculate regional moisture recycling for a specific area, such as isotope measurements (e.g., An et al., 2017) and recycling models (e.g., Burde & Zangvil, 2001). The most common recycling models are modifications of Budyko's model (Budyko, 1974; G. I. Burde & Zangvil, 2001), which are 1D or 2D analytical models. These models assume that the atmosphere is completely mixed, meaning that evaporated water directly mixes perfectly with advected water throughout the entire water column. Because of this assumption, first, these models overlook fast recycling, which describes local showers that yield rain before the evaporated water is fully mixed. Second, these models ignore the influence of vertical shear, which causes a significant error (Dominguez et al., 2020). Excluding fast recycling causes models to underestimate terrestrial moisture recycling for some regions (e.g., Amazon Basin) (Burde et al., 2006b). To obtain LMR, evaporated moisture is tracked through the atmosphere with a Lagrangian model in three spatial dimensions. Our method minimizes the errors due to fast recycling and vertical shear because of two model aspects. First, at each time step, each parcel has a small chance of getting mixed, causing each parcel to move approximately once in the vertical direction every 24 hours, besides the displacement caused by vertical wind. As parcels are released from the surface, this process minimizes complete mixing and reduces the error due to shear and fast recycling. Second, the error due to fast recycling also becomes smaller because lower atmospheric levels contribute more to the total precipitation than higher levels due to the skewed vertical moisture profile. Despite the error reduction, the representation of fast recycling in UTrack should be studied in more detail, as fast recycling is expected to influence LMR significantly.

Regardless of the importance of vertical shear in atmospheric moisture tracking models (Van der Ent et al., 2013) we do not find a clear correlation between local moisture recycling and vertical shear between 750 and 650 hPa. Shear is the friction between air layers that minimizes complete mixing, which for some regions around the world, is strongest between 650 and 750 hPa (Dominguez et al., 2016). A possible explanation is that due to its small spatial scale the temporal scale of LMR is also small, which causes the air not to reach 700 hPa within the spatial scale of LMR. Furthermore, it is possible that our study design is insufficient to capture the relation between LMR and shear throughout the year over the globe. We aim for a general analysis to identify the main drivers of LMR. A more detailed study that distinguishes seasons and different climate zones is necessary to identify more drivers.

The spatial patterns of LMR, obtained in our study, resemble the spatial patterns of the regional recycling ratio (LMR is smaller than regional recycling) obtained by Van der Ent & Savenije (2011), who estimated average regional recycling ratios within a 1.5° grid cells globally between 1999 and 2008, using a Eulerian moisture tracking model. Due to different model set-up and grid cell sizes, differences in the magnitude of recycling are expected; hence, here we only look at the qualitative patterns. The spatial pattern of LMR shows some overlap with global agricultural water management (Salmon et al., 2015). Generally, the tropics have a high LMR and mainly rainfed agriculture (Salmon et al., 2015), indicating these agricultural regions are self-dependent concerning rainfall to some extent. Also, agriculture in the Mediterranean Basin and South Australia is mainly rainfed. For semi-arid regions dependent on rainfed agriculture, changes in precipitation might have a significant impact (Keys et al., 2016). LMR in the Mediterranean basin exceeds LMR in Southern Australia, indicating that a larger fraction of evaporated moisture returns locally. Thus, when evaporation is maintained in the Mediterranean Basin, part of the precipitation will sustain here, which holds to a lesser extent for Southern Australia. Besides LMR (i.e., local evaporation recycling), local precipitation recycling can help to fully understand the precipitation dependence on local evaporation for each region. Irrigated agriculture is important in India and China (Salmon et al., 2015), which are regions with a relatively low LMR, indicating that only a small amount of the evaporated moisture returns as rainfall locally. For irrigated agriculture in regions that are characterized by a high LMR, a relatively large amount of the evaporated water returns to its source, which reduces the amount of water that is necessary for irrigation. Terrestrial evaporation is an important source for precipitation and freshwater availability (Keune & Miralles, 2019). Therefore, spatial planning using LMR might improve agricultural water management.

Global climate change likely affects atmospheric moisture connections due to changes in atmospheric dynamics. For example, due to global warming, tropical atmospheric circulation may weaken (Vecchi et al., 2006), and the Hadley cells may move poleward (Shaw, 2019), which will affect the updraft and downdraft of air around the globe, which we found to be an important driver of LMR. Furthermore, climate change has different opposing impacts on storm tracks which have an important role in moisture transport by transporting latent heat poleward (Shaw et al., 2016). However, our study does not account for any

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impacts of climate change. As our results indicate that wetness and convection enhance LMR, LMR will likely change due to, for example, drying and wetting of regions, changes in Hadley cell circulation, and circulation in the tropics.

