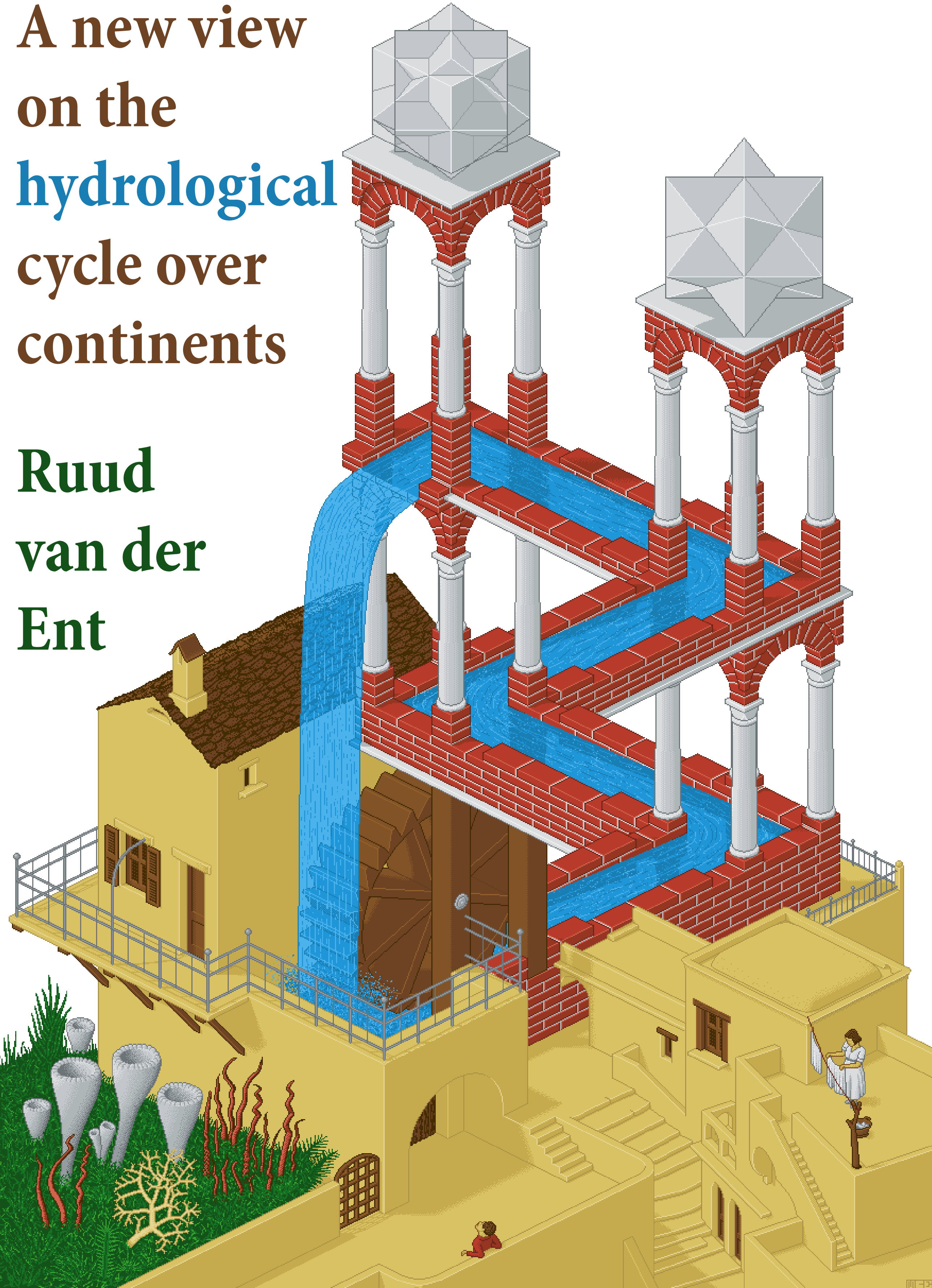
A new view on the hydrological cycle over continents

Ruud van der Ent



A NEW VIEW ON THE HYDROLOGICAL CYCLE OVER CONTINENTS

Proefschrift

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A scientist in his laboratory is not a mere technician: he is also a child confronting natural phenomena that impress him as though they were fairy tales.

Marie Curie

CONTENTS

1

INTRODUCTION

Are we ants or are we giants?

Hubert Savenije

This chapter is based on:

Van der Ent, R. J., H. H. G. Savenije, B. Schaefli, and S. C. Steele-Dunne, *Origin and fate of atmospheric moisture over continents*, Water Resources Research, **46**, W09525, 2010.

Van der Ent, R. J., and H. H. G. Savenije, *Length and time scales of atmospheric moisture recycling*, Atmospheric Chemistry and Physics, **11**, 1853–1863, 2011.

Van der Ent, R. J., and H. H. G. Savenije, *Oceanic sources of continental precipitation and the correlation with sea surface temperature*, Water Resources Research, **49**, 3993–4004, 2013.

1.1. WHERE DOES PRECIPITATION COME FROM?

It is not easy to answer the question where precipitation comes from because of the complex and energy-intensive processes that bring moisture to a certain location and cause moisture to precipitate highly heterogeneously in space and variable over time. However, this question is highly relevant for a wide range of disciplines in Earth sciences. It is of importance for seasonal weather forecasting [e.g., Dominguez et al., 2009; Tuinenburg et al., 2011; Van den Hurk et al., 2012], land and water management [e.g., Bagley et al., 2012; Keys et al., 2012; Spracklen et al., 2012; Tuinenburg et al., 2012], as well as for our understanding of the role of the hydrological cycle in our climate system [e.g., Dominguez et al., 2008; Dirmeyer et al., 2009b; Van den Hurk and Van Meijgaard, 2009; Goessling and Reick, 2011; Rios-Entenza and Miguez-Macho, 2013]. Part of the precipitation comes from so-called “moisture recycling”, which is moisture from land evaporation that returns to the land surface as precipitation.

1.2. HISTORICAL VIEWS

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, 1949, and references therein]. 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, 1949; Budyko, 1974; McDonald, 1962]. Then again, Shukla and Mintz [1982] showed that terrestrial evaporation is in fact of major importance for continental rainfall.

1.3. MOISTURE RECYCLING

Nowadays, it is widely accepted that land-atmosphere interactions can play a crucial role in the global climate [e.g., Seneviratne et al., 2006]. One expression of these interactions is moisture recycling through continental evaporation. Humans are known to change evaporation through land use and water management [e.g., Gordon et al., 2008]. 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). It is also known that our global water resources are becoming more and more stressed [e.g., Rockström et al., 2012]. 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 [e.g., Lettau et al., 1979; Brubaker et al., 1993; Savenije, 1995a; Eltahir and Bras, 1996; Kunstmann and Jung, 2007].

1.4. RESEARCH QUESTIONS

The main research question to be answered in this thesis is:

"How important is land evaporation in the hydrological cycle over continents?"

Chapter 2 explains the main methodology used in the dissertation, while the other chapters of answer several sub-questions:

- Chapter 3: "Which regions on Earth depend significantly on land evaporation, and which regions provide most evaporation for continental precipitation?"
- Chapter 4: "Can we quantify the local importance of evaporation-precipitation feedback in a scale-independent way?"
- Chapter 5: "How important are the components of evaporation (interception and transpiration) to sustain precipitation over continents?"
- Chapter 6: "Can we find atmospheric equivalents for watersheds, in order to provide useful information for land and water management?"

Chapter 7 summarises the answers to these research questions, discusses the implications of this research and provides an outlook for further research.

2

WATER ACCOUNTING MODEL-2LAYERS

> *To those who ask what the infinitely small quantity in mathematics is, we answer that it is actually zero. Hence there are not so many mysteries hidden in this concept as they are usually believed to be.*
>
> Leonhard Euler

In this chapter, the offline Eulerian atmospheric moisture tracking model, WAM-2layers (Water Accounting Model-2layers) is presented. In general, we use ERA-Interim reanalysis data as input to the model, but this is, however, not a requirement. WAM-2layers can be used to track tagged moisture on both the regional and global scale, and both forward and backward in time. This model is very fast for large scale atmospheric moisture tracking, while the two layers ensure that problems such as wind shear are adequately dealt with.

This chapter is based on:

Van der Ent, R. J., O. A. Tuinenburg, H. R. Knoche, H. Kunstmann, and H. H. G. Savenije, *Should we use a simple or complex model for moisture recycling and atmospheric moisture tracking?*, Hydrology and Earth System Sciences, **17**, 4869-4884, 2013.

Van der Ent, R. J., L. Wang-Erlandsson, P. W. Keys, and H. H. G. Savenije, *Contrasting roles of interception and transpiration in the hydrological cycle – Part 2: Moisture recycling*, Earth System Dynamics Discussions, **5**, 281–326, 2014.

2.1. INTRODUCTION

Studying where the rain comes from is of growing interest in the scientific community. In the beginning of the second half of the twentieth century several pioneer researchers were addressing this question [e.g., Benton, 1949; McDonald, 1962; Budyko, 1974; Molion, 1975]. Many studies thereafter used simple bulk methods or conceptualizations of the hydrological cycle in order to estimate the amount of precipitation that recycled within a certain region [e.g., Lettau et al., 1979; Brubaker et al., 1993; Eltahir and Bras, 1996; Schär et al., 1999; Trenberth, 1999]. The results obtained were, however, only a rough estimate over a large region and subject to several assumptions [Burde and Zangvil, 2001a,b; Fitzmaurice, 2007]. Other studies focused on finding the recycling along a streamline [Savenije, 1995a,b; Lintner et al., 2013; Schaefli et al., 2012], which added to the conceptual understanding of moisture feedback, but has not yet proven to provide reliable estimates in real-world cases. A completely different approach, namely the use of stable isotopes of water: δ^2H, δ^{18}O and the corresponding d-excess value, has been shown to be a good indicator for moisture recycling and moisture recycling variability [e.g., Salati et al., 1979; Njitchoua et al., 1999; Henderson-Sellers et al., 2002; Pang et al., 2004; Tian et al., 2007; Froehlich et al., 2008; Liu et al., 2008; Risi et al., 2013]. However, good temporal and spatially consistent isotope records are generally not available, and additional meteorological observations are needed to pinpoint the origin of the water more accurately.

There also exist many studies that numerically track moisture (we use the term moisture in this paper for all possible phases of water) in the atmosphere. The first studies, to our knowledge, that can be characterized as atmospheric moisture tracking studies were those of Joussaume et al. [1986] and Koster et al. [1986]. The latter used a water vapour tracing scheme in a coarse resolution general circulation model (GCM) to estimate the origin of precipitation in several regions. In contrast to most bulk methods, atmospheric moisture tracking can determine the spatio-temporal distribution of moisture origin rather than merely the recycling rate over a large temporal and spatial scale.

Moisture tracking can be done either parallel (online) to a climate or weather model run [e.g. Bosilovich and Schubert, 2002; Bosilovich and Chern, 2006; Sodemann et al., 2009; Goessling and Reick, 2013a; Knoche and Kunstmann, 2013] or a posteriori (offline) with reanalysis data [e.g., Yoshimura et al., 2004; Dominguez et al., 2006; Dirmeyer and Brubaker, 2007; Bisselink and Dolman, 2008; Van der Ent et al., 2010; Tuinenburg et al., 2012], operational analysis data [e.g. Stohl and James, 2005; Nieto et al., 2006; Sodemann et al., 2008; Gimeno et al., 2010; Spracklen et al., 2012] or output of a climate model run [e.g., Gangoiti et al., 2011; Goessling and Reick, 2011]. The advantage of the offline moisture tracking methods above the online moisture tracking methods is that the offline methods are far less computationally expensive, allow for backward tracking, and are thus much more flexible. The Dynamical Recycling Model (DRM) of Dominguez et al. [2006], is an example of an offline Lagrangian 2D atmospheric water vapour tracking model. The Quasi-Isentropic Back-Trajectory (QIBT) method [Dirmeyer and Brubaker, 1999, 2007] is a 3D Lagrangian model which does not use the “well-mixed” atmosphere assumption for horizontal transport, but still evokes the “well-mixed” assumption for the release and recovery (precipitation and evaporation) of their water vapour tracers. A modification of QIBT is 3D-Trajectories (3D-T) [Tuinenburg et al., 2012], but in contrast to QIBT, 3D-T does not use potential temperature as a vertical coordinate system. Instead it uses pressure coordinates and the vertical wind speed to calculate the vertical motion of tracked parcels. Two other widely used and advanced offline Lagrangian models are: FLEXPART [Stohl et al., 2005] and HYSPLIT [Draxler and Hess, 1998; Draxler and Rolph, 2014], which, however, have the disadvantage that they only consider the net interaction with the surface (precipitation – evaporation).

For global moisture tracking studies often 2D offline Eulerian models have been used [e.g., Yoshimura et al., 2004; Goessling and Reick, 2011; Van der Ent et al., 2010; Keys et al., 2012]. These models excel in computation speed due to their simplicity, but also due to their Eulerian grid allowing them to track moisture from large source areas just as fast as from small source areas. However, it has also been shown that these methods are less accurate in studies demanding high spatial and temporal resolution [Bosilovich, 2002; Goessling and Reick, 2013a; Van der Ent et al., 2013]. Problems occur mostly in areas with a lot of wind shear, and these areas are often located in the tropics [Goessling and Reick, 2013a; Van der Ent et al., 2013]. It has, however, also been shown that it is not necessary to have a full 3D representation of the atmosphere in the tracking model in order to obtain reliable results. In fact, an offline moisture tracking model with just two well-chosen layers can yield nearly identical results to a highly advanced online tracking model, but with much smaller computational cost [Van der Ent et al., 2013].

