# Origin and fate of atmospheric moisture over continents

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[1]   There has been a long debate on the extent to which precipitation relies on terrestrial evaporation (moisture recycling). In the past, most research focused on moisture recycling within a certain region only. This study makes use of new definitions of moisture recycling to study the complete process of continental moisture feedback. Global maps are presented identifying regions that rely heavily on recycled moisture as well as those that are supplying the moisture. An accounting procedure based on ERA-Interim reanalysis data is used to calculate moisture recycling ratios. It is computed that, on average, 40% of the terrestrial precipitation originates from land evaporation and that 57% of all terrestrial evaporation returns as precipitation over land. Moisture evaporating from the Eurasian continent is responsible for 80% of China's water resources. In South America, the Río de la Plata basin depends on evaporation from the Amazon forest for 70% of its water resources. The main source of rainfall in the Congo basin is moisture evaporated over East Africa, particularly the Great Lakes region. The Congo basin in its turn is a major source of moisture for rainfall in the Sahel. Furthermore, it is demonstrated that due to the local orography, local moisture recycling is a key process near the Andes and the Tibetan Plateau. Overall, this paper demonstrates the important role of global wind patterns, topography and land cover in continental moisture recycling patterns and the distribution of global water resources.

## 1. Introduction

[2]   Land-atmosphere interactions can play a crucial role in the global climate [*Seneviratne et al.*, 2006]. One expression of these interactions is moisture recycling through continental evaporation. Humans may modify terrestrial moisture fluxes through land-use change and water management. In general, evaporation is enhanced by reducing runoff (e.g., by constructing dams and reservoirs) or by leading runoff back onto the land (e.g., by irrigating on previously bare soil). Conversely, evaporation is reduced by enhancing drainage (e.g., by cutting forest or overgrazing). Quantifying terrestrial evaporation that sustains precipitation over land is thus key to understanding human impacts on climate. The magnitude of moisture recycling can be used as an indicator for the sensitivity of climate to land-use changes [see, e.g., *Brubaker et al.*, 1993; *Eltahir and Bras*, 1996; *Kunstmann and Jung*, 2007; *Lettau et al.*, 1979; *Savenije*, 1995a].

[3]   Views on the contribution of terrestrial evaporation to terrestrial precipitation have changed over time. Early studies on moisture recycling (in the late 19th century) focused on the continental landmass of North America, claiming that land cultivation resulted in more evaporation,

higher atmospheric moisture levels and hence more rainfall [*Eltahir and Bras*, 1996, and references therein]. It is the basis of legends such as "the rain follows the plough" [*Dirmeyer and Brubaker*, 2007, and references therein]. The idea that the contribution of terrestrial evaporation to precipitation in the same region is significant was widely accepted until the late 1930s [*Benton et al.*, 1950]. This view later changed dramatically and different estimates were presented claiming that the contribution of evaporation from a land region to precipitation in the same region is not very significant [*Benton et al.*, 1950; *Budyko*, 1974; *McDonald*, 1962].

[4]   In the 1990s different analytical models and formulas for estimating precipitation recycling were developed, each with their own (sometimes conflicting) assumptions. *Brubaker et al.* [1993] and *Eltahir and Bras* [1994] developed models to estimate precipitation recycling for a two-dimensional region and both studies concluded that recycling is not negligible but certainly not dominant. One of the major assumptions underlying these formulas is that of parallel flow along the study region and a linear decrease of atmospheric moisture. *Savenije* [1995a] developed another model which assumed that the atmospheric moisture decreases exponentially following a pathway along the isohyets going inland. However, this model only allowed moisture to leave the study region by runoff and not through the atmosphere. This lead to an overestimation of the recycling and the conclusion that further inland the recycling process becomes dominant. *Schär et al.* [1999] developed a model based on the integrated moisture budget

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of a region which has the advantage that the resulting formula can easily be applied on climate or weather model output, but the estimate is rough since it ignores the character of moisture distribution within the region [*Burde and Zangvil*, 2001a].

[5] The applications of different formulas can lead to completely different results and conclusions on the significance of moisture recycling. *Mohamed et al.* [2005] show that the formula of *Schär et al.* [1999] gives higher precipitation recycling ratios than the formula of *Brubaker et al.* [1993], and *Savenije*'s [1995a] formula higher ratios yet. One has to keep in mind, however, that all these formulas where derived for different regions and under different assumptions. One could for example argue that the studies of *Trenberth* [1999] and *Szeto* [2002] should have used the formula of *Schär et al.* [1999] instead of the formula of *Brubaker et al.* [1993] and *Eltahir and Bras* [1994], respectively.

[6] Recent studies pointed out that the commonly used formulas [*Brubaker et al.*, 1993; *Eltahir and Bras*, 1994] may underestimate precipitation recycling in general, because of the assumptions made in the modeling approach. These studies also developed methods to relax the modeling assumptions, generally leading to a more significant role for moisture recycling [see e.g., *Burde and Zangvil*, 2001a, 2001b; *Burde*, 2006; *Burde et al.*, 2006; *Dominguez et al.*, 2006; *Fitzmaurice*, 2007]. Many recent studies, using more powerful techniques than the rough bulk estimations, indicate that terrestrial evaporation makes a significant contribution to precipitation over land surfaces [*Bosilovich and Chern*, 2006; *Dirmeyer et al.*, 2009a; *Liu et al.*, 2008; *Stohl and James*, 2005]. Models that assumed a closed system indicated this to be even more dominant, but overestimated evaporation-precipitation feedback [e.g., *Molion*, 1975; *Savenije*, 1995a, 1995b, 1996].

[7] The lack of consensus on the importance of moisture recycling is not only due to the use of different methods and assumptions, but also to the use of different definitions. To date, most research has focused only on the question of whether precipitation recycles within a certain area of interest, such as a river basin [e.g., *Eltahir and Bras*, 1994; *Kunstmann and Jung*, 2007; *Lettau et al.*, 1979; *Mohamed et al.*, 2005; *Serreze and Etringer*, 2003; *Szeto*, 2002], grid cells of a certain dimension [e.g., *Dirmeyer and Brubaker*, 2007; *Dominguez et al.*, 2006; *Trenberth*, 1999] or other large regions [e.g., *Bisselink and Dolman*, 2008, 2009; *Brubaker et al.*, 1993; *Schär et al.*, 1999]. Hence, these localized studies looked at the degree to which local evaporation triggers precipitation within the same area of interest, but say little about the terrestrial or oceanic origin of precipitation.

[8] On the other hand, several studies did make a clear distinction between terrestrial and oceanic sources [*Savenije*, 1995a, 1995b, 1996], or identified the contribution of different terrestrial and oceanic source regions to precipitation in a certain region of study [*Bosilovich et al.*, 2002; *Bosilovich and Chern*, 2006; *Dominguez et al.*, 2009; *Koster et al.*, 1986; *Nieto et al.*, 2006; *Numaguti*, 1999; *Stohl and James*, 2005; *Yoshimura et al.*, 2004]. Some of these studies indicated that a substantial part of the precipitation on the northeast North America, the west of South America, central Africa and large parts of Siberia, Mongolia and China consisted of moisture of terrestrial origin.

[9] In this paper we seek to provide global maps indicating both the areas where moisture recycling sustains rainfall and, using a new concept, also the source areas on which they rely. As such, these maps generate new insights into the importance of and origin of continental moisture feedback. Our research permits a quantified first order estimate of the impact that land-use change may have on global rainfall and water resources. Such knowledge is particularly relevant to better understand global scale implications of regional land-use changes related to socioeconomic developments (e.g., currently ongoing deforestation for energy crops).