Furthermore, climate change enhances the risk of droughts (Rasmijn et al., 2018; Teuling, 2018) and LMR might be used to study drought resilience globally. Drought can result in arid-like conditions, which may lead to a decrease in LMR (Fig. 4). High LMR means that the local water cycle is relatively strong; therefore, a drought in a remote location is expected to have a small impact locally. However, a local drought might drastically impact the local water cycle.

We expect that the novel concept of LMR can be helpful in various ways, but specifically it can be used to study how changes in evaporation because of for example afforestation, affect the local water cycle beyond merely a loss of moisture. Thus, LMR can help us better predict the impact of land cover changes on the local water cycle. It might help us identify regions where reforestation does not cause local drying due to enhanced evaporation (Dijke et al., 2022; Tuinenburg et al., 2022). Overall, LMR gives us better insight into the atmospheric part of the local water cycle and can be used to contemplate terrestrial evaporation as a source for local freshwater availability.

5 Conclusions

We calculated the local moisture recycling ratio (LMR) from atmospheric moisture connections at a spatial scale of 0.5°. LMR is the fraction of evaporated moisture that rains out within approximately 50 km of its source location. On average, 1.6% of global terrestrial evaporation returns as rainfall locally, with peaks of approximately 6%. LMR peaks in summer and in wet and elevated regions. We identify orography, precipitation, wetness, latitude, and convective available potential energy as main drivers of LMR. LMR determines the local impacts of enhanced evaporation on precipitation and thus its role as a source for local freshwater availability. Therefore, LMR can be used to evaluate which locations may be suitable for regreening without largely disrupting the local water cycle.

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Appendix A

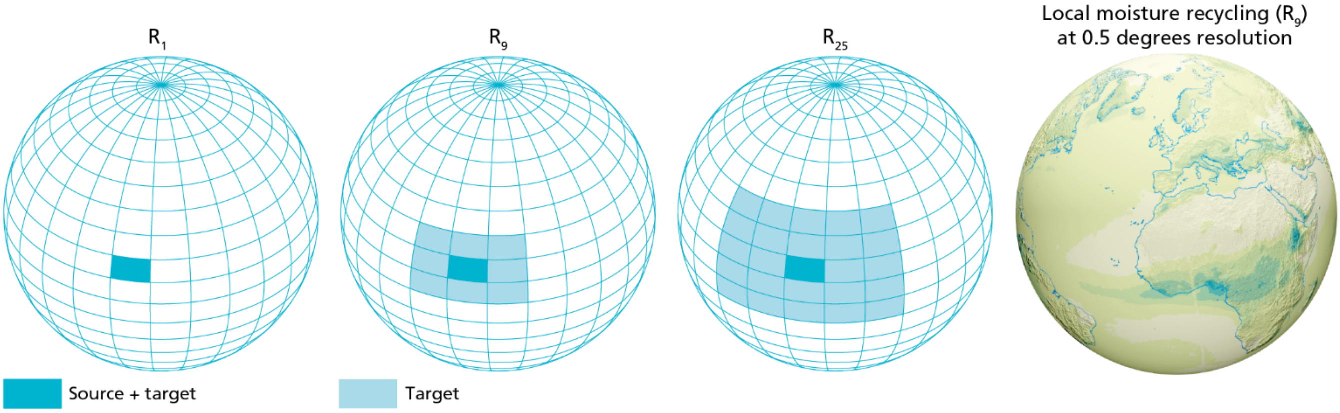

Figure A1. Three definitions of the local moisture recycling ratio (LMR) from left to right: r_1 describes the fraction of evaporated moisture that returns as precipitation in its source grid cell, r_9 describes the fraction of evaporated moisture that returns as precipitation in its source grid cell and 8 neighbouring grid cells, and r_{25} describes the fraction of evaporated moisture that returns as precipitation in its source grid cell and 24 neighbouring grid cells. LMR is calculated on a spatial scale of 0.5° and the first three plots do not have a similar resolution. The plot on the right shows LMR on a spatial scale of 0.5° which is the resolution at which we calculate all definitions (r_1, r_9 and r_{25}).