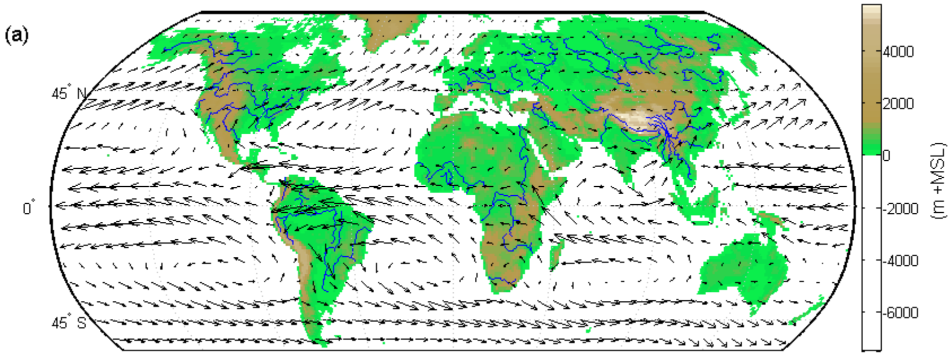
In this chapter, we present our offline atmospheric moisture tracking model, WAM-2layers (Water Accounting Model-2layers). This is an update to the previously used WAM-1layer [Van der Ent et al., 2010; Keys et al., 2012; Van der Ent and Savenije, 2013]. WAM-2layers can be used to track tagged moisture on both the regional and global scale, and both forward and backward in time. In case of forward tracking, the output of WAM-2layers is a spatial distribution of atmospheric moisture or precipitation which evaporated from a predefined region. In case of backward tracking, the output is a spatial distribution of atmospheric moisture or evaporation which will precipitate in a predefined region.

2.2. INPUT DATA

In this dissertation we use data from the ERA-Interim reanalysis (ERA-I) [Dee et al., 2011] on a 1.5° latitude × 1.5° longitude grid for the period of 1998–2009. ERA-I is provided by the European Centre for Medium Range Weather Forecasting (ECMWF) [Berrisford et al., 2009]. However, it should be noted that other data from other reanalysis products or climate models can be used as well in WAM-2layers [see e.g., Van der Ent et al., 2013; Keys et al., 2014]. Our results are always presented for 1999–2008, because we use 1 year as model spin-up for both backward and forward tracking (see Section 2.3). We use the data between the latitudes 57°S–79.5°N, which covers all continents except Antarctica. Tagged moisture (Section 2.4) advected over the northern or southern boundary is considered lost. The only chapter were we use other data besides ERA-I is Chapter 6 where we replace ERA-I's terrestrial evaporation with that of STEAM (Simple Terrestrial Evaporation to Atmosphere Model) [Wang-Erlandsson et al., 2014].

From ERA-I we use the 2D fields of 3-hourly precipitation and evaporation. Furthermore, we use 6-hourly specific humidity and zonal and meridional wind speed. We downloaded these data at model levels spanning the atmosphere from zero pressure to

Topography and moisture fluxes



Atmospheric moisture storage

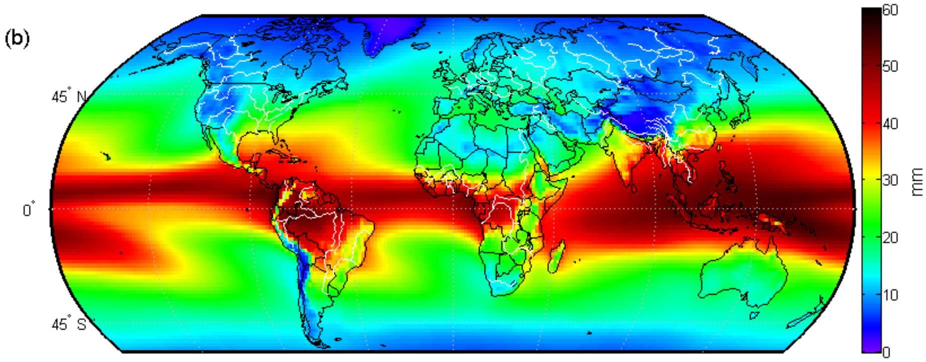


Figure 2.1: Physical geography of the study area. **(a)** Height above mean sea level (MSL), major rivers in blue, and the annual average horizontal (i.e., vertically integrated) moisture flux is indicated by the black arrows. **(b)** Annual average atmospheric moisture storage (i.e., precipitable water).

surface pressure. ERA-I has 60 model levels, of which we downloaded 17 distributed over the whole vertical, with most detail in the lower atmosphere as most moisture is present there. In the tracking we bring this back to 2 layers. We consider ERA-I as an adequate data source to perform realistic moisture tracking because it is among the state-of-the-art global estimates of evaporation and precipitation. It was shown that ERA-I performs better in reproducing the hydrological cycle than ERA-40 [Trenberth, 2011] and even performs better in terms of water balance closure than MERRA and CFSR [Lorenz and Kunstmann, 2012]. Keys et al. [2014] used both ERA-I and MERRA as input for WAM-2layers

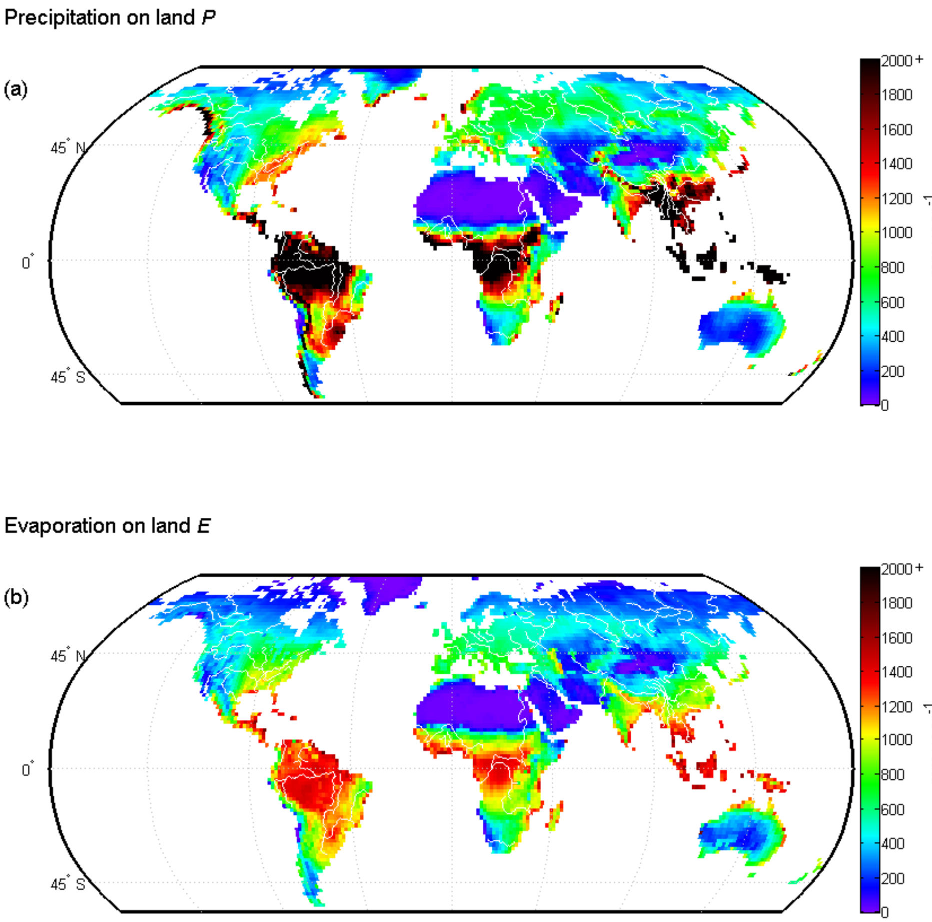


Figure 2.2: Annual average surface fluxes over continental areas. **(a)** Precipitation P and **(b)** Evaporation E.

and found moisture recycling patterns are not to be very different.

The topography of the study area and the horizontal (vertically integrated) moisture flux is shown in Fig. 2.1a. 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 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

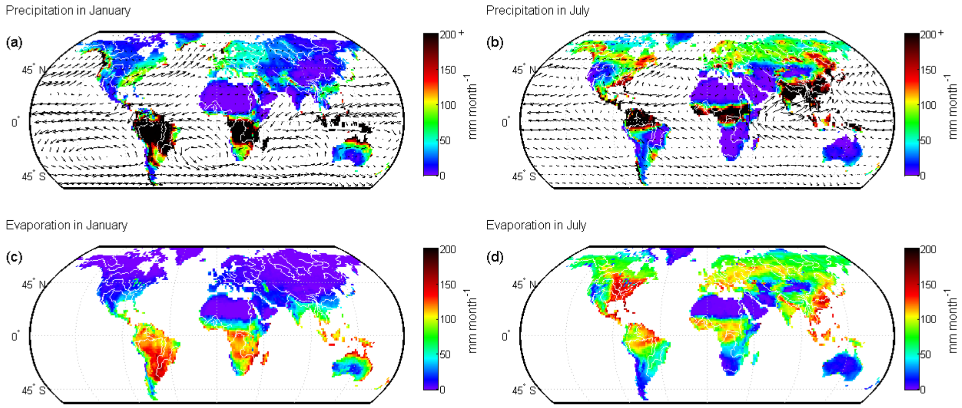


Figure 2.3: Terrestrial precipitation and evaporation for January (left column) and July (right column). The arrows in (a) and (b) indicate the average horizontal moisture fluxes.

Andes are blocking moisture from leaving the continent, thus creating favourable conditions for moisture recycling. The blocking and capturing of atmospheric moisture is also illustrated by the atmospheric moisture storage, which is shown in Fig. 2.1b.

The annual average precipitation and evaporation, as calculated from ERA-I, is shown in Fig. 2.2. It displays the high variability of precipitation and evaporation between climate zones (tropics, deserts, moderate climates) and orographic precipitation effects along the main mountain ranges. However, we should mention that in some regions we found that $P - E$ (Fig. 2.2a minus Fig. 2.2b) 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 data-assimilation in ERA-I. These regions are e.g., central U.S., West Africa, South Africa, the Mediterranean, northern China and Australia. On the other hand, we find that such errors do not influence our results significantly and do not affect our conclusions. However, when better data [e.g., Dufournet and Russchenberg, 2011; Bastiaanssen et al., 2012; Overeem et al., 2013] in the future will become available globally, this would of course increase the accuracy our local moisture recycling estimates. Furthermore, we analyse our results in Chapters 3–6 for the months of January and July, for which we show the climatology in Fig. 2.3.

2.3. WATER BALANCE

The underlying principle of WAM-2layers is the water balance:

$$\frac{\partial S_k}{\partial t} = \frac{\partial (S_k u)}{\partial x} + \frac{\partial (S_k v)}{\partial y} + E_k - P_k + \xi_k \pm F_\mathrm{v} \quad \left[\mathrm{L}^3\,\mathrm{T}^{-1}\right], \tag{2.1}$$

where S_k is the atmospheric moisture storage (i.e., precipitable water) in layer k (either the top or the bottom layer), t is time, u and v stand for the wind components in x (zonal) and y (meridional) direction, E_k is evaporation entering layer k, P_k is precipitation removed from layer k, ξ is a residual and F_v is the vertical moisture transport between the bottom and top layer. We calculate moisture transport over the boundaries of the grid cells. Change in atmospheric moisture due to horizontal transport is described by

$$\frac{\Delta(Su)}{\Delta x} = F^{-}_{k,x} - F^{+}_{k,x} \tag{2.2}$$

and

$$\frac{\Delta(Sv)}{\Delta y} = F^{-}_{k,y} - F^{+}_{k,y}, \tag{2.3}$$

where F_k is the moisture flux over the boundary of a grid cell in the bottom or top layer, which is positive from west to east and from south to north. Superscript "−" stands for the western and southern boundaries of the grid cell and "+" stands for the eastern and northern boundaries. The moisture flux can be calculated as follows:

$$F_k = \frac{L}{g\rho_\mathrm{w}} \int_{p_\mathrm{top}}^{p_\mathrm{bottom}} q u_\mathrm{h}\, \mathrm{d}p, \tag{2.4}$$

where L is the length of the grid cell perpendicular to the direction of the moisture flux, g is the gravitational acceleration, ρ_w the density of liquid water ($1000\ \mathrm{kg\,m^{-3}}$), p stands for pressure, q for specific humidity and u_h is the horizontal component in either x or y direction. For the top layer applies: $p_\mathrm{top} = 0$ and $p_\mathrm{bottom} = p_\mathrm{divide}$. For the bottom layer applies: $p_\mathrm{top} = p_\mathrm{divide}$ and $p_\mathrm{bottom} = p_\mathrm{surface}$. Here, p_divide is the pressure at the division between the bottom and top layer, which can be calculated by:

$$p_\mathrm{divide} = 7438.803 + 0.728786 \times p_\mathrm{surface}\ \ [\mathrm{Pa}], \tag{2.5}$$

which corresponds to 81,283 Pa at a standard surface pressure of 101,325 Pa. By trial and error investigation, this division appeared to best capture the division between sheared wind systems, where wind in the bottom layer goes in another direction than wind in the top layer [see Van der Ent et al., 2013, Fig. 11]. Over land, the bottom layer roughly accounts for 40–80 % of the total column moisture storage and for 30–70 % of the total horizontal moisture flux.