[10] The outline of the paper is as follows. Section 2 explains the methods used in this study. It describes the (new) definitions used in this paper. It presents the input data used and provides a schematization of the accounting model. Also, the assumptions and limitations of our method are discussed. Section 3 presents the results of the study. It shows why scale-dependent regional recycling ratios are not sufficient to show the full moisture recycling processes. On a global map, the annual average continental sources and sinks for precipitation are identified. And also, the typical winter and summer moisture cycling is discussed. Section 4 concludes with a discussion of where and to which extent moisture recycling plays a role in sustaining precipitation. The implications of the results for water resources management are discussed. Finally, an outlook on further research is given.

## 2. Methods

### 2.1. Definitions

[11] To bring clarity in the discussion on whether continental precipitation and evaporation feedback is important in a certain region, we distinguish different types of moisture recycling. The process that is most commonly referred to in the literature as moisture or precipitation recycling is here termed as regional precipitation recycling. It is the part of the precipitation falling in a region which originates from evaporation within that same region. The precipitation is considered to consist of two components:

$$P(t,x,y|A,\Delta) = P_r(t,x,y|A,\Delta) + P_a(t,x,y|A,\Delta) \qquad (1)$$

where $P_r$ is regionally recycled precipitation and $P_a$ is precipitation which originates from moisture that was brought into the region by advection. The regionally recycled precipitation depends on time $t$ and location of the region $(x, y)$, given an area size $A$ and shape $\Delta$. Hence, the regional precipitation recycling ratio is defined as

$$\rho_r(t,x,y|A,\Delta) = \frac{P_r(t,x,y|A,\Delta)}{P(t,x,y|A,\Delta)} \qquad (2)$$

This ratio describes the region's dependence on evaporation from within the region to sustain precipitation in that same region. In addition, we define the reverse process: how much of the evaporated water returns as precipitation in the same region (the regional evaporation recycling). Hence, the total evaporation in a region is described by

$$E(t,x,y|A,\Delta) = E_r(t,x,y|A,\Delta) + E_a(t,x,y|A,\Delta) \qquad (3)$$

where $E_r$ is the part of the evaporation from the region which returns as precipitation to the same region, and $E_a$ is

evaporated water that is advected out of the region. Averaged over a year $E_r$ equals $P_r$ (assuming no substantial change in atmospheric moisture storage over a year):

$$E_r(year, x, y | A, \Delta) = P_r(year, x, y | A, \Delta) \quad (4)$$

Similar to the regional precipitation recycling ratio, the regional evaporation recycling ratio depends on the shape $\Delta$ and size $A$ of the region and is thus scale-dependent. It is defined as

$$\varepsilon_r(t, x, y | A, \Delta) = \frac{E_r(t, x, y | A, \Delta)}{E(t, x, y | A, \Delta)} \quad (5)$$

Comparing regional recycling ratios from various studies or areas has proven to be difficult because of its scale-dependency. Various attempts were made to approximate the relation between region size and regional precipitation recycling ratio by either a power function [*Dirmeyer and Brubaker*, 2007; *Eltahir and Bras*, 1996] or a logarithmic function [*Bisselink and Dolman*, 2008; *Dominguez et al.*, 2006]. These approximations may be justifiable for a certain range of area sizes with the same shape; however, the overall validity of this approach is limited by the very nature of the regional precipitation recycling ratio which requires it to vary between zero and one, whereas these functions have no upper limit.

[12] Moreover, regional recycling ratios depend not only on a region's size but also on its shape. Imagine the case where a study region would be reduced to a long east-west oriented strip of only a few kilometers in width. In this case, even the slightest meridional moisture flux would result in calculated regional recycling ratios close to zero [see also *Bisselink and Dolman*, 2009] and the discussion linked to this paper. Consequently, regional recycling ratios alone are inadequate to assess the importance of continental moisture feedback.

[13] It is also possible to use local moisture recycling ratios which indicate the moisture recycling at a certain point $(x, y)$ embedded in a larger mother region $(x, y, A, \Delta)$ [*Bisselink and Dolman*, 2008, 2009; *Burde et al.*, 2006; *Dominguez and Kumar*, 2008; *Fitzmaurice*, 2007]. Although the regional and the local moisture recycling ratios may be of interest for certain political or hydrological boundaries, it is ambiguous as it depends on an arbitrary choice of shape and size of the mother region. Instead, we use all continental areas as the mother region. This natural choice allows us to define scale- and shape-independent moisture recycling ratios. We split precipitation into

$$P(t, x, y) = P_c(t, x, y) + P_o(t, x, y) \quad (6)$$

where $P_c$ denotes precipitation which has continental origin (i.e., most recently evaporated from any continental area), and $P_o$ is precipitation which has oceanic origin (i.e., most recently evaporated from the ocean). The corresponding continental precipitation recycling ratio is defined as

$$\rho_c(t, x, y) = \frac{P_c(t, x, y)}{P(t, x, y)} \quad (7)$$

This ratio shows the dependence of precipitation at a certain location $(x, y)$ on upwind continental evaporation to sustain precipitation as a function of time $t$. Similarly, we define

continental evaporation recycling. Terrestrial evaporation is considered to consist of two components:

$$E(t, x, y) = E_c(t, x, y) + E_o(t, x, y) \quad (8)$$

where $E_c$ is terrestrial evaporation that returns as continental precipitation and $E_o$ is terrestrial evaporation that precipitates on an ocean. Note that the total annual $E_c$ equals the total annual $P_c$ (assuming no substantial change in atmospheric storage over a year). It is a special case of equation (4) where the region $(x, y, A, \Delta)$ equals all continental areas:

$$\iint_{\substack{(x, y) \in \\ \text{continental} \\ \text{areas}}} E_c(year, x, y) \, dx \, dy = \iint_{\substack{(x, y) \in \\ \text{continental} \\ \text{areas}}} P_c(year, x, y) \, dx \, dy \quad (9)$$

Finally, this leads to a new definition: the continental evaporation recycling ratio:

$$\varepsilon_c(t, x, y) = \frac{E_c}{E} \quad (10)$$

This ratio indicates the importance of evaporation at a certain location $(x, y)$ to sustain downwind precipitation in a given time period $t$. Both continental moisture recycling ratios equations (7) and (10) can be seen as a typical characteristic of a certain location and, in contrast to the regional moisture recycling ratios equations (2) and (5), they do not suffer from scale- and shape-dependency of the study region. In sections 3.1 and 3.4 the combination of the precipitation and evaporation recycling ratio will prove to be a powerful tool to describe the global hydrological moisture cycle.

## 2.2. Data

[14] Most of the meteorological input data are taken from the ERA-Interim reanalysis. One of the main objectives of the ERA-Interim project was to improve the representation of the hydrological cycle [*Berrisford et al.*, 2009]. We have used specific humidity, and zonal and meridional wind speeds at the lowest 24 pressure levels (175–1000 hPa), and surface pressure, which are all instantaneous values given at 6 h intervals. Furthermore, we used precipitation and evaporation which are accumulated values at 3 h intervals. All reanalysis data are available at a 1.5°latitude × 1.5°longitude grid. We used the data between the latitudes 57°S–79.5°N, which cover all continents except Antarctica. The data used cover the period of 1998 to 2008. The year of 1998 has been omitted from the results, because about a month is necessary to spin-up the moisture accounting model to mitigate initial value errors. Consequently, the results are based upon the 10-year period of 1999 to 2008. The land-sea-mask of the ERA-Interim reanalysis data has been used to distinguish between continental and oceanic grid cells. Those grid cells with a sea-mask but without actual connection to the ocean, such as the North American Great Lakes and the Caspian Sea, have been assigned to the continent.