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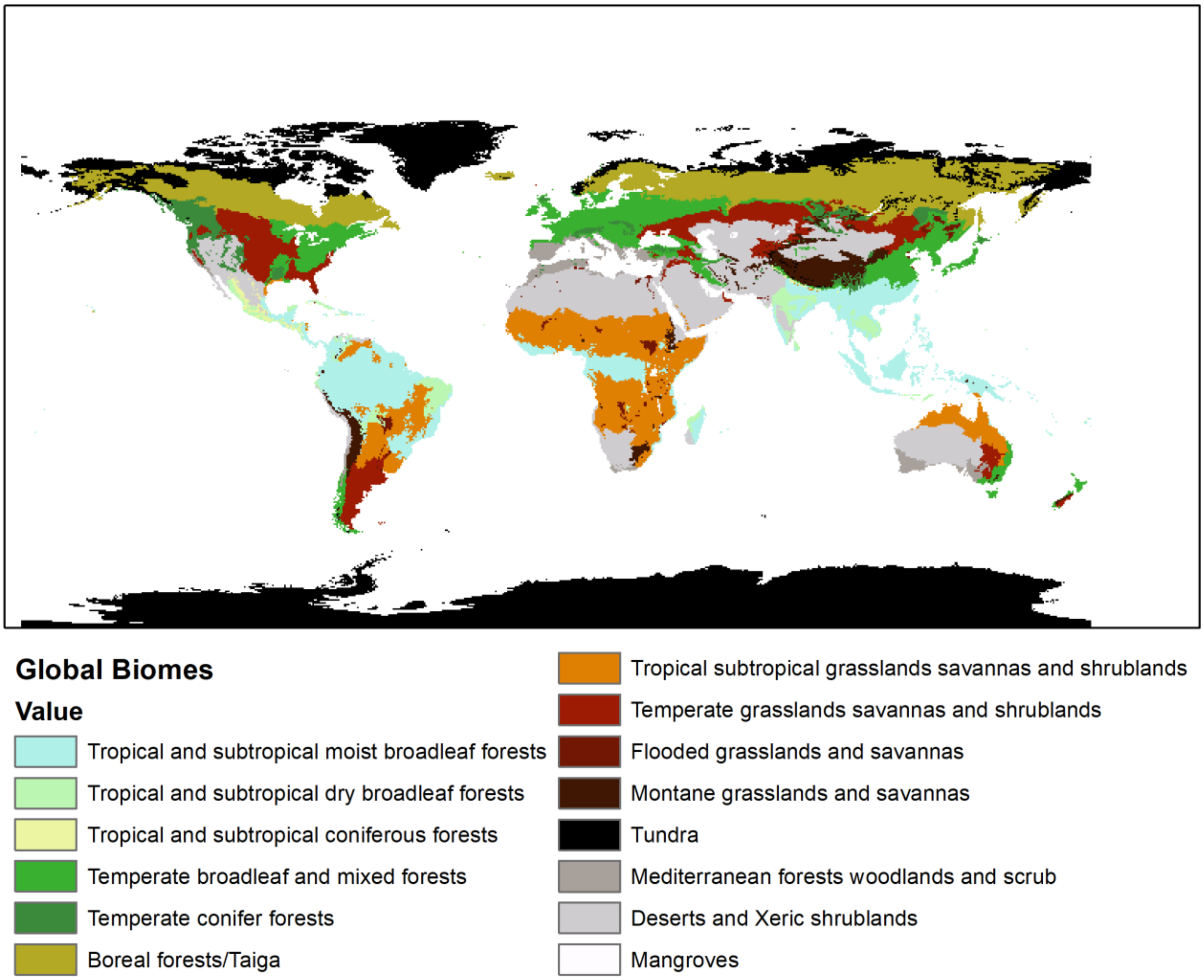

Figure A2. Major global biomes Ecoregions 2017 (https://ecoregions.appspot.com/).