Looking further at Eq. 2.1, evaporation E) enters only in the bottom layer, thus $E_k = E$ in the bottom layer and $E_k = 0$ in the top layer. Precipitation is assumed to be immediately removed from the moisture storage (i.e., no exchange of falling precipitation between the top and bottom layer) and we assume "well-mixed" conditions for precipitation:

$$P_k = P\frac{S_k}{S}, \tag{2.6}$$

where P is total precipitation and S total atmospheric storage in the vertical. The residual ξ in Eq. 2.1 is the result of data-assimilation in ERA-I and the fact that our offline tracking scheme calculates the water balance on a coarser spatial and temporal resolution.

The vertical transport of moisture F_v in Eq. 2.1 is difficult to calculate because besides transport by average vertical wind speed there is dispersive moisture exchange due to the convective scheme in ERA-I. Therefore, we assume the vertical exchange to be the closure term of our water balance. However, as a result of the residual ξ, we cannot always fully close the water balance. Hence, closure is here defined by the ratio of residuals in the top and bottom layer being proportional to the moisture content of the layers:

$$\frac{\xi_{\text{top}}}{S_{\text{top}}} = \frac{\xi_{\text{bottom}}}{S_{\text{bottom}}}. \tag{2.7}$$

Using Eq. 2.7 vertical moisture transport can be calculated as follows:

$$F_{\text{v}} = \frac{S_{\text{bottom}}}{S}\left(\xi^*_{\text{bottom}} + \xi^*_{\text{top}}\right) - \xi^*_{\text{bottom}}, \tag{2.8}$$

where ξ^*_{bottom} and ξ^*_{top} are the residuals before vertical transport was taken into account. Note that including F_{v} (positive downward), as calculated by Eq. 2.8, in Eq. 2.1 will lead to Eq. 2.7 being satisfied.

2.4. TRACKING OF TAGGED MOISTURE

In WAM-2layers we apply the same water balance on moisture of a certain origin. For example, the water balance of tagged evaporation (denoted by subscript g) in the bottom layer of the atmosphere for forward tracking is described by:

$$\frac{\partial S_{g,\text{bottom}}}{\partial t} = \frac{\partial (S_{g,\text{bottom}}\, u)}{\partial x} + \frac{\partial (S_{g,\text{bottom}}\, v)}{\partial y} + E_g - P_g \pm F_{\text{v},g}. \tag{2.9}$$

Equations that are similar to Eq. 2.9 apply to the top layer and backward tracking. The tagged moisture in the model can represent any area of interest ranging from a single grid cell to all grid cells of the model. These equations are solved using an explicit numerical scheme on Eulerian coordinates (the same as the input data). The time step of the calculation is, however, reduced to 0.25 h to reduce the Courant-number for numerical stability. By trial and error we found that the vertical flux as calculated by Eq. 2.8 was too small to adequately take care of the vertical transport of tagged water (bottom/top bucket completely filled with the other bucket being nearly empty). We attribute this to turbulent moisture exchange (especially during rain events) between the top and bottom layer. To solve this we have retained F_{v} as the net vertical moisture flux, but during the tagging experiments we have used a vertical flux of $4F_{\text{v}}$ in the direction of the net flux and $3F_{\text{v}}$ in opposite direction. We acknowledge that this is a simplification of the turbulent moisture exchange, but we consider this is an adequate parameterization for our purposes. Moreover, our results were not found to be very sensitive to the turbulent moisture exchange. Different forward and backward tagging runs with WAM-2layers allowed for the computation of the continental moisture recycling metrics presented in Chapters 3–6.

2.5. WATER AGE TAGGING EXPERIMENTS

We are also interested in the time that evaporated moisture spends in the atmosphere. Therefore, we introduce a tracer that keeps track of the age of the atmospheric moisture in the forward tagging runs. This age increases linearly with time and at each time step t

the model calculates the age N_g of the tagged moisture present at that location according to the following formula:

$$N_g(t) = \frac{\begin{pmatrix} S_g(t-1)\left(N_g(t-1)+\Delta t\right) + \sum F_g^{\text{in}} \Delta t \left(N_g^{\text{in}}(t-1)+\Delta t\right) \\ -\sum F_g^{\text{out}} \Delta t \left(N_g(t-1)+\Delta t\right) - P_g \Delta t \left(N_g(t-1)+\Delta t\right) + E_g \Delta t \frac{\Delta t}{2} \end{pmatrix}}{S_g(t)}, \qquad (2.10)$$

where the subscript g stands for tagged water. N_g^{in} stands for the age of the tagged water coming into the grid cell and F_g^{in} and F_g^{out} are the incoming and outgoing fluxes over the boundaries of a grid cell. These age tagging experiments allowed for the computation of the atmospheric residence times of precipitated and evaporated moisture (Chapter 6).

3

ORIGIN AND FATE OF ATMOSPHERIC MOISTURE OVER CONTINENTS

> *What goes up must come down.*
>
> Isaac Newton

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 chapter 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. 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 supplies up to 80 % of China's water resources. In South America, the La Plata basin depends heavily on evaporation from the Amazon forest. The main source of rainfall in West Africa is moisture evaporated over East Africa, particularly the Great Lakes region. 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 chapter demonstrates the important role of global wind patterns, topography and land cover in continental moisture recycling patterns and the distribution of global water resources.

This chapter is based on:

Van der Ent, R. J., H. H. G. Savenije, B. Schaefli, and S. C. Steele-Dunne, *Origin and fate of atmospheric moisture over continents*, Water Resources Research, **46**, W09525, 2010.

3.1. INTRODUCTION

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 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].

The applications of different formulas can lead to completely different results and conclusions on the significance of moisture recycling. Mohamed et al. [2005] showed that the formula of Schär et al. [1999] gives higher precipitation recycling ratios than the formula of Brubaker et al. [1993], and the formula of Savenije [1995a] 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.

Recent studies pointed out that the commonly used bulk formulas [Brubaker et al., 1993; Eltahir and Bras, 1994] may underestimate precipitation recycling in general, because of the assumptions made in the modelling approach. These studies also developed methods to relax the modelling assumptions, generally leading to a more significant role for moisture recycling [Burde and Zangvil, 2001a,b; 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 [Stohl et al., 2005; Bosilovich and Chern, 2006; Liu et al., 2008; Dirmeyer et al., 2009a]. Models that assumed a closed system indicated this to be even more dominant, but overestimated evaporation-precipitation feedback [e.g., Molion, 1975; Savenije, 1995a, 1996, 1995b].

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. 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., Lettau et al., 1979; Eltahir and Bras, 1994; Szeto, 2002; Serreze and Etringer, 2003; Mohamed et al., 2005; Kunstmann and Jung, 2007], grid cells of a certain dimension [e.g., Trenberth, 1999; Dominguez et al., 2006; Dirmeyer and Brubaker, 2007] or other large regions [e.g., Brubaker et al., 1993; Schär et al., 1999; Bisselink and Dolman, 2008]. 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.

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

In this chapter 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 socio-economic developments (e.g., currently ongoing deforestation for energy crops).

3.2. NEW DEFINITIONS FOR MOISTURE RECYCLING

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:

$$P(t,x,y|A,\varsigma) = P_{\mathrm{r}}(t,x,y|A,\varsigma) + P_{\mathrm{a}}(t,x,y|A,\varsigma), \tag{3.1}$$

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 ς. Hence, the "regional precipitation recycling ratio" is defined as

$$\rho_{\mathrm{r}}(t,x,y|A,\varsigma) = \frac{P_{\mathrm{r}}(t,x,y|A,\varsigma)}{P(t,x,y|A,\varsigma)}. \tag{3.2}$$

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

$$E(t,x,y|A,\varsigma) = E_{\mathrm{r}}(t,x,y|A,\varsigma) + E_{\mathrm{a}}(t,x,y|A,\varsigma), \tag{3.3}$$

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 large time period ΔT, which should be large compared to the atmospheric residence time (e.g., a year), we can assume that there is no substantial change in atmospheric moisture, and E_{r} is approximately equal to P_{r}:

$$E_{\mathrm{r}}(\Delta T, x, y|A, \varsigma) \approx P_r(\Delta T, x, y|A, \varsigma). \tag{3.4}$$

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

$$\varepsilon_{\mathrm{r}}(t, x, y|A, \varsigma) = \frac{E_{\mathrm{r}}(t, x, y|A, \varsigma)}{E(t, x, y|A, \varsigma)}. \tag{3.5}$$

Comparing regional recycling ratios from various studies or areas has proven to be difficult because of its scale- and shape-dependency. Imagine the case where a study region would be reduced to a long east-west oriented strip of only a few kilometres in width. In this case, even the slightest meridional moisture flux would result in calculated regional recycling ratios close to zero. Consequently, regional recycling ratios alone are inadequate to assess the importance of continental moisture feedback.

It is also possible to use sink-region-dependent moisture recycling ratios which indicate the moisture recycling at a certain point (x, y) embedded in a larger mother region (x, y, A, ς) [Burde, 2006; Fitzmaurice, 2007; Dominguez et al., 2008; Bisselink and Dolman, 2008, 2009], which some of these studies confusingly termed local moisture recycling ratios. Although the regional and sink-region-dependent 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, in this chapter 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 two parts:

$$P(t, x, y) = P_{\mathrm{c}}(t, x, y) + P_{\mathrm{o}}(t, x, y), \tag{3.6}$$

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

$$\rho_{\mathrm{c}}(t, x, y) = \frac{P_{\mathrm{c}}(t, x, y)}{P(t, x, y)}. \tag{3.7}$$

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:

$$E(t, x, y) = E_{\mathrm{c}}(t, x, y) + E_{\mathrm{o}}(t, x, y), \tag{3.8}$$

where E_{c} is terrestrial evaporation that returns as continental precipitation and E_{o} is terrestrial evaporation that precipitates on an ocean. Note that over a large period ΔT, E_{c} is approximately equal to P_{c}, assuming no substantial change in atmospheric storage.

It is a special case of Eq. (3.4), where the region (x, y, A, ς) equals all continental areas:

$$\iint\limits_{\substack{(x,y)\,\in\\ \text{continental}\\ \text{areas}}} E_\mathrm{c}(\Delta T, x, y)\,\mathrm{d}x\,\mathrm{d}y \approx \iint\limits_{\substack{(x,y)\,\in\\ \text{continental}\\ \text{areas}}} P_\mathrm{c}(\Delta T, x, y)\,\mathrm{d}x\,\mathrm{d}y. \tag{3.9}$$

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

$$\varepsilon_\mathrm{c}(t, x, y) = \frac{E_\mathrm{c}}{E} \tag{3.10}$$

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 (Eqs. 3.7 and 3.10) can be seen as a typical characteristic of a certain location and, in contrast to the regional moisture recycling ratios equations 3.2 and 3.5, they do not suffer from scale- and shape-dependency of the study region. In Section 3.3.1 the combination of the continental precipitation and evaporation recycling ratio will prove to be a powerful tool to describe the global hydrological moisture cycle.

3.3. RESULTS AND DISCUSSION

3.3.1. CONTINENTAL MOISTURE RECYCLING

Figure 3.1 presents the continental precipitation recycling ratio ρ_c (Eq. 3.7) 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 ρ_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 3.2 shows the continental evaporation recycling ratio ε_c (Eq. 3.10). High values of ε_c indicate locations from where the evaporated moisture will fall again as precipitation over continents.

Yet, these maps (Figs. 3.1 and 3.2) become far more meaningful when considered together. Major source regions for continental precipitation (Fig. 3.2) are the west of the North American continent, the entire Amazon region, central and East Africa and a very large area in the centre of the Eurasian continent. The areas that are major sinks for continentally evaporated water (Fig. 3.1) are the north-east 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 since 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.

Together these scale-independent moisture recycling ratios fully describe continental moisture feedback within the hydrological cycle. For North America, Fig. 3.1 indicates that oceanic sources are dominant over continental moisture recycling. Figure 3.2, 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.

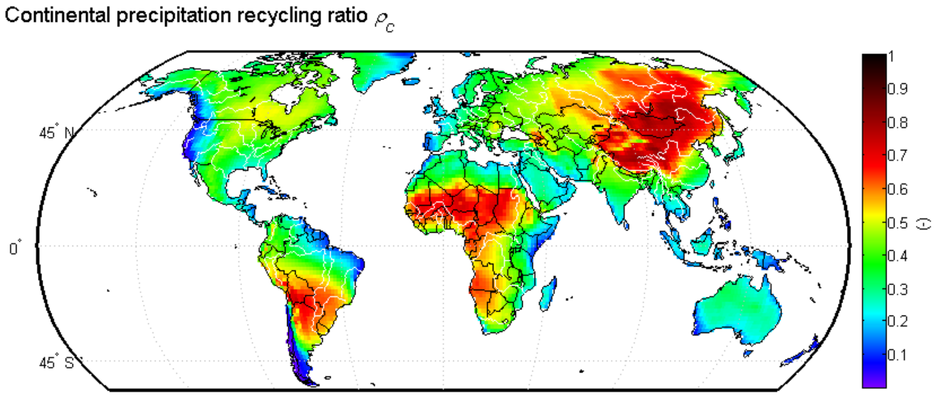


Figure 3.1: Annual average continental precipitation recycling ratio ρ_c.