[15] The topography of the study area and the horizontal (vertically integrated) moisture flux is shown in Figure 1. It can be observed that the main moisture flux on the Northern Hemisphere from 30°N up to higher latitudes is westerly, whereas the main moisture flux between 30°S and 30°N is easterly. At latitudes lower than 30°S, the main moisture
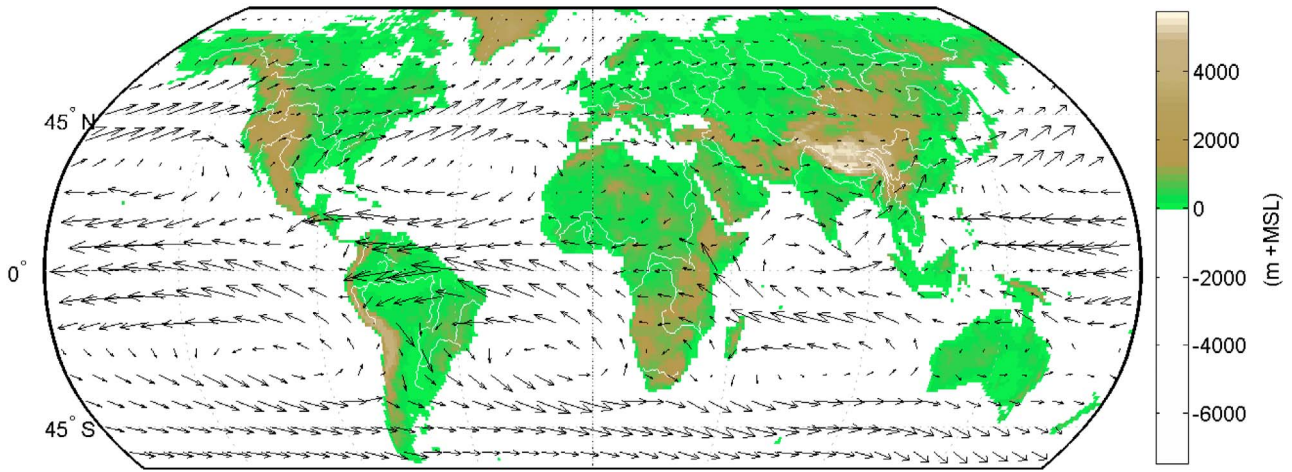
**Figure 1.** Global topography: height above Mean Sea Level (MSL), major rivers, and average horizontal (vertically integrated) moisture flux (1999–2008).

flux is again westerly but few continental areas are present at this latitude. Locally, these directions are disturbed by the presence of mountain ranges. For example, the Rocky Mountains in North America and the Great Rift Valley in Africa are blocking oceanic moisture from entering the rest of the continent. The opposite is true in South America where the Andes are blocking moisture from leaving the continent, thus creating favorable conditions for moisture recycling. The annual average precipitation and evaporation, as calculated from the ERA-Interim data set, is shown in Figure 2. Figure 2 displays the high variability of precipitation and evaporation between climate zones (tropics, deserts, moderate climates) and orographic precipitation effects along the main mountain ranges. In some regions we found that $P - E$ (Figure 2a minus Figure 2b) is negative. Although this can occur due to horizontal flows it is not likely to be correct in most cases, and is probably due to model error. These regions are e.g., central U.S., West Africa, South Africa, the Mediterranean, northern China and Australia.

### 2.3. Accounting Model

#### 2.3.1. Mathematical Framework

[16] The underlying principle for our accounting model, as well as for all recycling models [*Burde and Zangvil*, 2001a], is the atmospheric water balance:

$$\frac{\partial S_a}{\partial t} + \frac{\partial (S_a u)}{\partial x} + \frac{\partial (S_a v)}{\partial y} = E - P \left[ L^3 \, T^{-1} \right] \tag{11}$$

where $S_a$ is atmospheric moisture storage (i.e., precipitable water), $u$ the wind speed in the $x$ direction and $v$ the wind speed in the $y$ direction. From which follows that $\frac{\partial (S_a u)}{\partial x}$ is the horizontal (vertically integrated) moisture flux in the $x$ direction and $\frac{\partial (S_a v)}{\partial y}$ is the horizontal (vertically integrated) moisture flux in the $y$ direction:

$$\frac{\partial (S_a u)}{\partial x} = \frac{W}{g \rho_w} \int\limits_{p=0}^{p_s} q u \, \mathrm{d}p \tag{12}$$

$$\frac{\partial (S_a v)}{\partial y} = \frac{W}{g \rho_w} \int\limits_{p=0}^{p_s} q v \, \mathrm{d}p \tag{13}$$

where $W$ is the horizontal width perpendicular to the direction of the moisture flux, $g$ is the gravitational acceleration, $\rho_w$ the density of liquid water, $p_s$ the surface pressure and $q$ the specific humidity. This mass conservation principle can also be applied on water of a certain origin $\Omega$ (i.e., evaporated from $\Omega$):

$$\frac{\partial S_{a\_\Omega}}{\partial t} + \frac{\partial (S_{a\_\Omega} u)}{\partial x} + \frac{\partial (S_{a\_\Omega} v)}{\partial y} = E_\Omega - P_\Omega \tag{14}$$

where $S_{a\_\Omega}$ is the part of the atmospheric moisture storage that is of origin $\Omega$, $E_\Omega$ the evaporation from $\Omega$ and $P_\Omega$ is the
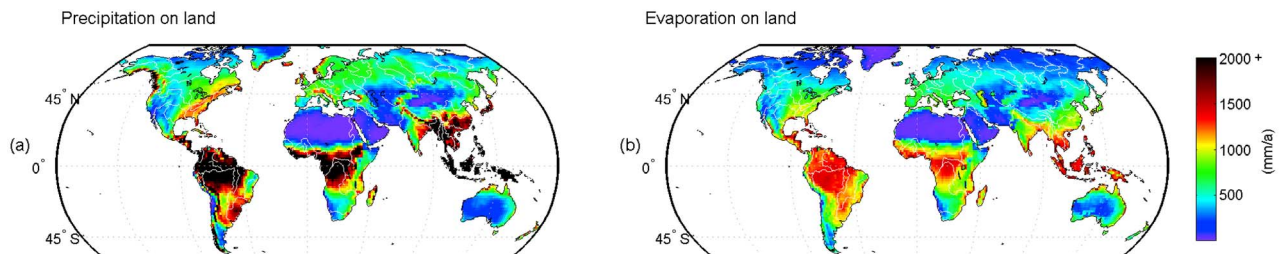


**Figure 2.** Annual average precipitation $P$ and evaporation $E$ over continental areas (1999–2008).

part of the precipitation that has origin $\Omega$. In our approach we assume that moisture in the atmosphere is well-mixed, which implies that

$$\frac{S_{a\_\Omega}}{S_a} = \frac{\frac{\partial(S_{a\_\Omega}u)}{\partial x}}{\frac{\partial(S_a u)}{\partial x}} = \frac{\frac{\partial(S_{a\_\Omega}v)}{\partial y}}{\frac{\partial(S_a v)}{\partial y}} = \frac{P_\Omega}{P} \qquad (15)$$