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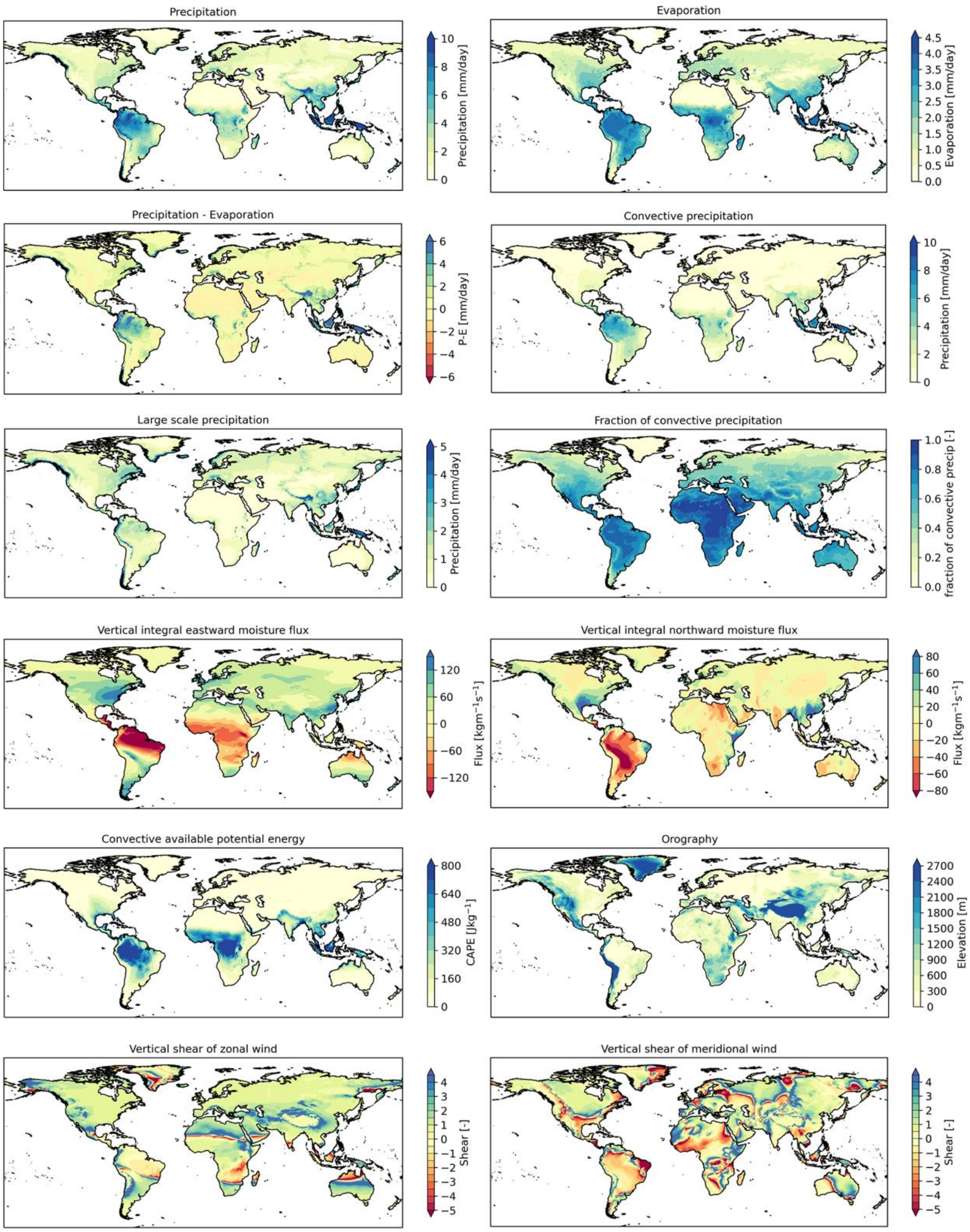

260 **Figure A3. Global multi-year (2008–2017) averaged maps of (from top to bottom and left to right) precipitation, evaporation, precipitation – evaporation, convective precipitation, large-scale precipitation, fraction of convective precipitation, vertical integral of moisture flux in eastward direction, vertical integral of moisture flux in northward direction, CAPE, orography, vertical shear (between 650 and 750 hPa) of zonal wind, and vertical shear (between 650 and 750 hPa) of meridional wind.**