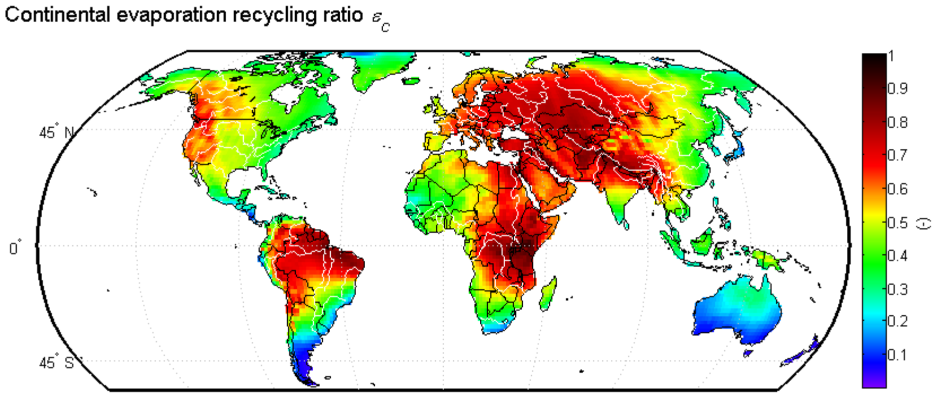


Figure 3.2: Annual average continental evaporation recycling ratio ε_c.

South America shows three distinct moisture recycling patterns. The first of these patterns is the evaporation from the Guianas and the Amazon region (Fig. 3.2) that is transported downwind to the La Plata basin, where it precipitates (Fig. 3.1) [see also Marengo, 2006, Fig. 4]. The second pattern is the local recycling just east of the Andes, where high values of Figs. 3.1 and 3.2 overlap. The third pattern is visible in Patagonia where very little to no moisture recycling takes place.

From Fig. 3.1, it is clear that the Indian Ocean is a major source of precipitation in East Africa. From here (Fig. 3.2) and from central Africa almost all the evaporation is recycled regionally or transported to West Africa (Fig.3.1). In the latter region, the conti-

Table 3.1: Annual average regional moisture recycling ratios (Eqs. 3.2 and 3.5) at different scales on the continent of South America.

Region	Location	ρ_r (%)	ε_r (%)
1.5° × 1.5°	centre: 6°S, 67.5°W	4	7
3° × 3°	centre: 6.75°S, 66.75°W	5	10
6° × 6°	centre: 6.75°S, 66.75°W	9	16
9° × 9°	centre: 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°S–15.75°S, 75.75°W–47.25°W	28	48
South America	11.25°S–54.75°S, 81.75°W–35.25°W	36	59

nental 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 [see also Van der Ent and Savenije, 2013]. On average, about 50 to 60 % of the precipitation originates from continental evaporation. This estimate is in line with GCM water vapour tracer studies [Koster et al., 1986; Bosilovich, 2002].

Between Europe and Asia, the main moisture flux is westerly. This is reflected in the increase of the precipitation recycling ratio in eastward direction (Fig. 3.1). By the time the moisture reaches western China, the original oceanic moisture only accounts for about 20 to 40 % of the precipitation (Fig. 3.2). This is in line with earlier findings [Numaguti, 1999; Bosilovich et al., 2002; Serreze and Etringer, 2003; Yoshimura et al., 2004; Stohl and James, 2005; Dirmeyer et al., 2009a], 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 (Fig. 3.2), which shows that on average 40 to 70 % of the evaporation from any region in Europe returns to a continental area. The Tibetan Plateau appears to be a hot spot for local moisture recycling as both ρ_c and ε_c are high. Earlier studies on the isotopic compositions of rainfall in this area also indicated local recycling to play a major role around the Tibetan Plateau [Tian et al., 2001; Yu et al., 2007; Liu et al., 2008]. The dominant moisture fluxes converge to the plateau creating favourable conditions for localized moisture feedback.

Finally, in the south of India, south-east Asia, and Oceania, the average fraction of the precipitation originating from continental evaporation is not dominant, but with about 30 % (Fig. 3.1) it still plays an important role in the 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 % (Fig. 3.2). 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 total precipitation remains small.

3.3.2. REGIONAL MOISTURE RECYCLING

To highlight the scale-effect in regional moisture recycling, we computed the regional recycling ratios (Eqs. 3.2 and 3.5) as a function of the study area size on the continent of South America (see Table 3.1). 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 Amazon region. This estimate is in line with the GCM water vapour tracer study of Bosilovich and Chern [2006], but lower than the 41 % found by Burde et al. [2006], who used an advanced analytical model. This difference is likely due to slightly different study region, method and data. Additionally, we present estimates for the fraction of evaporation which recycles within the same region; for the Amazon region this value is 48 %.

3.3.3. INCREASE OF FRESH WATER RESOURCES DUE TO CONTINENTAL EVAPORATION

Much research has been done on how continental evaporation can trigger precipitation. Many studied the role of soil moisture content [e.g., Findell and Eltahir, 1997; Koster et al., 2004; Kunstmann and Jung, 2007; Findell et al., 2011; Taylor et al., 2012], while Bierkens and Van den Hurk [2007] investigated the role of groundwater. The debated theoretical analysis of Makarieva and Gorshkov [2007] speculated that forested areas favour the occurrence of more precipitation and Spracklen et al. [2012] showed that rainfall is higher when air passed over forests.

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 Eq. 3.6 consists of two components. We define the "continental precipitation multiplier" as

$$m_{\mathrm{c}}(t,x,y) = \frac{P}{P_{\mathrm{o}}} = 1 + \frac{P_{\mathrm{c}}}{P_{\mathrm{o}}} = \frac{1}{1-\rho_{\mathrm{c}}}. \tag{3.11}$$

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 non-linear relation between precipitation and precipitable water [Savenije, 1995b]. When integrated over a year and all continental areas the multiplier is also an estimation of the average number of times a water particle has sequentially fallen on the continent, but probably this estimate is slightly on the high side [Van der Ent, 2013; Goessling and Reick, 2013b].

Figure 3.3 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 $117 \times 10^3\,\mathrm{km}^3\,\mathrm{year}^{-1}$ which is slightly higher than the other estimates: $111 \times 10^3\,\mathrm{km}^3\,\mathrm{year}^{-1}$ [Oki and Kanae, 2006] and $113 \times 10^3\,\mathrm{km}^3\,\mathrm{year}^{-1}$ [Trenberth et al., 2007]. This obviously also means that we found more evaporation from the land surface: $82 \times 10^3\,\mathrm{km}^3\,\mathrm{year}^{-1}$ or $81 \times 10^3\,\mathrm{km}^3\,\mathrm{year}^{-1}$ if we do not account for the evaporation from the big lakes, compared to $65.5 \times 10^3\,\mathrm{km}^3\,\mathrm{year}^{-1}$ [Oki and Kanae, 2006] and

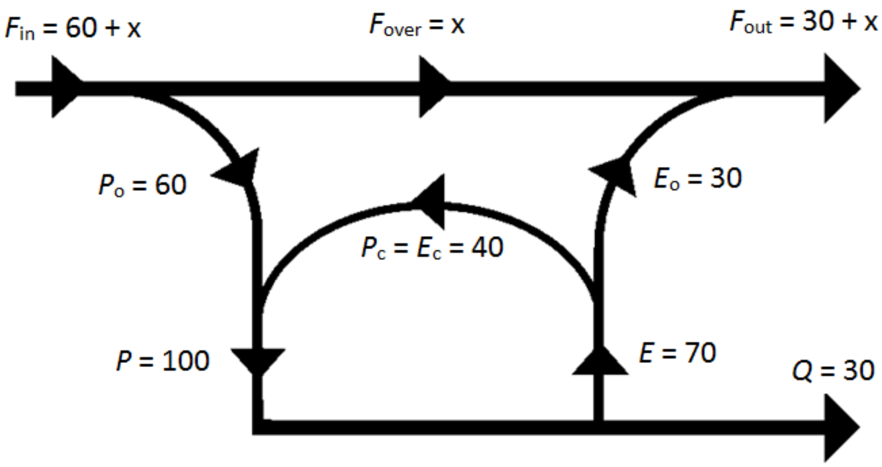


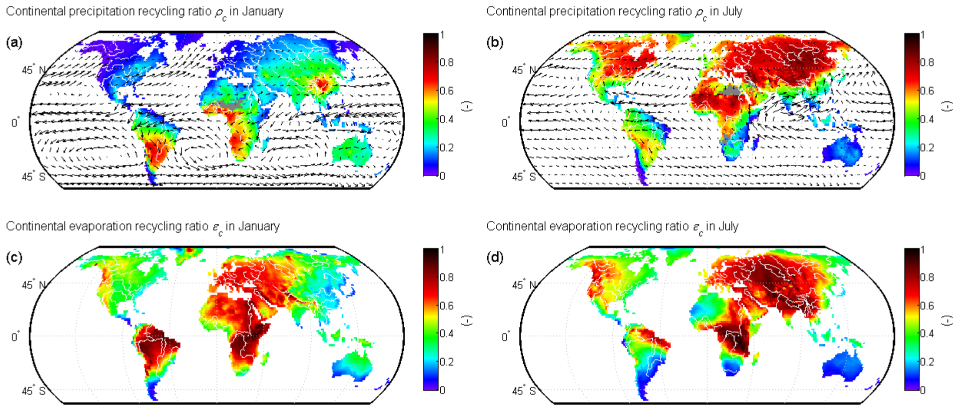
Figure 3.3: Water balance of all continental areas in percent, normalized to the total precipitation. F_{in} is the atmospheric moisture flux directed towards the land over the land-ocean boundary, F_{out} is the atmospheric moisture flux from the land to the ocean and F_{over} is oceanic moisture transported over the continent without precipitating, which value is given as x as this value is extremely dependent on the in- or exclusion of many small islands. Q represents runoff and the other symbols are explained in Section 3.2

$73 \times 10^3\,\text{km}^3\,\text{year}^{-1}$ [Trenberth et al., 2007]. Potentially, the ERA-I data slightly overestimate the intensity of the hydrological cycle over continents and therefore we might also overestimate continental moisture recycling. However, we have seen that the directions of the moisture flux are the main drivers for the continental recycling patterns (Figures 2.1, 3.1, and 3.2) and therefore we do not expect the patterns nor our conclusions to alter significantly with other data sets.

Table 3.2: Annual average moisture recycling per continent[a]

Region	Location	ρ_r (%)	ε_r (%)	ρ_c (%)	ε_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 “location” are not considered in the regional recycling and by definition also not in the continental moisture recycling.


Continental precipitation recycling ratio ρ_c in January

Continental precipitation recycling ratio ρ_c in July

Continental evaporation recycling ratio ε_c in January

Continental evaporation recycling ratio ε_c in July

Figure 3.4: Continental moisture recycling in January (left column) and July (right column). The arrows in (a) and (b) indicate the vertically integrated moisture flux field.

Table 3.2 summarizes the recycling ratios of all continents and the entire continental area, including the rainfall multiplier m_{c} (Eq. 3.11) 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 3.1). In Asia ($m_{\mathrm{c}} = 1.91$) and Africa ($m_{\mathrm{c}} = 1.95$) 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 Asia, an image which can only be seen through the combination of the two continental moisture recycling ratios presented here.

3.3.4. SEASONAL VARIATIONS OF THE CONTINENTAL MOISTURE BUDGET

This section presents continental moisture recycling for typical summer and winter situations of the world (Fig. 3.4). To see the annual cycle of recycling for the entire globe we refer to Animation 1 (Supplement) that shows the proportion of continental moisture in the atmosphere day by day. 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.

Focusing on Eurasia (Fig. 3.4), it is striking to see that even in January about 40 to 60 % of the precipitation (looking at ρ_{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, western Asia and a source region covering Myanmar and Thailand (looking at ε_{c}). In July 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.

Furthermore, almost all terrestrial evaporation in Eurasia 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.

3.4. CONCLUSIONS

We conclude that continental moisture recycling plays an important role in the global climate. The most striking example is China, which depends greatly on terrestrial evaporation from the Eurasian continent for its water resources (Figs. 3.1 and 3.2). In this chapter 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 (Eq. 3.11), but locally this can amount to a factor 3 (e.g., in the La Plata basin in South America), or even a factor 10 in western China in summer. 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.

We found that 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). 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.

4

LENGTH AND TIME SCALES OF ATMOSPHERIC MOISTURE RECYCLING

A man has always to be busy with his thoughts if anything is to be accomplished.