### 2.3.2. Numerical Implementation

[17] Our accounting model uses the input data described in section 2.2. It is based on the $1.5° \times 1.5°$grid on which all ERA-Interim reanalysis data are provided. These grid cells are approximated by trapezoids. The reanalysis data set has been reduced to 0.5-h resolution to reduce the Courant number. When numerically implemented, the well-mixed assumption (equation (15)) allows us to calculate different recycling ratios from simple proportional relations of atmospheric moisture of a certain origin $S_{a\_\Omega}$ to total atmospheric moisture $S_a$. The regional precipitation recycling ratio (equation (2)) for a certain region $reg(x, y, A, \Delta)$ is calculated as follows:

$$\rho_{r\_reg}\left(t_{\text{begin-end}}, x, y | A, \Delta\right)$$
$$= \frac{\sum\limits_{t=t\_\text{begin}}^{t\_\text{end}} \left[ \sum\limits_{(x,y)\,\in\,\text{region}} P(t,x,y|A,\Delta)\frac{S_{a\_reg}(t,x,y|A,\Delta)}{S_a(t,x,y|A,\Delta)} \right]}{\sum\limits_{t=t\_\text{begin}}^{t\_\text{end}} \left[ \sum\limits_{(x,y)\,\in\,\text{region}} P(t,x,y|A,\Delta) \right]} \qquad (16)$$

where $\rho_{r\_reg}$ is the regional precipitation recycling ratio in region $reg(x, y, A, \Delta)$ and $S_{a\_reg}$ is the part of the atmospheric moisture of regional origin. The regional evaporation recycling ratio (equation (5)) for a certain region $reg(x, y, A, \Delta)$ is calculated as follows:

$$\varepsilon_{r\_reg}\left(t_{\text{begin-end}}, x, y | A, \Delta\right)$$
$$= \frac{\sum\limits_{t=t\_\text{begin}}^{t\_\text{end}} \left[ \sum\limits_{(x,y)\,\in\,\text{region}} P(t,x,y|A,\Delta)\frac{S_{a\_reg}(t,x,y|A,\Delta)}{S_a(t,x,y|A,\Delta)} \right]}{\sum\limits_{t=t\_\text{begin}}^{t\_\text{end}} \left[ \sum\limits_{(x,y)\,\in\,\text{region}} E(t,x,y|A,\Delta) \right]} \qquad (17)$$

where $\varepsilon_{r\_reg}$ is the regional evaporation recycling ratio in region $reg(x, y, A, \Delta)$. Note that equation (17) makes use of the relationship $P_r = E_r$ (equation 4). The continental precipitation recycling ratio (equation (7)) for a certain location $loc(x, y)$ is

$$\rho_{c\_loc}\left(t_{\text{begin-end}}, x, y\right) = \frac{\sum\limits_{t=t\_\text{begin}}^{t\_\text{end}} P(t,x,y)\frac{S_{a\_con}(t,x,y)}{S_a(t,x,y)}}{\sum\limits_{t=t\_\text{begin}}^{t\_\text{end}} P(t,x,y)} \qquad (18)$$

where $\rho_{c\_loc}$ is the continental precipitation recycling ratio for a certain location $loc(x, y)$ and $S_{a\_con}$ is the atmospheric moisture storage that is of continental origin (i.e., evaporated from a land area or lake). The continental evaporation

recycling ratio (equation (10)) for location $loc(x, y)$ can be calculated as follows:

$$\varepsilon_{c\_loc}\left(t_{\text{begin-end}}, x, y\right)$$
$$= \frac{\sum\limits_{t=t\_\text{begin}}^{t\_\text{end}} \left[ \sum\limits_{(x,y)\,\in\,\text{all continental areas}} P(t,x,y)\frac{S_{a\_loc}(t,x,y)}{S_a(t,x,y)} \right]}{\sum\limits_{t=t\_\text{begin}}^{t\_\text{end}} E_{loc}(t,x,y)} \qquad (19)$$

where $\varepsilon_{c\_loc}$ is the continental evaporation recycling ratio for location $loc(x, y)$ and $S_{a\_loc}$ is moisture that originated from that location $loc(x, y)$. Note that the number of locations is equal to the amount of continental grid cells, and thus the simulations in order to calculate $\varepsilon_{c\_loc}$ for all continental areas have to be repeated as many times as there are grid cells.

[18] One of the problems with reanalysis data is that they are not always mass-conservative. In addition to the atmospheric moisture storage obtained from the water balance (equation (11)), the atmospheric moisture storage can also be obtained by integrating over the vertical:

$$S_a = \frac{A}{g \cdot \rho_w} \int\limits_0^{p_s} q \, \mathrm{d}p \qquad (20)$$

where $A$ is the area of a grid cell. The difference between $S_a$ from equation (20) and $S_a$ from equation (11) is the residual factor $\alpha$. When implementing the model with reanalysis data we therefore modify equation (11) into

$$\frac{\partial S_a}{\partial t} + \frac{\partial(S_a u)}{\partial x} + \frac{\partial(S_a v)}{\partial y} = E - P + \alpha \qquad (21)$$

And equation (14) into

$$\frac{\partial S_{a\_\Omega}}{\partial t} + \frac{\partial(S_{a\_\Omega}u)}{\partial x} + \frac{\partial(S_{a\_\Omega}v)}{\partial y} = E_\Omega - P_\Omega + \alpha_\Omega \qquad (22)$$

*Bisselink and Dolman* [2008] and *Dominguez et al.* [2006] argued that such a residual factor is essentially a correction on either precipitation or evaporation, but does not influence the recycling patterns heavily. Within a time step, we found our residuals seldom to be larger than 1% of the moisture storage. We can assume that the residual factor $\alpha$ has the same ratio of moisture from a certain origin to total moisture. This is also the approach of *Yoshimura et al.* [2004], which implies that

$$\frac{S_{a\_\Omega}}{S_a} = \frac{\alpha_\Omega}{\alpha} \qquad (23)$$

We used this approach in order to calculate $\rho_c$, and $\rho_r$ and $\varepsilon_r$ for areas larger than a single grid cell.

### 2.3.3. Model Assumptions

[19] In classical bulk recycling models, three common assumptions are generally made [*Burde and Zangvil*, 2001a; *Fitzmaurice*, 2007]: (1) the use of time-averaged data, (2) the neglect of the atmospheric storage term, and (3) the well-mixed assumption. Our approach does not suffer from the first two assumptions, since we have used time-accumulated data and the atmospheric moisture storage term is taken into account.

Continental precipitation recycling ratio $\rho_c$
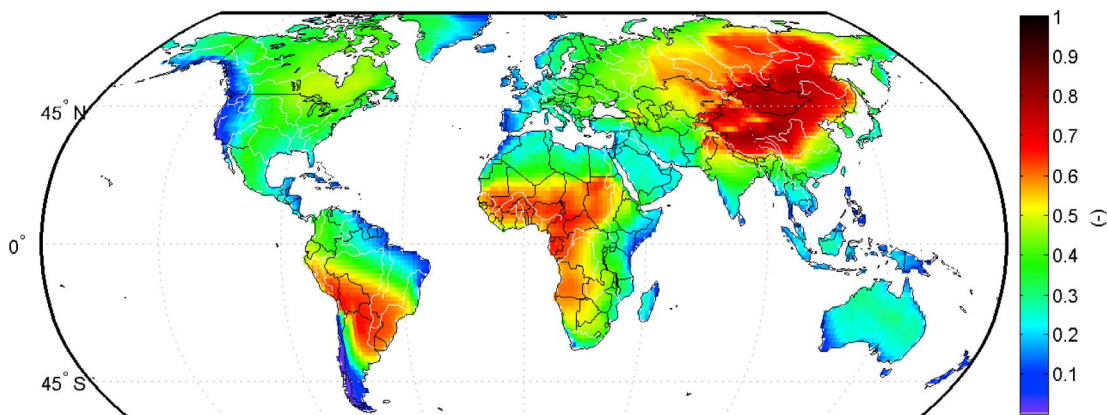
**Figure 3.** Average continental precipitation recycling ratio $\rho_c$ (1999–2008).