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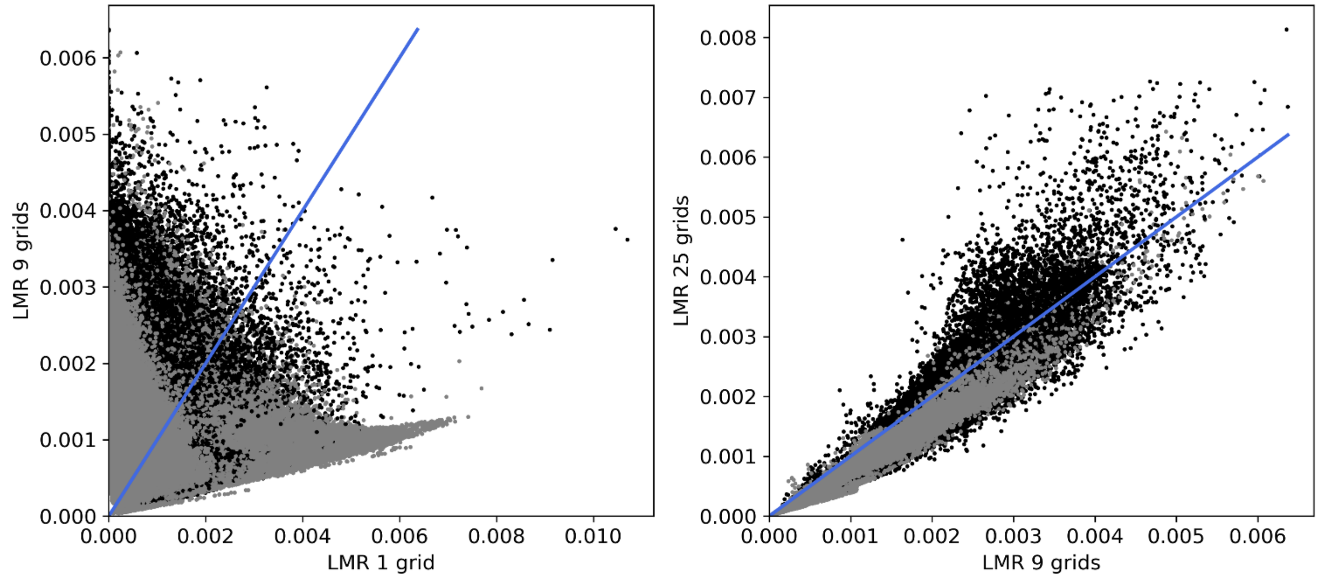

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Figure A4. Comparison of three definitions of the local moisture recycling ratio (LMR) that are each scaled to its number of grid cells. Left r_1 vs r_9 and right r_9 vs r_{25}. Gray and black scatters indicate grid cells over the ocean and land respectively. The blue line indicates x=y.

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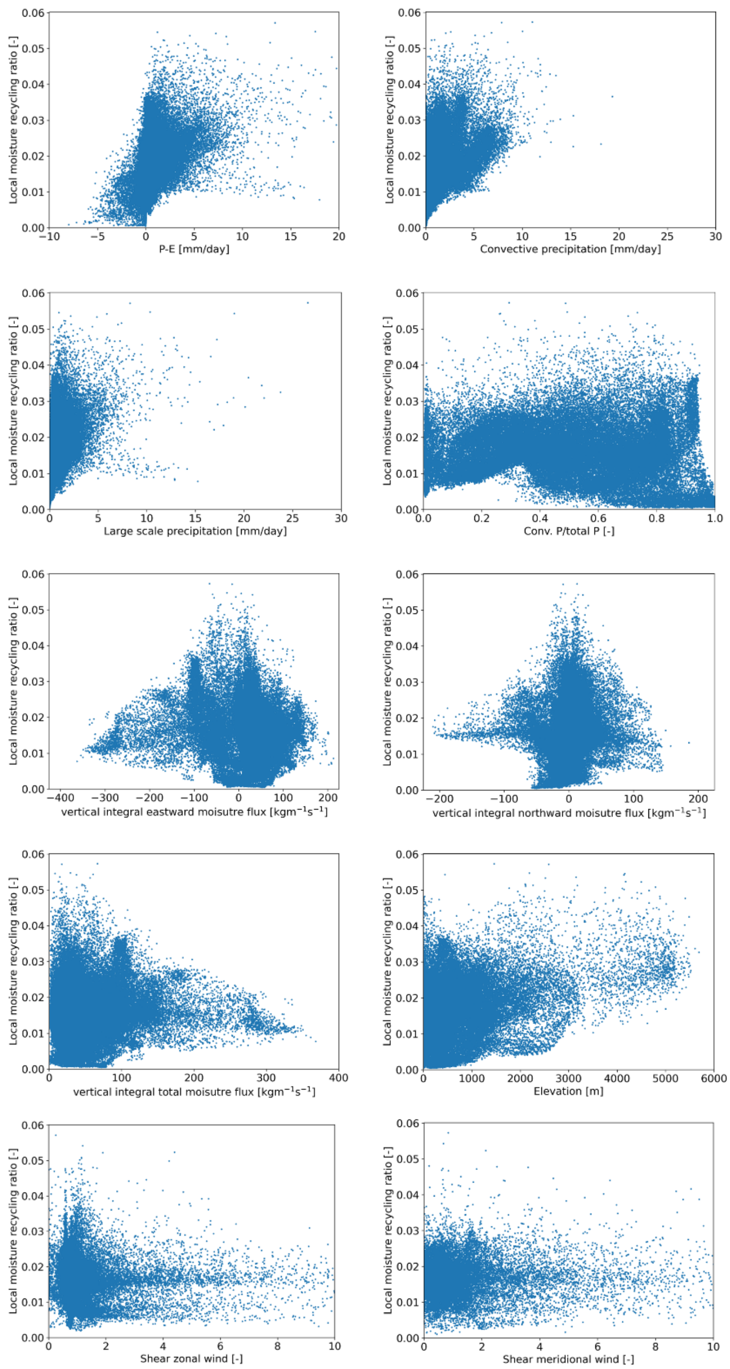