Antoni van Leeuwenhoek

It is difficult to quantify the degree to which terrestrial evaporation supports the occurrence of precipitation within a certain study region (i.e., regional moisture recycling) due to the scale- and shape-dependence of regional moisture recycling ratios. In this chapter we present a novel approach to quantify the local spatial and temporal scale of moisture recycling, independent of the size and shape of the region under study. In contrast to previous studies, which essentially used curve fitting, the scaling laws presented by us follow directly from the process equation. Thus, allowing a fair comparison between regions and seasons. It is shown that in the tropics or in mountainous terrain the length scale of recycling can be as low as 500 to 2000 km. In temperate climates the length scale is typically between 3000 to 5000 km whereas it amounts to more than 7000 km in desert areas. The time scale of recycling ranges from 3 to 20 days, with the exception of deserts, where it is much longer. The most distinct seasonal differences can be observed over the Northern Hemisphere: in winter, moisture recycling is not very significant, but in summer it plays a major role in the climate. The length and time scales of atmospheric moisture recycling can be useful metrics to quantify local climatic effects of land-use change.

This chapter is based on:

Van der Ent, R. J., and H. H. G. Savenije, *Length and time scales of atmospheric moisture recycling*, Atmospheric Chemistry and Physics, **11**, 1853–1863, 2011.

4.1. INTRODUCTION

The land surface can play a major role in regional climate [e.g., Pielke Sr et al., 2007]. In fact, many types of land-atmosphere feedback exist that influence precipitation locally (moisture exchange, energy partitioning, particle emissions, etc.). Several studies focused on the sensitivity of precipitation to soil moisture variations [e.g., Findell and Eltahir, 1997; Koster et al., 2004; Dirmeyer et al., 2006; Kunstmann and Jung, 2007] implicitly taken into account various feedbacks mechanisms. Unfortunately, these studies generally result in model-based statistics about the strength of land-atmosphere coupling that is often hard to interpret.

This chapter presents a different approach whereby we focus on the feedback of moisture to the atmosphere. This approach allows the definition of physically meaningful and easy-to-interpret metrics that quantify land-atmosphere coupling through moisture feedback. In this perspective, a widely used metric [e.g., Brubaker et al., 1993; Eltahir and Bras, 1996; Schär et al., 1999; Trenberth, 1999; Burde and Zangvil, 2001a; Mohamed et al., 2005; Dominguez et al., 2006; Dirmeyer and Brubaker, 2007; Bisselink and Dolman, 2008] is what in this study is termed the regional precipitation recycling ratio: the ratio of regionally recycled precipitation to total precipitation in a region (see Eq. 3.1). A disadvantage of this metric is that its magnitude depends on the scale and shape of the region under study. As a result, it remains difficult to compare and classify regions accordingly.

The aim of this research is to derive and present scale- and shape-independent metrics that quantify land-atmosphere coupling through moisture feedback. To that effect we derive a formula to compute the spatial scale of moisture recycling, which is directly based on the process equation. Additionally, we compute the temporal scale of moisture recycling as well. In contrast to the scale- and shape-dependent regional precipitation recycling ratio, these newly derived metrics allow for a fair comparison among regions and seasons and are thus useful in classifying regions according to their local land-atmosphere feedback properties.

4.2. METHODS

4.2.1. SCALE- AND SHAPE-DEPENDENCE OF REGIONAL MOISTURE RECYCLING

Recall that Eqs. 3.1 to 3.5 define the regional moisture recycling process. Comparing these regional recycling ratios cross-regional or across studies has proven to be difficult because of their scale-dependence. Several studies tried to find a relation between the regional precipitation recycling ratio and region scale (see Table 4.1). We observe that the formulas presented in the upper part of Table 4.1 may be justifiable for the spatial range for which they have been derived, but that none of them holds in their limit of applicability, i.e. the very nature of ρ_r requires it to vary between 0 (in a point) and 1 (whole Earth). Moreover, the formulas in Table 4.1 have the drawback that their coefficients are not dimensionless.

In a global study one typically has grid cells of a fixed latitude and longitude; such grid cells are smaller at higher latitudes. In order to compare strength of land-atmosphere feedback in different regions, Dirmeyer and Brubaker [2007] use the global exponent (0.457) of their exponential function (see Table 4.1) to scale regional precip-

Table 4.1: The relationship between scale and precipitation recycling ratio, as found by several authors. Note that the first four studies give an areal average estimate of the recycling ratio, whereas the last gives an estimate for the recycling in a point depending on the recycling distance x before that point.

Study	Formula for ρ_r [–] (Eq. 3.2), with Δx in km, and A in km^2	Derived for (linear scale Δx or area size A)	Study region	Period	Method
Eltahir and Bras, 1994, 1996	$0.0056\Delta x^{0.5}$	Δx: 250–2500 km	Amazon	1985–1990	Eltahir and Bras iterative recycling model
Dominguez et al., 2006[a]	$0.0573\ln(A/1000)$ -0.2748	A: 2.5×10^4–4×10^6 km^2	Contiguous USA	1979–2000	Dynamic recycling model
Dirmeyer and Brubaker, 2007[b], Dirmeyer et al., 2009a[c]	$0.000440A^{0.457}$	A: 10^4–10^6 km^2 A: 10^3–3.5×10^7 km^2	Global continental areas	1979–2004	Quasi-isentropic back-trajectory analysis
Bisselink and Dolman, 2008[d]	~logarithm of A	A: 1.5×10^5–5×10^6 km^2	Central Europe	1979–2001	Dynamic recycling model
	Formula for ρ_{X_1} [–] (Eq. 4.1) with Δx in km	Derived for distance Δx			
Savenije, 1995a, 1996[e]	$1-\exp(-\Delta x/306)$	Δx: 0–1000 km	West Africa to Southern Sahel	1951–1990	Savenije analytical recycling model

[a] This formula is an average of monthly averages (Dominguez et al., 2006, Fig. 8). Dominguez et al. (2006) also present a formula for the months June, July and August only. It should be noted that this formula is the result of curve fitting, and that it is thus not based on their own process equation (Dominguez et al., 2006, Eq. 20).

[b] This is the global formula taken from Dirmeyer and Brubaker (2007, Table 1). They present additional formulas for individual regions.

[c] Note that on the basis of Dirmeyer and Brubaker (2007, Fig. 3) we can estimate their global formula to be different: $\rho_r=0.0003A^{0.457}$, and in the work of Dirmeyer et al. (2009a, Fig. 3) we can estimate it to be: $\rho_r=0.00035A^{0.457}$. Fortunately, this inconsistency does not matter when scaling regional recycling ratios, because for that only the value of the exponent (0.457) is of interest.

[d] No formula given (see Bisselink and Dolman, 2008, Fig. 4).

[e] This formula is not given explicitly, but obtained after filling in the parameters that were calibrated in the work of Savenije (1995a, p. 70).

itation recycling ratios of different grid cells to a common reference area (10^5 km^2). Dirmeyer et al. [2009a] use the same approach to scale precipitation recycling in countries to a common reference area. Dirmeyer and Brubaker [2007, Table 1] also showed that there is in fact a significant spread in the value of the exponent per region, which highlights one of the drawbacks of this approach. But most importantly, their approach does not take into account the effect of the orientation of the moisture flux compared to the orientation and shape of the study region (e.g., grid cell or country). This may lead to an underestimation of the regional feedback process in rectangular shaped grid cells which are oriented perpendicular to the moisture flux, and an overestimation when they are oriented in the same direction as the moisture flux.

4.2.2. SPATIAL SCALE FOR LOCAL PRECIPITATION-EVAPORATION FEEDBACK

In order to derive a new spatial measure we start from the assumption that the atmospheric moisture follows a certain streamline, along with the wind direction, over which it interacts with the land surface. The streamline starts in point X_0, ends in point X_1 and the distance between X_0 and X_1 is Δx. The process equation describing the relationship between precipitation recycling and distance travelled along an atmospheric streamline was derived by Dominguez et al. [2006, Eq. 20], which in our symbols reads:

$$\rho_{X_1}(\Delta x) = 1 - \left(\exp\left(-\frac{E}{Su_\mathrm{h}}\Delta x\right)\right), \tag{4.1}$$

where, ρ_{X_1} is the precipitation recycling ratio in X_1, E is evaporation, S is atmospheric moisture storage (i.e., precipitable water), u_h is horizontal wind speed and Δ_x is the distance along a streamline (starting in x=0), whereby E, S and u_h vary in time and space. These latter variables can be grouped into one simple and meaningful metric, the "local length scale of precipitation recycling":

$$\lambda_\rho = \frac{Su_\mathrm{h}}{E}. \tag{4.2}$$

Substituting Eq. 4.2 in Eq. 4.1 leads to the following equation:

$$\rho_{X_1}(\Delta x) = 1 - \exp\left(-\frac{\Delta x}{\lambda_\rho}\right). \tag{4.3}$$

Note that ρ_{X_1} is defined in a point and not as an areal average. We also want to obtain the average precipitation recycling ratio over a distance, i.e., the regional precipitation recycling ratio ρ_r (Eq. 3.2). Therefore, we integrate Eq. (4.3), fill in the boundary condition ρ_r=0 if Δx=0, and divide by the distance Δx, yielding:

$$\rho_\mathrm{r}(\Delta x) = \frac{\Delta x + \lambda_\rho \exp\left(-\frac{\Delta x}{\lambda_\rho}\right) - \lambda_\rho}{\Delta x}. \tag{4.4}$$

Equations (4.3) and (4.4) both satisfy the condition that ρ=0 if Δx=0, and ρ=1 if $\Delta x=\infty$, independent of the length scale λ_ρ.

The formulation for the evaporation recycling ratio ε is similar; it must likewise hold that ε=0 if x=0, and ε=1 if $x=\infty$, yielding:

$$\varepsilon_{X_0}(\Delta x) = 1 - \left(\exp\left(-\frac{P}{Su_\mathrm{h}}\Delta x\right)\right), \tag{4.5}$$

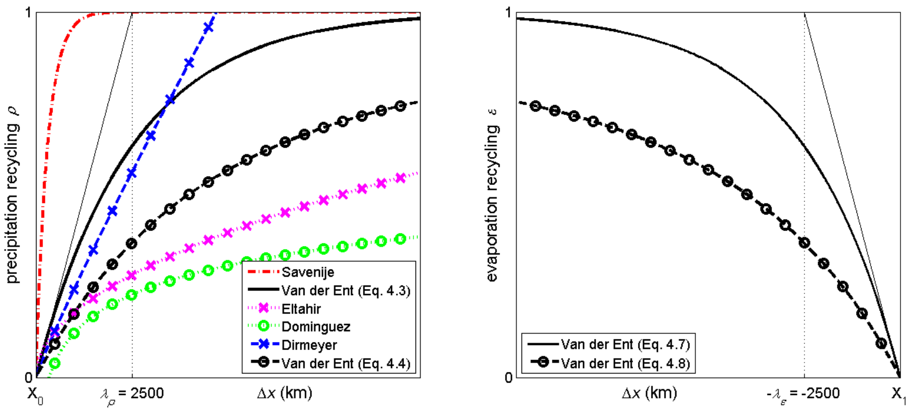


Figure 4.1: The relationship between recycling ratios and distance using different formulas (see Table 4.1. The formula of Savenije [1995a] and Eqs. (4.3) and (4.7) are defined in a point, while the other formulas are defined as an areal average recycling ratio. Note that in the formulas of Dominguez et al. [2006] and Dirmeyer and Brubaker [2007] the area A was replaced by Δx^2, thus we assumed a square region. The results displayed here are meant to highlight different formula behaviour, not to compare magnitudes, since all have parameters that were calibrated for different regions.

where, ε_{X_0} is the evaporation recycling ratio in X_0, i.e., the fraction of evaporation in X_0 that returns to the land surface as precipitation P along the streamline. The "local length scale of evaporation recycling" can be defined as

$$\lambda_\varepsilon = \frac{S u_\mathrm{h}}{P}. \tag{4.6}$$

Substituting Eq. 4.6 in Eq. 4.5 leads to the following equation:

$$\varepsilon_{X_0}(\Delta x) = 1 - \exp\left(-\frac{\Delta x}{\lambda_\varepsilon}\right). \tag{4.7}$$

The average evaporation recycling ratio over a distance, i.e., the regional evaporation recycling ratio ε_r, Eq. 3.5) can be obtained by:

$$\varepsilon_\mathrm{r}(\Delta x) = \frac{\Delta x + \lambda_\varepsilon \exp\left(-\frac{\Delta x}{\lambda_\varepsilon}\right) - \lambda_\varepsilon}{\Delta x}. \tag{4.8}$$

The length scales λ (Eqs. 4.2 and 4.6) have dimension length [L] and can be physically interpreted as average travel distances if the quantities $\frac{S u_\mathrm{h}}{E}$ and $\frac{S u_\mathrm{h}}{P}$ remain constant over the distance Δx. However, it is generally unlikely for these quantities to remain equal over a large distance [Schaefli et al., 2012], so λ must be interpreted as the local process scale of recycling. Figure 4.1 shows how the new formulations (Eqs. 4.3, 4.4, 4.7 and 4.8) behave compared to formulations found by other studies if we assume recycling with a length scale λ of 2500 km. Note that ε depends on the distance that moisture still has to travel until point X_1, while ρ depends on the distance that was already travelled by the moisture from point X_0.