We only make use of the third assumption, that of a well-mixed atmosphere. The well-mixed atmosphere assumption could be relaxed by either using an incomplete vertical mixing approach [e.g., *Burde et al.*, 2006; *Fitzmaurice*, 2007; *Lettau et al.*, 1979] or by using GCM water vapor tracers [e.g., *Bosilovich et al.*, 2002; *Bosilovich and Chern*, 2006; *Koster et al.*, 1986; *Numaguti*, 1999]. Both approaches, however, add complexity and parameters that are hard to establish, resulting in more model-based rather than data-based results.

[20] According to *Fitzmaurice* [2007] the well-mixed assumption tends to either underestimate or overestimate regional precipitation recycling ratios depending on the precipitation mechanism: (a) underestimation is likely to occur in case of convective precipitation, (b) overestimation can be expected in case of upper level storms, where energy and moisture is derived from outside the region and (c) for regions and periods that experience frequent deep convections, such as the monsoonal period in Thailand, the well-mixed assumption is likely to hold. For the continental moisture recycling ratios (Figures 3 and 4), we could, thus,

expect small upwind shifts for convective events and small downwind shifts for upper level storms.

## 3. Results and Discussion

### 3.1. Continental Moisture Recycling

[21] Figure 3 presents the continental precipitation recycling ratio $\rho_c$ (equation (7)) for all the major continental areas. This map compares well to similar maps shown by *Bosilovich et al.* [2002] and *Yoshimura et al.* [2004], albeit that the map shown by the latter does not represent an annual average. In areas of high $\rho_c$, such as China and central Asia, the western part of Africa and central South America, most of the precipitation is of terrestrial origin. Figure 4 shows the continental evaporation recycling ratio $\varepsilon_c$ (equation (10)). High values of $\varepsilon_c$ indicate locations from where the evaporated moisture will fall again as precipitation over continents.

[22] Yet, these maps (Figures 3 and 4) become far more meaningful when considered together. Major source regions for continental precipitation (Figure 4) are the west of the
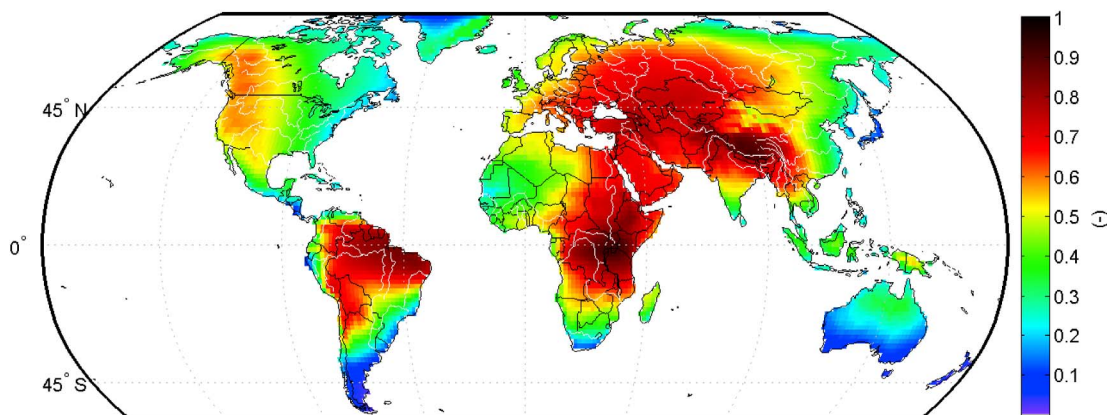
Continental evaporation recycling ratio $\varepsilon_c$

**Figure 4.** Average continental evaporation recycling ratio $\varepsilon_c$ (1999–2008).

**Table 1.** Annual Average Regional Moisture Recycling Ratios at Different Scales on the Continent of South America for the Period 1999–2008[a]

| Region | Location | $\rho_r$ (%) | $\varepsilon_r$ (%) |
|---|---|---|---|
| 1.5° × 1.5° | center: 6°S, 67.5°W | 4 | 7 |
| 3° × 3° | center: 6.75°S, 66.75°W | 5 | 10 |
| 6° × 6° | center: 6.75°S, 66.75°W | 9 | 16 |
| 9° × 9° | center: 6.75°S, 66.75°W | 12 | 21 |
| Bolivia | (11.25°S–21.75°S, 69.75°W–59.25°W) | 17 | 21 |
| Amazon | (3.75°N–15.75°S, 75.75°W–47.25°W) | 28 | 48 |
| South America | (11.25°N–54.75°S, 81.75°W–35.25°W) | 36 | 59 |

[a]The symbols are explained in the text.

North American continent, the entire Amazon region, central and East Africa and a very large area in the center of the Eurasian continent. The areas that are major sinks for continentally evaporated water (Figure 3) are the northeast of North America, the region around the line Peru-Uruguay, central and West Africa and large areas in China, Mongolia and Siberia. The areas east of the Andes and the Tibetan Plateau are hot spots where both continental moisture recycling ratios are high. Apparently, it is difficult for moisture to leave these regions because the major wind directions are toward the mountains and due to orographic lifting of moisture this leads repeatedly to precipitation. Thus, in these areas, local recycling is the major source of precipitation.

[23] Together these scale-independent moisture recycling ratios fully describe continental moisture feedback within the hydrological cycle. For North America, Figure 3 indicates that oceanic sources are dominant over continental moisture recycling. Figure 4, however, shows that in the West about 60% of the evaporation returns to the continent downwind. Hence, recycling is not negligible; over most of the continent, annual average precipitation relies for about 40% on recycled moisture.

[24] South America shows three distinct moisture recycling patterns. The first of these patterns is the evaporation from the Guianas and the Amazon region (Figure 4) that is transported downwind to the Río de la Plata basin, where it precipitates (Figure 3) [see also *Marengo*, 2006, Figure 4]. The second pattern is the local recycling just east of the Andes, where high values of Figures 3 and 4 overlap. The third pattern is visible in Patagonia where very little to no moisture recycling takes place.

[25] From Figure 3, it is clear that the Indian Ocean is a major source of precipitation in East Africa. From here (Figure 4) and from central Africa almost all the evaporation is recycled regionally or transported to West Africa (Figure 3). In the latter region, the continental precipitation recycling plays a major role. The Sahel, which often has been subject of research in the context of moisture recycling, receives its moisture (in)directly from three large water bodies: the Mediterranean Sea, the South Atlantic Ocean and the Indian Ocean. On average, about 50 to 60% of the precipitation originates from continental evaporation. This estimate is in line with GCM water vapor tracer studies [*Bosilovich et al.*, 2002; *Koster et al.*, 1986].