Figure A5. Scatter plots of the multi-year (2008–2017) averaged terrestrial local moisture recycling ratio and (from top to bottom and left to right) precipitation – evaporation, convective precipitation, large-scale precipitation, fraction of convective precipitation, vertical integral of moisture flux in eastward direction, vertical integral of moisture flux in northward direction, orography, vertical shear (between 650 and 750 hPa) of zonal wind, and vertical shear (between 650 and 750 hPa) of meridional wind. Each scatter represents one grid cell.

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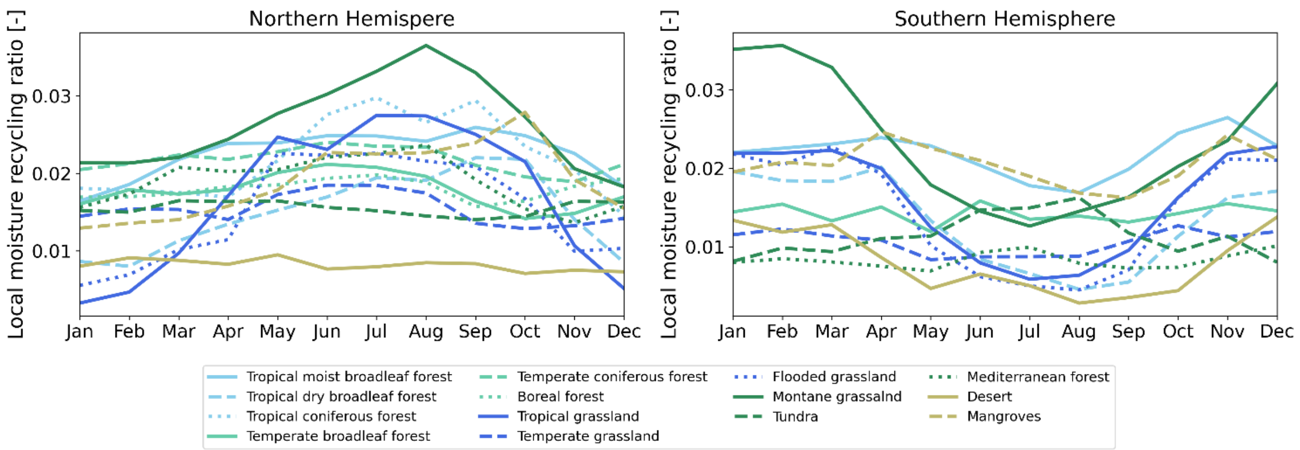

Figure A6. Time series of the local moisture recycling ratio for global biomes on the Northern (left) and Southern (right) Hemispheres. The values are multi-year (2008–2017) averages.

Code availability

The code that was used to calculate the local moisture recycling ratio and for the analyses is available from the corresponding author upon reasonable request.

Data availability

The atmospheric moisture connections (Tuinenburg et al., 2020) are available from the PANGAEA archive at 0.5 and 1.0 degrees resolution (https://doi.pangaea.de/10.1594/PANGAEA.912710).

Author contributions

JT designed the study with contributions from all authors. JT carried out the research. JT wrote the first draft of the manuscript in close collaboration with AS. All authors contributed to the discussion and the final version of the manuscript.

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