4.2.3. CALCULATING THE LOCAL LENGTH SCALE OF MOISTURE RECYCLING

Here, we aim to find an explicit expression for λ as a function of the regional moisture recycling ratio. If we assume a linear approximation of $\rho_\mathrm{r}(\Delta x)$ trough the origin in Eq. (4.4) for small values of Δx, then

$$\rho_\mathrm{r}\left(\Delta x\right) \approx \frac{\rho_{X_1}}{2}. \tag{4.9}$$

Substituting Eq. (4.9) in Eq. (4.4) and solving for λ_ρ yields:

$$\lambda_\rho \approx -\frac{\Delta x}{\ln(1-2\rho_\mathrm{r})}. \tag{4.10}$$

Using Wolfram|Alpha [2010] we obtained an exact solution of Eq. (4.4) for λ_ρ:

$$\lambda_\rho = \frac{\Delta x}{\mathrm{W}\left(\frac{\exp\left(\frac{1}{\rho_r-1}\right)}{\rho_r-1}\right)+\frac{1}{1-\rho_r}}, \tag{4.11}$$

where $\mathrm{W}\left(a\right)$ is the Lambert W-Function [e.g., Corless et al., 1996], which is defined as the function $\mathrm{W}\left(a\right)$ that satisfies:

$$\mathrm{W}\left(a\right)\exp\left(\mathrm{W}\left(a\right)\right) = a. \tag{4.12}$$

Analogous to Eq. (4.11) the "local length scale of evaporation recycling" can be found by:

$$\lambda_\varepsilon = \frac{\Delta x}{\mathrm{W}\left(\frac{\exp\left(\frac{1}{\varepsilon_\mathrm{r}-1}\right)}{\varepsilon_\mathrm{r}-1}\right)+\frac{1}{1-\varepsilon_\mathrm{r}}}. \tag{4.13}$$

As can be seen from Eqs.(4.11) and(4.13) we need the regional moisture recycling ratios ρ_r and ε_r to compute λ. We have derived these ratios for each 1.5° latitude × 1.5° longitude grid cell (Chapter 2) by performing a special water tagging run. In this run we compute for all grid cells at once the moisture that originated from the "home" grid cell. Horizontal moisture transport of tagged water out of the "home" grid cell is assumed not to return any more to this grid cell. This also means that these runs can be performed with larger time steps, which was indeed confirmed by several tests in which the results were found to be insensitive to the chosen time step. The tagged precipitation originating from and returning to the same grid cell P_r is assumed to be equal to the tagged regional evaporation E_r (see Eq. 3.4). However, this is not really the same due to the residence time of water in the atmosphere, but it is not likely to be dramatically different. Furthermore, we need a representative value for the distance Δx the water travels in a grid cell. We approximate this as follows:

$$\Delta x = L_x\frac{\overline{F}_{\mathrm{bottom},x}}{\overline{F}_{\mathrm{bottom},x}+\overline{F}_{\mathrm{bottom},y}} + L_y\frac{\overline{F}_{\mathrm{bottom},y}}{\overline{F}_{\mathrm{bottom},x}+\overline{F}_{\mathrm{bottom},y}}, \tag{4.14}$$

where, L_x and L_y are the lengths of a grid cell in zonal and meridional direction respectively. Note that the moisture fluxes in the bottom layer (Eqs. 2.4 and 2.5) are used because this is where virtually all of the regional (grid cell) scale recycling takes place.

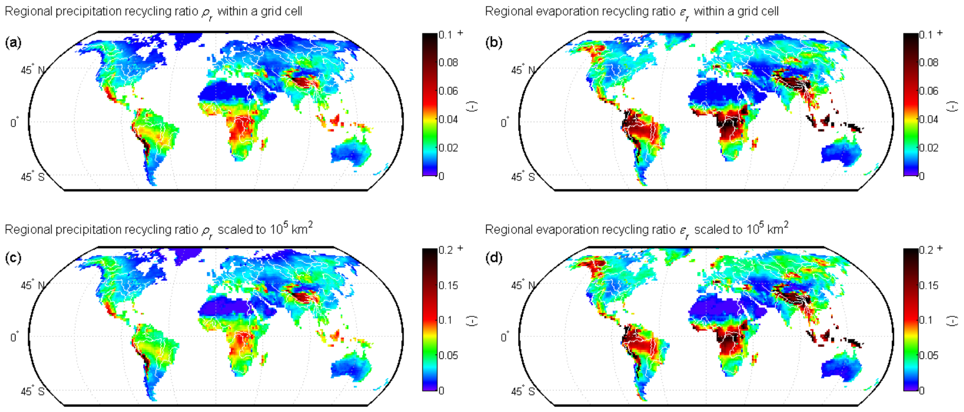


Figure 4.2: Average regional moisture recycling ratios. **(a)** regional precipitation recycling ratio ρ_r within a 1.5°×1.5° grid cell, **(b)** regional evaporation recycling ratio ε_r within a 1.5°×1.5° grid cell, **(c)** regional precipitation recycling ratio ρ_r scaled to a reference area of 10^5 km^2, and **(d)** regional evaporation recycling ratio ε_r scaled to a reference area of 10^5 km^2.

4.2.4. LOCAL TIME SCALE OF MOISTURE RECYCLING

Besides the length scales of precipitation-evaporation interactions we are also interested in its time scales. Trenberth et al. [1998] offers an approach to calculate these time scales; he defines the "local depletion time of atmospheric moisture" as

$$T_\mathrm{P} = \frac{\overline{S}}{\overline{P}}, \tag{4.15}$$

where S is atmospheric moisture storage (i.e., precipitable water). Similarly, Trenberth [1998] defines the restoration time, which we prefer to term the "local replenishment time of atmospheric moisture":

$$T_\mathrm{E} = \frac{\overline{S}}{\overline{E}}. \tag{4.16}$$

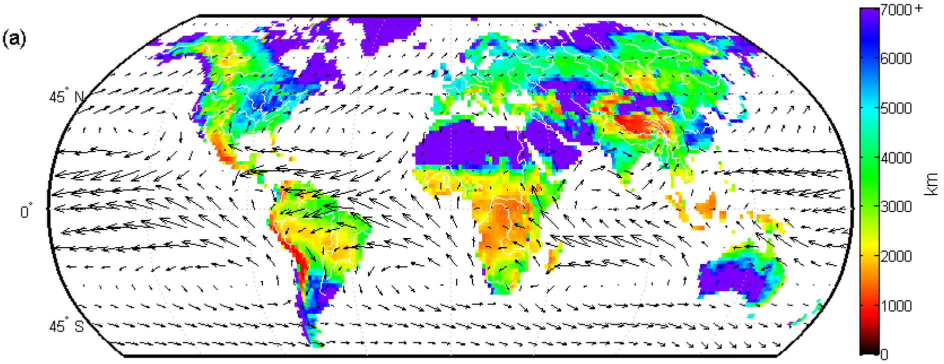
When both replenishment time T_E and depletion time T_P in a region are small one would expect high regional moisture recycling, but this obviously also depends on the horizontal atmospheric moisture fluxes coming in and out of a region. Note that both T_E and T_P (Eqs. 4.15 and 4.16) are local timescales for precipitation and evaporation, which give an indication for the residence time of atmospheric moisture if horizontal moisture transport is small. Actual residence time should be calculated by including age tracers (Section 2.5 and Chapter 5). However, that does not yield local metrics, which is the objective of this chapter.

4.3. RESULTS AND DISCUSSION

4.3.1. LENGTH AND TIME SCALES OF MOISTURE FEEDBACK

Figure 4.2a, b shows the annual average regional moisture recycling ratios (ρ_r and ε_r) on the 1.5° latitude×1.5° longitude grid. Following the approach of Dirmeyer and Brubaker

Local length scale of precipitation reycling λ_ρ



Local length scale of evaporation reycling λ_ε

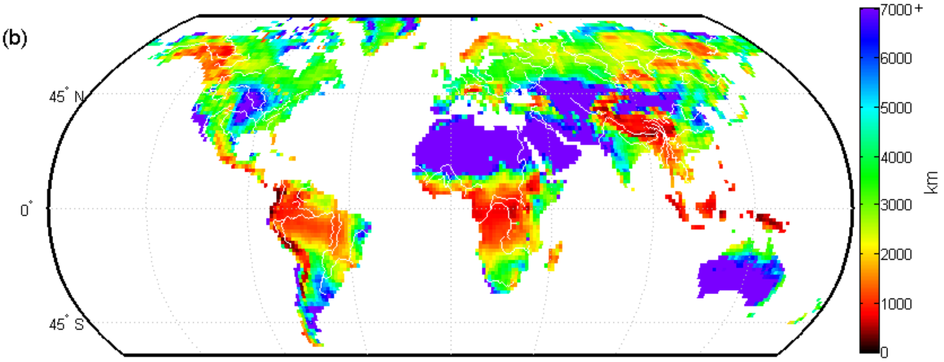


Figure 4.3: Average length scales of moisture recycling (Eqs. 4.11 and 4.13). **(a)** local length scale of precipitation recycling λ_ρ, and **(b)** local length scale of evaporation recycling λ_ε. These are local characteristics of feedback strength, which can be interpreted as travel distances of atmospheric water, under the local conditions of a grid cell. The arrows in (a) indicate the moisture fluxes in the lowest part of the atmosphere (approximately the lowest 2 km of the atmosphere at standard pressure, Eq. 2.5).

[2007] we have scaled these ratios with an exponent (0.457) to a common reference area of 10^5 km^2 (Fig. 4.2c, d). We see that on higher latitudes new regions of high regional recycling pop up. However, as mentioned before, this scaling approach does not take into account the orientation of the moisture flux compared to the shape of a region.

Figure 4.3 shows the annual average length scales of moisture recycling (λ_ρ and λ_ε) calculated with Eqs. (4.11) and (4.13). We like to emphasize that these length scales are local scale-independent characteristics. They are process scales: the inverse value of λ represents the spatial gradient of the recycling process and λ itself is a length scale of the spatial variability of moisture recycling. Note, that these process scales are different from actual travel distances [e.g., Sodemann et al., 2008; Dirmeyer et al., 2014; Van der Ent et al., 2014]. However, the length scales λ_ρ and λ_ε can be interpreted as the mean distance a water particle travels under local hydrological and climatological conditions. This is analogous to e.g. human travel, where someone's local speed can differ significantly from his average speed. Furthermore, it should be noted that a smaller length scale indicates a higher feedback strength, since this means that there is more recycling of moisture (see Eqs. 4.10, 4.11 and 4.13). As a result, we believe that these length scales (Fig. 4.3) have more physical meaning than the scaled regional recycling ratios (Fig. 4.2c, d). From visual comparison, the patterns in Figs. 4.2c, d and 4.3 appear to be similar, except at higher latitudes, where the approach of scaling (Fig. 4.2c, d) is weak.

Therefore, we have made a numerical comparison in Table 4.2 between different metrics for moisture feedback for two differently shaped grid cells (one in North-West Canada and one in the Amazon). If one would look at the ρ_r within a 1.5°×1.5° grid cell one would conclude that the local feedback strength is higher in the Amazon grid cell. Next, taking into account the difference in grid size, and thus scaling ρ_r following the approach of Dirmeyer and Brubaker [2007], one would consider the local feedback strength to be about the same. However, taking into account also the orientation of the moisture flux compared to the shape of the grid cell, we can observe that the length scale of precipitation recycling λ_ρ for the grid cell in North-West Canada is shorter than for the grid cell in the Amazon, thus indicating a higher feedback strength. The same reasoning can be followed for evaporation recycling. The time scales of moisture also indicate higher feedback strength for the Canadian grid cell.

To complete the picture, Fig. 4.4 shows the local depletion and replenishment time of atmospheric moisture (T_P and T_E, Eqs. 4.15 and 4.16), computed following the approach of Trenberth et al. [1998]. Looking at Figs. 4.3 and 4.4 jointly, we can observe that the local moisture feedback strength is very heterogeneously distributed over the world. In general, the highest feedback is observed in tropical and/or mountainous regions, while the least feedback is observed in arid climate zones.

4.3.2. LOCAL MOISTURE RECYCLING BY CONTINENT

Looking at North America the length scale of precipitation recycling λ_ρ (Fig. 4.3a) is typically between 1500 and 4000 km over the Rocky Mountains. This indicates relatively high local feedback, but the average precipitable water S is low (see Fig. 2.1. The windward side of the Canadian Rocky Mountains beautifully illustrates the difference between λ_ρ (Fig. 4.3a) and λ_ε (Fig. 4.3b): most precipitation is brought to the continent over the ocean indicated by low λ_ρ, but λ_ε is only about 1500 km, thus indicating a relative fast feedback of evaporated moisture. In the east of North America, depletion and replenishment times (T_P and T_E, Fig. 4.4) remain in the same order (3–12 days) as in the west of the continent. However, Fig. 4.3 indicates that local recycling plays a less dominant role and moisture is transported over greater distances, signifying that the horizontal moisture fluxes are greater.

In the northern part of the Amazon region, the length scale of precipitation recycling

Table 4.2: Different measures of moisture feedback for a rectangular grid cell (in North-West Canada) an almost square grid cell (in the Amazon region). Note that a shorter length scale indicates more moisture recycling.