[26] Between Europe and Asia, the main moisture flux is westerly. This is reflected in the increase of the precipitation recycling ratio in eastward direction (Figure 3). By the time the moisture reaches western China, the original oceanic moisture only accounts for about 10 to 20% of the precip-

itation (Figure 4). This is in line with earlier findings [*Bosilovich et al.*, 2002; *Dirmeyer et al.*, 2009a; *Numaguti*, 1999; *Serreze and Etringer*, 2003; *Stohl and James*, 2005; *Yoshimura et al.*, 2004], where terrestrial moisture recycling was seen as a major contributor to precipitation over Siberia, Mongolia and China. The importance of recycling can also be seen in the continental evaporation recycling ratio (Figure 4), which shows that on average 40 to 70% of the evaporation from any region in Europe returns to a continental area. A hot spot, where the local moisture recycling (Figures 3 and 4) is high, is the area around the Tibetan Plateau. Earlier studies on the isotopic compositions of rainfall in this area also indicated local recycling to play a major role around the Tibetan Plateau [*Liu et al.*, 2008; *Tian et al.*, 2001; *Yu et al.*, 2007]. The dominant moisture fluxes converge to the plateau creating favorable conditions for localized moisture feedback.

[27] Finally, in the south of India, Southeast Asia, and Oceania, the average fraction of the precipitation originating from continental evaporation is not dominant, but with about 30% (Figure 3) it still plays an important role in climate. However, in the northern part of Australia, Indonesia and Papua New Guinea, which are very wet areas, the fraction of the evaporation returning to the continent is about 40% (Figure 4). A priori, we think this indicates a fast regional recycling process, but since so much oceanic moisture is present as well, the contribution of recycling to the total precipitation remains small.

## 3.2. Regional Moisture Recycling

[28] To highlight the scale-effect in regional moisture recycling, we computed the regional recycling ratios (equations (2) and (5)) as a function of the study area size on the continent of South America (see Table 1). The dependence of the regional recycling ratios on the study area size is clearly visible. For precipitation recycling they range from 4% at the scale of a grid cell to 28% for the entire Amazon region. This estimate is in line with the GCM water vapor tracer study of *Bosilovich and Chern* [2006], but lower than the 41% found by *Burde et al.* [2006], who did not use the well-mixed assumption of the atmosphere. Additionally, we present estimates for the fraction of evaporation which recycles within the same region; for the Amazon region this value is 48%.

[29] Figure 5 shows the annual average regional precipitation and evaporation recycling ratios on the 1.5°latitude × 1.5°longitude grid. Considering that the scale and shape of a grid cell depends on latitude, the pattern (not the absolute values) of Figure 5a compares reasonably well to other studies, that do scale their results to a common area [*Dirmeyer and Brubaker*, 2007; *Trenberth*, 1999]. Since regional recycling ratios are scale-dependent, the exact values of the recycling ratios are of little matter here. The results give, however, an indication of where the regional moisture feedback mechanism is significant. High regional recycling ratios occur over very wet areas, such as the tropical forests of South America, of Africa and of Southeast Asia. Over the Caspian Sea and over the North American Great Lakes, the precipitation recycling (Figure 5a) is slightly higher than in the surrounding grid cells. This indicates immediate feedback from areas where the evaporation is not limited by moisture availability. Furthermore, regional recycling (Figure 5) is particularly high in mountainous areas or just upwind of these
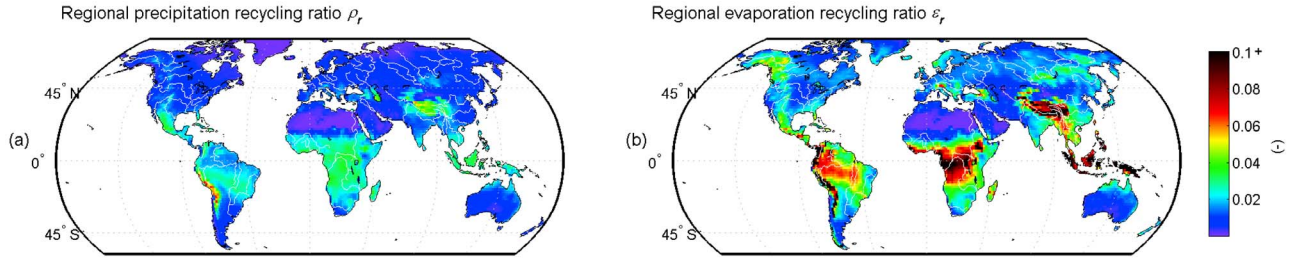
**Figure 5.** Average regional precipitation recycling ratio $\rho_r$ and evaporation recycling ratio $\varepsilon_r$ within a $1.5° \times 1.5°$grid cell (1999–2008).

areas. This effect is clearly visible near the Andes, the Tibetan Plateau, the mountain ranges of South Africa and the Great Rift Valley in East Africa.

[30] In some places, negative values of $P - E$ in the ERA-Interim data (see section 2.2) may lead to an overestimation of the regional precipitation recycling ratio (Figure 5a): e.g., central U.S., West Africa, South Africa, the Mediterranean, northern China and Australia. The regional evaporation recycling ratio (Figure 5b) may be underestimated in these regions, since percentagewise more evaporation would recycle within a grid cell in case of less total evaporation. The effect on the regional recycling ratio of actual evaporation compared to reanalysis evaporation is for example shown in the work of *Dominguez and Kumar* [2008, Figure 3] and *Dominguez et al.* [2008, Figure 1]. Yet again, in our study the exact values do not significantly affect our conclusions.

## 3.3. Increase of Fresh Water Resources due to Continental Evaporation

[31] Much research has been done on how continental evaporation can trigger precipitation. [*Dirmeyer et al.*, 2009b; *Eltahir*, 1998; *Koster et al.*, 2004; *Kunstmann and Jung*, 2007; *Zheng and Eltahir*, 1998] investigated the role of soil moisture content, while [*Bierkens and Van den Hurk*, 2007] investigated the role of groundwater. [*Makarieva and Gorshkov*, 2007] described how forested areas favor the occurrence of more precipitation.

[32] Another way of looking at the importance of continental moisture feedback is by defining the continental precipitation multiplier [*Savenije*, 1995a]. For this definition it is important to realize that precipitation according to equation (6) consists of two components. We define the continental precipitation multiplier as

$$m_c(t,x,y) = \frac{P}{P_o} = 1 + \frac{P_c}{P_o} = \frac{1}{1 - \rho_c} \qquad (24)$$

The multiplier has physical meaning; it is amplification of precipitation due to continental evaporation. Its value is in fact a conservative estimate, since the actual precipitation triggered by continental evaporation is higher due to the nonlinear relation between precipitation and precipitable water [*Savenije*, 1995b]. When integrated over a year and all continental areas the multiplier is also the average number of times a water particle has sequentially fallen on the continent.

[33] Figure 6 illustrates moisture recycling over the entire continental area. It shows that, on average, 40% of all precipitation is derived from continental sources and 57% of all

terrestrial evaporation returns as precipitation to continents. The global runoff coefficient of 30% is lower than other estimates: 41% (excluding Antarctica) [*Oki and Kanae*, 2006] and 35% (including Antarctica) [*Trenberth et al.*, 2007]. For total precipitation over land we found $117 \times 10^3$ km$^3$/a which is slightly higher than the other estimates: $111 \times 10^3$ km$^3$/a [*Oki and Kanae*, 2006] and $113 \times 10^3$ km$^3$/a [*Trenberth et al.*, 2007]. This obviously also means that we found more evaporation from the land surface: $82 \times 10^3$ km$^3$/a, or $81 \times 10^3$ km$^3$/a if we do not account for the evaporation from the big lakes, compared to $65.5 \times 10^3$ km$^3$/a [*Oki and Kanae*, 2006] and $73 \times 10^3$ km$^3$/a [*Trenberth et al.*, 2007]. Potentially, the ERA-Interim data slightly overestimate the intensity of the hydrological cycle over continents and therefore we might also overestimate the continental moisture recycling. However, we have seen that the directions of the moisture flux are the main drivers for the continental recycling patterns (Figures 1, 3, and 4) and therefore we do not expect the patterns nor our conclusions to alter significantly with other data sets.