	Grid cell in North-West Canada	comparison for spatial measures	Grid cell in the Amazon region
Coordinates of the centre of the grid cell (latitude, longitude)	64.5° N, 129° W		6° S, 49.5° W
Area size grid cell A (km^2)	1.20×10^4		2.76×10^4
Zonal length L_x (km)	76		165
Meridional length L_y (km)	167		167
Regional precipitation recycling ratio ρ_r within a $1.5° \times 1.5°$ grid cell (–)	0.017	$<$	0.027
Regional precipitation recycling ratio ρ_r scaled (with exponent 0.457) to a reference area of 10^5 km^2 (–)	0.047	$\approx$	0.049
Local length scale of precipitation recycling λ_ρ (km)	2.4×10^3	$<$	3.0×10^3
Depletion time of atmospheric moisture T_P (days)	4.2		5.6
Regional evaporation recycling ratio ε_r within a $1.5° \times 1.5°$ grid cell (–)	0.045	$<$	0.059
Regional evaporation recycling ratio ε_r scaled (with exponent 0.457) to a reference area of 10^5 km^2 (–)	0.122	$\approx$	0.108
Local length scale of evaporation recycling λ_ε (km)	0.9×10^3	$<$	1.3×10^3
Replenishment time of atmospheric moisture T_E (days)	11.0		12.3

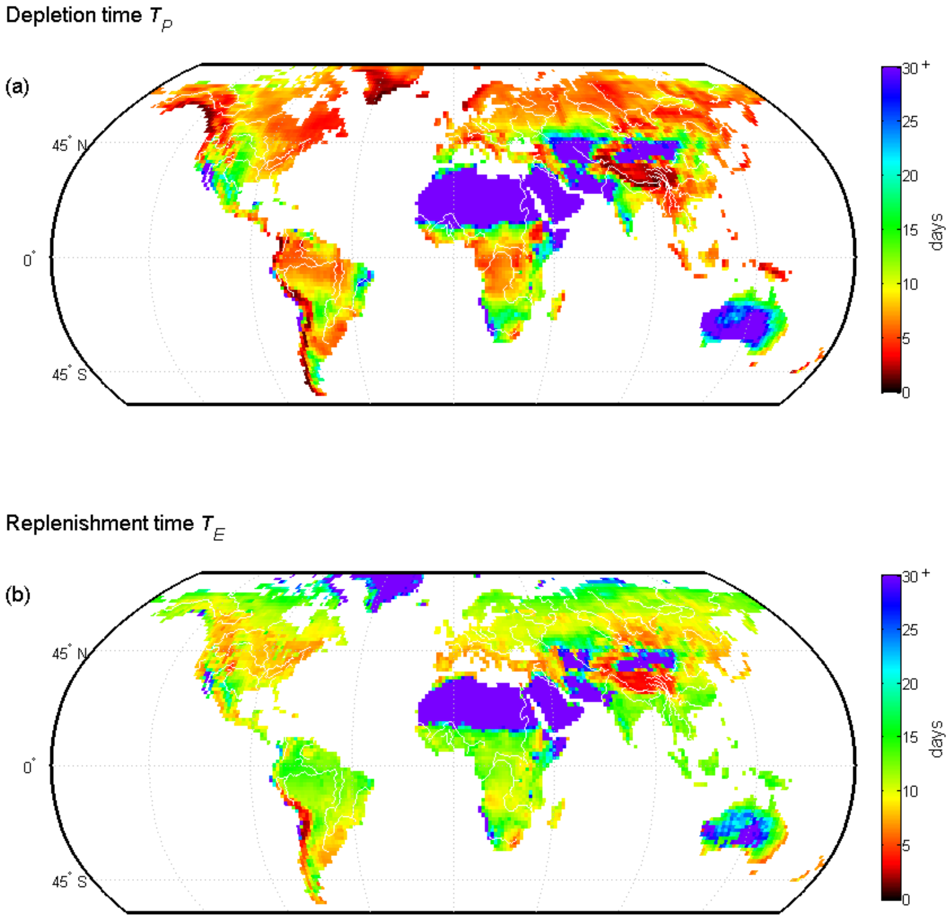


Figure 4.4: Average time scales of moisture feedback. **(a)** local depletion time T_{P} (Eq. 4.15), i.e., the time it takes to completely deplete atmospheric moisture assuming precipitation to remain constant and not considering lateral fluxes, and **(b)** local replenishment time T_{E} (Eq. 4.16), i.e., the time it takes to completely replenish atmospheric moisture by assuming evaporation to remain constant and not considering lateral fluxes.

λ_ρ (Fig. 4.3a) is about 3500 km but in the southern part of the Amazon region λ_ρ is less than 2000 km, indicating a less important role for large scale convergence and a more important role for local moisture recycling. The length scale of evaporation recycling λ_ε is less than 2000 km for the whole Amazon region, and this in fact corresponds with Fig. 3.1 where we can observe that 70% of the precipitation in the centre of the South American continent is of terrestrial origin. Local moisture recycling is highest near the Andes mountains, which is indicated by both Figs. 4.3 and 4.4.

In Africa we can observe two very different systems. First there is the Sahara, which basically has no water and therefore no local moisture feedback. Second, we can observe a relative strong moisture feedback over the rest of the continent, especially in the Congo basin, where the length scale of evaporation recycling λ_ε (Fig. 4.3b) can be as low as 500 to 1000 km, and depletion time T_P (Fig. 4.4a) well below 7 days. The Congo region lacks major mountain ridges to trigger rainfall, and in this light the forests, sustaining atmospheric moisture through evaporation, are of utmost importance for the region's water resources.

The strongest local feedback in Europe is observed around the Mediterranean (Figs. 4.3 and 4.4). Furthermore, the northern part of Eurasia is characterized by a long belt wherein the length scale of precipitation recycling λ_ρ (Fig. 4.3a) is around 4000 km and replenishment time T_E (Fig. 4.4b) around 10 days. Below that belt, in the Middle East, central Asia and the Gobi desert, land-atmosphere feedback is very low and this is also reflected by small precipitation amounts (Fig. 2.2a) observed for these regions. In the most northern parts of Siberia, average depletion time T_P (Fig. 4.4a) is as low as 5 days. This does not necessarily reflect strong moisture feedback, since replenishment time T_E (Fig. 4.4b) is around 15 days.

Over the Tibetan Plateau we can observe very strong local moisture recycling, with both λ_ρ and λ_ε (Fig. 4.3) around 1000 km. This strong feedback was also found by earlier studies on the isotopic compositions of rainfall around the Tibetan Plateau [e.g., Tian et al., 2001; Yu et al., 2007; Liu et al., 2008]. In India and the east of China, local moisture recycling plays again a less important role. Very strong local recycling is observed in the tropical regions of Southeast Asia where λ_ε (Fig. 4.3b) can be well below 1000 km. Given that total P and E (Fig. 2.2a) are very high as well, there is also a high absolute feedback of moisture.

Finally, local recycling of moisture is of little significance over the central part of Australia; the length scales (λ_ρ and λ_ε Fig. 4.3) are over 7000 km, and the time scales are over 30 days. Local recycling is only significant in the outer north and east of Australia as well as in New Zealand. In New Zealand the length scales (λ_ρ and λ_ε, Fig. 4.3) are around 4000 km while the time scales of recycling are around 7 days (T_P and T_E, Fig. 4.3). As the spatial resolution of ERA-I data used here does not very well capture some of the mountainous terrain in New Zealand, local recycling could in reality be of more importance.

4.3.3. SEASONAL VARIATIONS

Figure 4.5 shows the length and time scales of moisture recycling for typical winter and summer conditions. For the calculation of the regional evaporation recycling ε_r (and thus also the length scale λ_ε, Figs. 4.5c and d) we did invoke the assumption that $P_\mathrm{r} = E_\mathrm{r}$, which is only true if there is no substantial change in atmospheric moisture storage (Eq. 3.4), so these results should be interpreted with caution.

Yet it is clear that there is considerable seasonal variation in local moisture feedback. For example, the Northern Hemisphere above 45° N in winter shows a depletion time of atmospheric moisture T_P (Fig. 4.5e) which is generally lower than 10 days, however replenishment time T_E (Fig. 4.5g) is over 30 days, resulting in λ_ρ (Fig. 4.5a) being over 7000 km. Even though λ_ε (Fig. 4.5c) above 45° N indicates a relative fast feedback of evaporated moisture, total evaporation in winter is known to be low for this region. Local

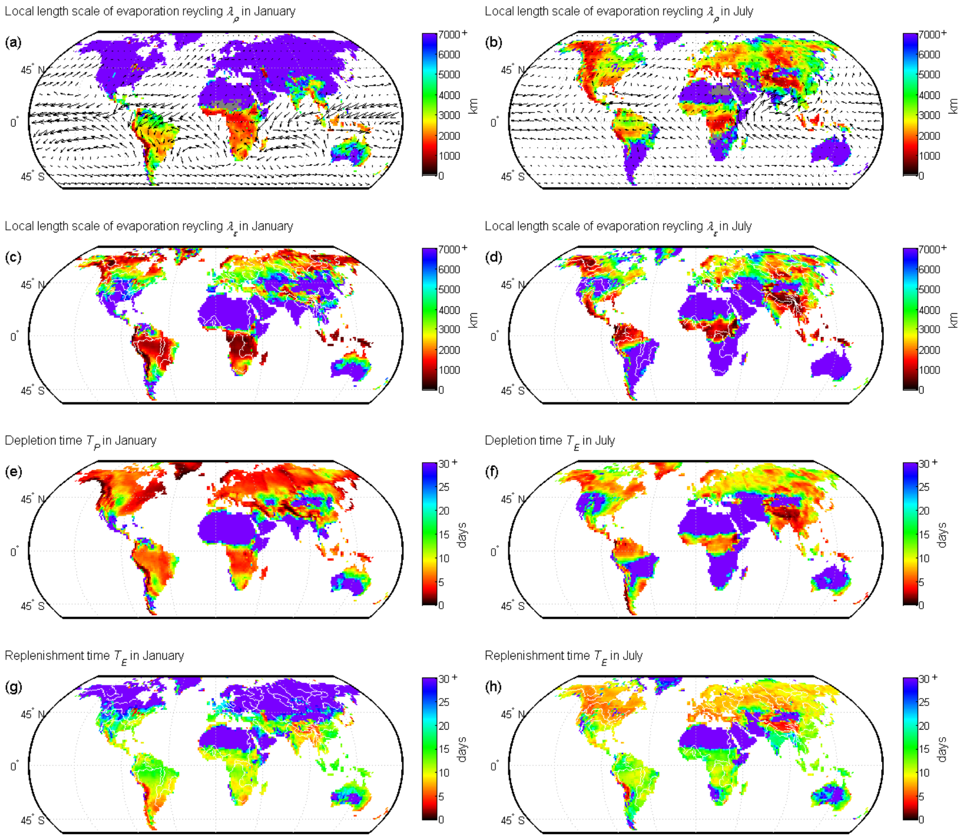


Figure 4.5: Average length and time scales of moisture recycling in January (left column) and July (right column). The arrows in (a) and (b) indicate the moisture fluxes in the lowest part of the atmosphere (approximately the lowest 2 km of the atmosphere at standard pressure, Eq. 2.5.

moisture recycling can be observed to play a much more important role in July (Fig. 4.5e–h). For other regions similar differences between winter and summer conditions can be observed, whereby land-atmosphere feedback is generally (and not surprisingly) greater during wet and warm periods.

4.4. CONCLUSIONS

We have successfully found a method that can convert scale- and shape-dependent regional moisture recycling ratios into representative, and physical meaningful, local length scales of moisture recycling, λ_ρ and λ_ε (Fig. 4.3), that do not suffer from scale- or shape-dependence. They allow for a fair comparison of local moisture recycling strength between regions and seasons. Moreover, they consider recycling from both a precipitation and an evaporation perspective. For the study of land-atmosphere interactions these new metrics are therefore more useful than the regional precipitation recycling ratio ρ_r (Fig. 4.2a, c) alone.

In addition, we calculated the representative time scales of moisture recycling (T_P and T_E, Fig. 4.4). Analysis of both the length and times scales yielded the identification of several hot spots of high local moisture recycling, in particular in and around mountainous areas (such as the Rocky Mountains, Andes, Alps, Caucasus and Tibetan Plateau), and in the regions with tropical forest (such as the Amazon, Congo, Indonesia). Moreover, considerable seasonal differences can be observed which overall indicate that local moisture recycling is most significant in summer.

Although this paper provided a global analysis of local moisture recycling, the methodology may also be applied on smaller grids, with more detailed topography, and on periods smaller than years and months. Potentially, it can thus be a useful tool for detailed analysis of local effects of land-use change. Whereby the length scale of precipitation recycling λ_ρ (Eqs. 4.2 and 4.11) can provide a measure to quantify the effect of, for instance, deforestation on local climate. A priori, we presume λ_ρ to be larger after deforestation.

5

CONTRASTING ROLES OF INTERCEPTION AND TRANSPIRATION IN THE WATER CYCLE

Such is the audacity of man, that he hath learned to counterfeit Nature, yea, and is so bold as to challenge her in her work.