[34] Table 2 summarizes the recycling ratios of all continents and the entire continental area, including the rainfall multiplier $m_c$ (equation (24)) which is the amplification of precipitation due to continental evaporation. Globally the multiplier is 1.67 and this implies that there is at least 67% more precipitation on the continent than in the hypothetical case where there is no continental feedback at all. In South America, Asia and Africa, continentally recycled moisture plays a major role (Table 2). In Asia ($m_c = 1.91$) and Africa ($m_c = 1.95$) there is about twice as much rainfall due to moisture recycling. A large difference between the regional and continental evaporation recycling ratio can be observed in Europe (66–27 = 39%). Inversely, in Asia there is a big difference between the regional and continental precipitation recycling ratio (48–34 = 14%). This demonstrates that Europe is a major source of moisture for precipitation in
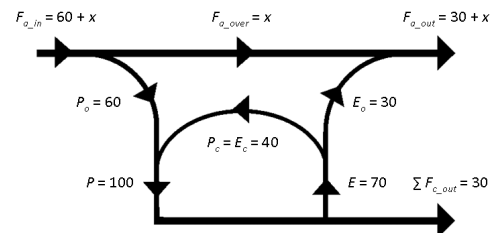


**Figure 6.** Water balance of all continental areas in percent normalized to the total precipitation (1999–2008).

**Table 2.** Annual Average Moisture Recycling per Continent[a]

| Region | Location | $\rho_r$ (%) | $\varepsilon_r$ (%) | $\rho_c$ (%) | $\varepsilon_c$ (%) | $m_c$ |
|---|---|---|---|---|---|---|
| North America | (79°N–11°N, 167°W–53°W) | 27 | 35 | 31 | 42 | 1,45 |
| South America | (11°N–55°S, 82°W–35°W) | 36 | 59 | 39 | 59 | 1,65 |
| Africa | (37°N–34°S, 17°W–59°E) | 45 | 55 | 49 | 62 | 1,95 |
| Europe | (71°N–37°N, 10°W–59°E) | 22 | 27 | 35 | 66 | 1,53 |
| Asia | (77°N–8°N, 59°E–179°E) | 34 | 52 | 48 | 58 | 1,91 |
| Oceania | (7°N–46°S, 59°E–179°E) | 18 | 27 | 20 | 29 | 1,25 |
| All Continents | (79°N–55°S, 180°W–180°E) | 40 | 57 | 40 | 57 | 1,67 |

[a]Note that the oceanic masses within the study area are not considered in the regional recycling and by definition also not in the continental moisture recycling. The results presented in this table span the period of 1999–2008. The symbols are explained in the text.

Asia, an image which can only be seen through the combination of the two continental moisture recycling ratios presented here.

### 3.4. Seasonal Variations of the Continental Moisture Budget

[35] This section presents continental moisture recycling for typical summer and winter situations of the world (Figures 7 and 8). To see the annual cycle of recycling for the entire globe we refer to Animation 1 that shows the proportion of continental moisture in the atmosphere day by day.[1] We can observe that in winter continental moisture feedback is a far less dominant process than it is in summer, when continental evaporation is high. We thus observe a

positive feedback mechanism between continental evaporation and rainfall.

[36] Focusing on Eurasia, it is striking to see that even in January (Figure 7) about 40 to 60 % of the precipitation (looking at $\rho_c$) in China is derived from recycling over the Eurasian continent. China's main rivers are fed by sources of continental evaporation over eastern Europe and western Asia (looking at $\varepsilon_c$) and a source region covering Burma and Thailand (looking at $E_c$).

[37] In July (Figure 8) continental moisture recycling is a very significant process on the Northern Hemisphere. In western Europe, the continental precipitation recycling ratio is already about 30%, which indicates transport of moisture with a continental origin from North America, or from eastern Europe in case wind is blowing from the East.
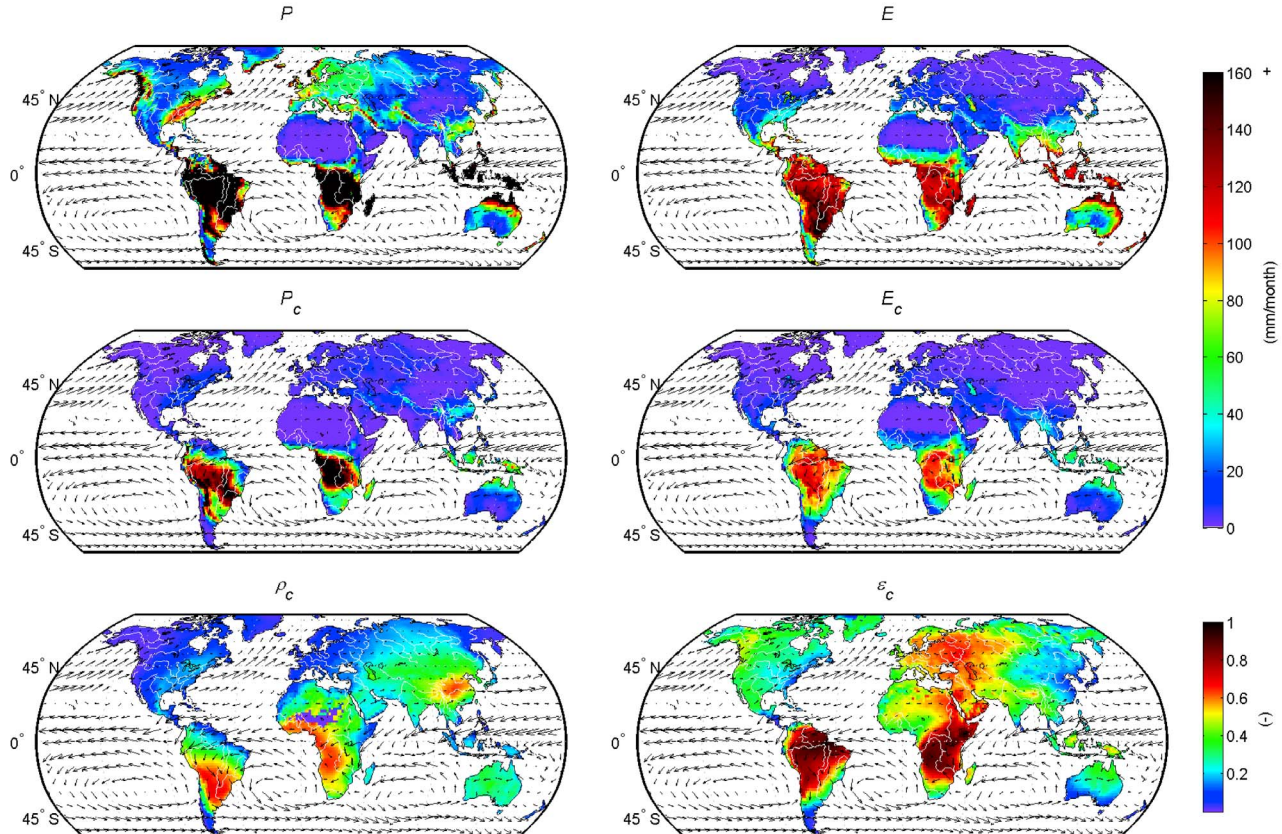
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[1]Animation 1 is available in the HTML.



**Figure 7.** Moisture recycling in January. The arrows indicate the horizontal moisture flux field and the other symbols are explained in the text.
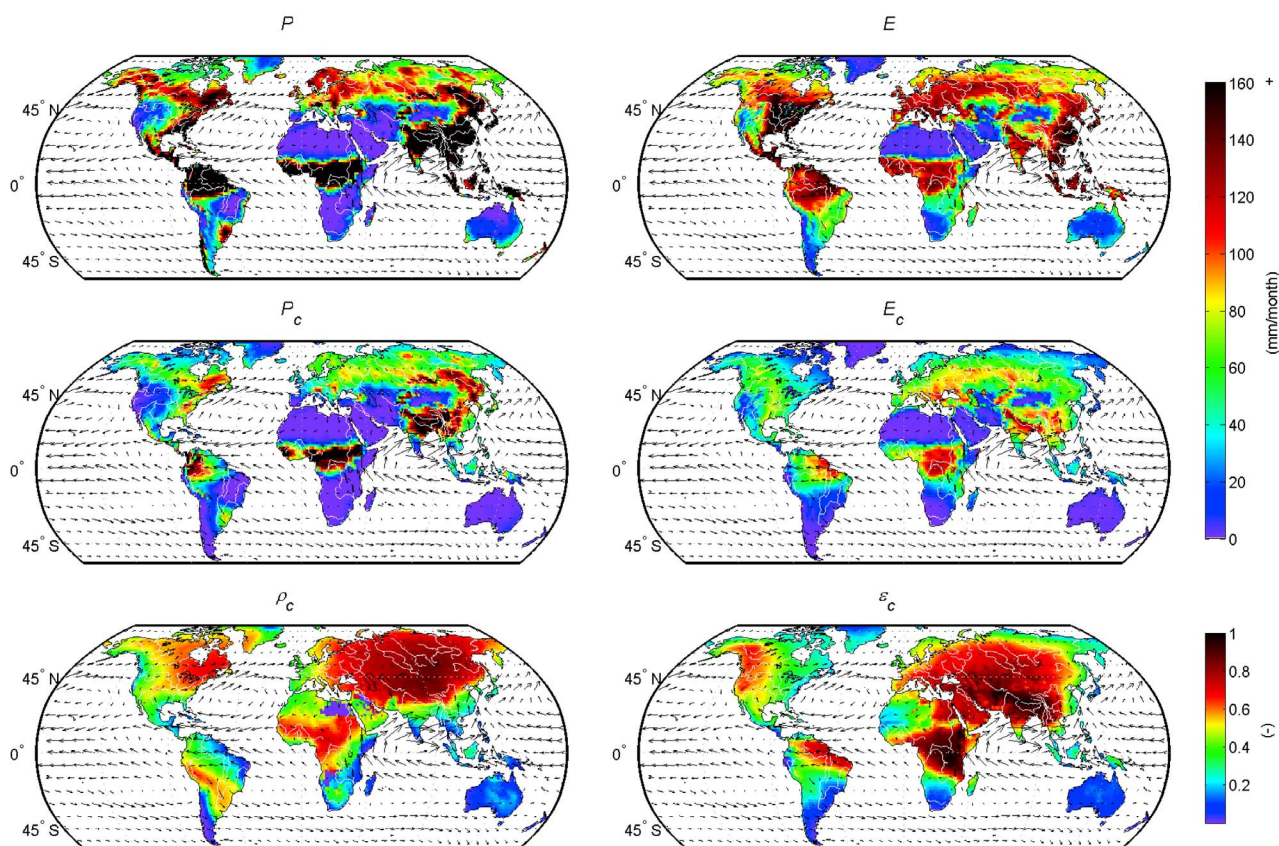
**Figure 8.** Moisture recycling in July. The arrows indicate the horizontal moisture flux field and the other symbols are explained in the text.

Furthermore, almost all the continental evaporation returns to the continent, which can be seen from the continental evaporation recycling ratio which is overall very high in Eurasia, 50 to 100% over most of the continent. Consequently, continental moisture feedback accounts for 70 to 90% of the precipitation falling in an area ranging all the way from eastern Europe to the Pacific Ocean and from the Arctic ocean to the north of India.

## 4. Conclusions

[38] We conclude that continental moisture recycling plays an important role in the global climate. The most striking example is China, which depends for its water resources almost entirely on terrestrial evaporation from the Eurasian continent (Figures 3 and 4). In this paper we have stressed the fact that all water that evaporates eventually precipitates: what goes up must come down. Although this is popular knowledge, in hydrology this idea is not mainstream. In most water resources studies evaporation is considered a loss to the system. In addition, precipitation is often merely seen as external forcing. For many basin-scale studies this approach may be sufficient, but we have demonstrated that a direct and indirect feedback mechanism can be very important in water resources accounting. Globally, recycled moisture multiplies our fresh water resources by a factor 1.67, but locally this can amount to a factor three (e.g., the Río de la Plata basin in South America), or even a factor ten in western China. Moreover, as we have shown, almost all evaporation from

East and central Africa returns to the continent. Thus, we can, for example, conclude that draining wetlands in the Nile basin may increase the discharge of the Nile [*Mohamed et al.*, 2005], but will also lead to a reduction of Africa's total fresh water resources.

[39] In general, we found regional recycling to be most significant in wet environments and can be greatly enhanced by topography. Mountain ranges can play an important role in moisture recycling either by 'blocking' moisture from entering the continent (e.g., the Rocky Mountains and the Great Rift Valley), or by 'capturing' the moisture from the atmosphere to enhance recycling (e.g., the Andes and the Tibetan Plateau).

[40] Our results suggest that decreasing evaporation in areas where continental evaporation recycling is high (e.g., by deforestation), would enhance droughts in downwind areas where overall precipitation amounts are low. On the other hand, water conservation in these areas would have a positive multiplier effect on rainfall downwind. We suggest more detailed research to be done on the effect of land-use change in critical regions with high moisture recycling ratios, such as the Río de la Plata basin in South America, where negative trends in precipitation may already be identifiable.

[41] This study has identified the regions where continental moisture recycling plays an important role by supplying moisture, receiving moisture, or both. An interesting addition to this research would be to show global maps of typical travel distances and travel times of precipitated

water (backward trajectories) and of evaporated water (forward trajectories). Previous moisture recycling studies have mainly focused on the sources of precipitation [e.g., *Bosilovich and Chern*, 2006; *Dirmeyer et al.*, 2009a; *Koster et al.*, 1986; *Nieto et al.*, 2006; *Yoshimura et al.*, 2004]. We suggest further research to focus on the destinations of evaporation as well. Potentially, our approach can be extended to calculate travel distances and travel times of atmospheric moisture.

[42] Finally, it would be interesting to compute the different contributions to moisture recycling by, on the one hand transpiration, which is a productive flux, and on the other hand evaporation from interception, soil evaporation and open water evaporation, which are non-productive fluxes. Validation of our results can be done by performing a comparison between moisture recycling and stable isotope compositions in precipitation [*Froehlich et al.*, 2008; *Henderson-Sellers et al.*, 2002; *Liu et al.*, 2008; *Njitchoua et al.*, 1999; *Salati et al.*, 1979; *Tian et al.*, 2001; *Yu et al.*, 2007] or in the atmosphere [*Frankenberg et al.*, 2009; *Worden et al.*, 2007]. Furthermore, based on the work of *Joussaume et al.* [1984] and *Yoshimura et al.* [2003], our approach can be extended by keeping account of stable isotope compositions.

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