Pliny the Elder

The contribution of land evaporation to local and remote precipitation (i.e., moisture recycling) is of significant importance to sustain water resources and ecosystems. But how important are different evaporation components in sustaining precipitation? We separately track the direct (interception, soil moisture evaporation) and delayed (transpiration) components of evaporation through the atmosphere, forward, as well as, backward in time. We also include age tracers to study the atmospheric residence times of these components. As the main result we present a new image of the global hydrological cycle that includes quantification of partitioned evaporation and moisture recycling, as well as the atmospheric residence times of all fluxes. We demonstrate that evaporated interception is

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This chapter is based on:

Van der Ent, R. J., L. Wang-Erlandsson, P. W. Keys, and H. H. G. Savenije, *Contrasting roles of interception and transpiration in the hydrological cycle – Part 2: Moisture recycling*, Earth System Dynamics Discussions, **5**, 281–326, 2014.

more likely to return as precipitation on land than transpired water. On average, direct evaporation (essentially interception) is found to have an atmospheric residence time of 8 days, while transpiration typically resides 9 days in the atmosphere. Interception recycling has a much shorter local length scale than transpiration recycling, thus interception generally precipitates closer to its evaporative source than transpiration, which is particularly pronounced outside the tropics. We conclude that interception mainly works as an intensifier of the local hydrological cycle during wet spells. On the other hand, transpiration remains active during dry spells and is transported over much larger distances downwind where it can act as a significant source of moisture. Thus, as various land-use types can differ considerably in their partitioning between interception and transpiration, our results stress that land-use changes (e.g., forest to cropland conversion) do not only affect the magnitude of moisture recycling, but could also influence the moisture recycling patterns and hence lead to a redistribution of water resources.

5.1. INTRODUCTION

In Chapter 3 we have shown global maps of continental precipitation recycling, indicating that about 40 % of the continental precipitation is of continental origin, but that this number can be much higher, e.g. in China [see also Bosilovich et al., 2002; Yoshimura et al., 2004; Goessling and Reick, 2011, 2013a]. Numaguti [1999] included a wide variety of moisture tracers into a general circulation model (GCM) to track water and its age through the atmosphere as well as through the soil. It was found, for example, that, counting from the moment of evaporation from the ocean, the mean water age of precipitating water in north-eastern Asia could exceed 0.5 year, whereby a water particle had been recycled on average 2 times. A comprehensive overview and quantification of import and export of water vapour between countries was given by Dirmeyer et al. [2009a]. While nearly all previous studies focused on the "recycled" part of precipitation, in Chapter 3 [Van der Ent et al., 2010] we also focused on the "recycled" part of evaporation. We, for example, found that in evaporation recycling "hot spots" such as East Africa and the northern Amazon about 60 to 90 % of the evaporation returns as continental precipitation. In Chapter 4 [Van der Ent and Savenije, 2011] we showed that in the tropics and in mountainous terrain the local length scales of moisture recycling can be as low as 500 to 2000 km.

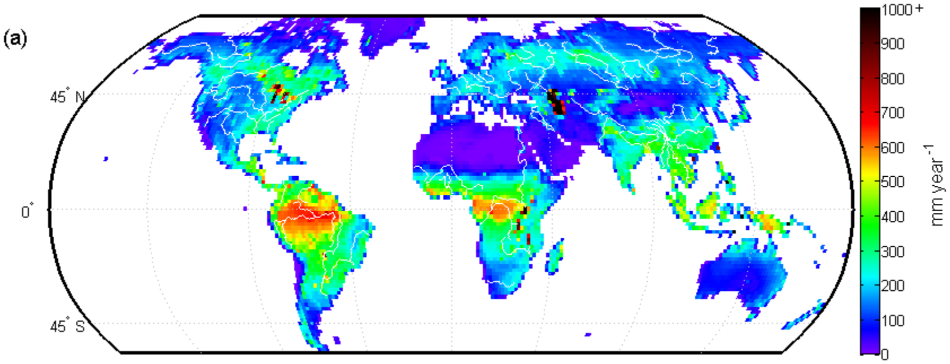
From the numbers above it is evident that moisture recycling is of significant importance for water resources, agriculture, and ecosystems. Some studies have looked specifically at these issues. For instance, Dominguez and Kumar [2008] studied the central United States plains and concluded that local evaporative fluxes ensure ecoclimatological stability through a continued moisture contribution when advective fluxes diminish. Another example of ecosystem importance is the study by Spracklen et al. [2012] who found that air passing over dense vegetation produces much more rain than air passing over sparse vegetation. Regarding agriculture, Bagley et al. [2012] reported that reduced moisture recycling due to land-cover change may lead to potential crop yield reductions of 1 to 17 % in the world's breadbasket regions, while other studies looked at the positive effect of irrigation in increasing moisture recycling [e.g., Tuinenburg et al., 2012; Wei et al., 2012].

Land-use change does not only alter total evaporation, but also its partitioning into its direct and delayed components. It is therefore somewhat surprising that all moisture recycling studies have reported their results in terms of moisture recycling due to total evaporation only. It has been speculated, however, that interception (direct evaporation) and transpiration (delayed evaporation) are likely to play a different role in moisture recycling [Savenije, 2004]. This has, however, never been quantified. A possible method would be to try to link stable water isotope measurements to moisture recycling [e.g., Kurita et al., 2004; Tian et al., 2007; Risi et al., 2013]. Gat and Matsui [1991] used the d-excess value of stable water isotopes to estimate that 20–40 % of the evaporative flux in the Amazon basin is fractionating the isotopic composition. Theoretically, d-excess values in precipitation from for example the Global Network of Isotopes in Precipitation (GNIP) database [Froehlich et al., 2001] could be combined with estimates of moisture recycling to infer the contributions of fractionating and non-fractionating evaporation. However, the spatial and temporal resolution of available isotopic data is rather limited. Another difficulty is the fact that while it is generally accepted that open water evaporation is fractionating and evaporation of transpired water is not, for vegetation interception and floor interception the extent of fractionation is less clear [e.g., Gat and Matsui, 1991; Henderson-Sellers et al., 2002].

Global land-surface models generally include a partitioning of terrestrial evaporation into several direct and delayed components. These components include evaporation from transpiration, vegetation interception, floor interception, soil moisture and open water, although the names and exact definitions of these terms can differ from model to model. In any case, information on these individual components is not often reported and data are generally not provided [e.g., Mueller et al., 2013]. This is probably the reason that, to our knowledge, no studies applying numerical atmospheric moisture tracking [see Gimeno et al., 2012; Van der Ent et al., 2013] have considered the different components of terrestrial evaporation separately. In order to obtain a tailor-made dataset of partitioned evaporation, Wang-Erlandsson et al. [2014] developed STEAM (Simple Terrestrial Evaporation to Atmosphere Model). This is a global hydrological land-surface model, which is specifically focused on realistic estimations of partitioned evaporation and how this depends on vegetation and land use.

The goal of this chapter is to investigate and quantify the importance of the different components of evaporation in the hydrological cycle over continents. We aim to present a new image of the global hydrological cycle which includes quantification of partitioned evaporation and moisture recycling as well as the atmospheric residence times of the individual components. Furthermore, we aim to provide spatially distributed global maps of different moisture recycling metrics that describe the role of interception and transpiration for local and remote moisture recycling processes in time and space. This provides new information on the susceptibility of regions to land-use changes. For example, if region A receives precipitation from transpiration in region B's dry season, then region A may experience increased dryness if region B was to be desertified.

Direct evaporation E_i



Transpiration E_t

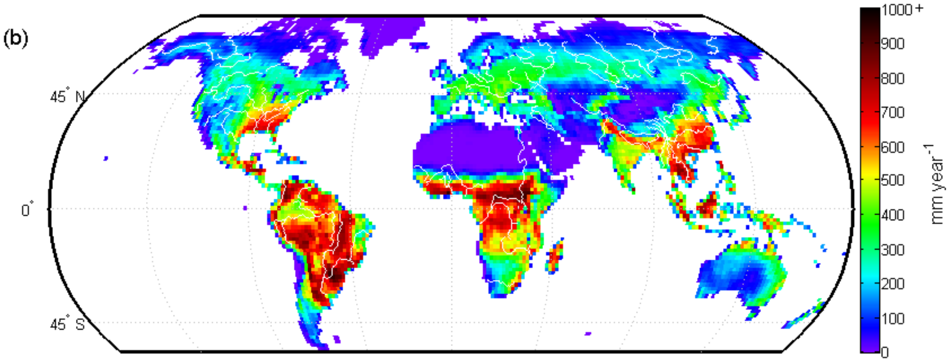


Figure 5.1: Annual average partitioned evaporation on the continent. **(a)** Direct evaporative flux, dominated by interception (Eq. 5.2), and **(b)** Delayed evaporative flux, i.e., transpiration (Eq. 5.3).

5.2. METHODS

5.2.1. INPUT DATA

As input to our atmospheric moisture tracking model, WAM-2layers (Water Accounting Model-2layers) (see Chapter 2) we use all regular ERA-I data, but replace the evaporation field (not over the oceans) by the output from STEAM (Simple Terrestrial Evaporation to Atmosphere Model) [Wang-Erlandsson et al., 2014]. STEAM evaporation data is also based on ERA-I [see Wang-Erlandsson et al., 2014, for details]. The output of STEAM is

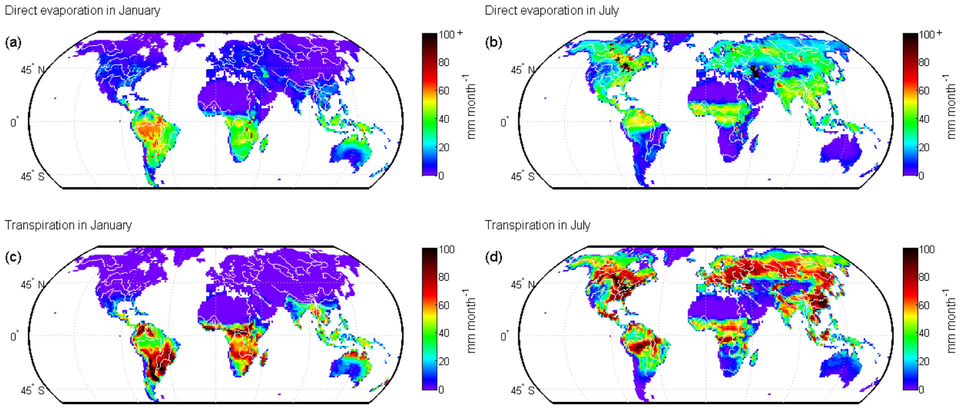


Figure 5.2: Partitioned evaporation for January (left column) and July (right column).

the terrestrial evaporation E partitioned into five components:

$$E = E_{\text{vegetation\_interception}} + E_{\text{floor\_interception}} + E_{\text{soil\_moisture}} + E_{\text{inland\_waters}} + E_{\text{transpiration}}. \tag{5.1}$$

Here we combine the direct (purely physical) evaporative fluxes into one term E_{i}, containing evaporation from interception, soil moisture and inland waters:

$$E_{\text{i}} = E_{\text{vegetation\_interception}} + E_{\text{floor\_interception}} + E_{\text{soil\_moisture}} + E_{\text{inland\_waters}}. \tag{5.2}$$

This term consists of the direct fluxes from vegetation interception, floor interception and soil moisture evaporation, which have a small storage reservoir and small residence time at the surface [Wang-Erlandsson et al., 2014, Figs. 4 and 5]. As the relative global contribution from the soil moisture and inland waters is quite small [Wang-Erlandsson et al., 2014, Fig. 2], this term mainly represents interception. Transpiration, the delayed (biophysical) evaporative flux, on the other hand provides a slow feedback with a large storage reservoir, which is the other component that we track:

$$E_{\text{t}} = E_{\text{transpiration}}. \tag{5.3}$$

The figures of partitioned evaporation that follow from STEAM's output are shown in Fig. 5.1 and Fig. 5.2. Figure 5.1 presents the annual averages, while Fig. 5.2 presents the January and July figures.

5.2.2. DEFINITIONS OF MOISTURE RECYCLING EXTENDED TO PARTITIONED EVAPORATION

Here we extend the definitions for moisture recycling metrics to reflect the feedback from interception and transpiration separately. First, we start with the metrics related to continental moisture recycling, which are measures for land-atmosphere coupling at continental scale (see Chapter 3). Second, we define metrics related to the atmospheric residence time of the moisture recycling process (new). Finally, we define metrics that act as measure for local moisture feedback (see Chapter 4).

CONTINENTAL MOISTURE RECYCLING

In the context of continental moisture recycling precipitation on land P can be separated as follows:

$$P = P_o + P_c = P_o + P_{c,i} + P_{c,t}, \tag{5.4}$$

where P_o is the part that is of oceanic origin and P_c is the continentally recycled part of the precipitation (i.e., most recently evaporated from a continental area). P_c can be split further into $P_{c,i}$ (i.e., the recycled precipitation that originates from vegetation interception, floor interception, soil moisture and inland waters) and $P_{c,t}$ (i.e., the recycled precipitation that originates from transpiration). The “continental precipitation recycling ratio for interception” is defined as

$$\rho_{c,i} = \frac{P_{c,i}}{P} \tag{5.5}$$

and the “continental precipitation recycling ratio for transpiration” as

$$\rho_{c,t} = \frac{P_{c,t}}{P};. \tag{5.6}$$

Also in the context of continental moisture recycling, we split land evaporation E:

$$E = E_o + E_c = E_{o,i} + E_{o,t} + E_{c,i} + E_{c,t}, \tag{5.7}$$

where E_o is the part of the evaporation that precipitates on the ocean and E_c is the continental recycling part (i.e., returns as continental precipitation). Subscripts “i” and “t” denote interception (Eq. 5.2) and transpiration (Eq. 5.3) respectively. This also allows us to define the “continental evaporation recycling ratio for interception”:

$$\varepsilon_{c,i} = \frac{E_{c,i}}{E} \tag{5.8}$$

and the “continental evaporation recycling ratio for transpiration”:

$$\varepsilon_{c,t} = \frac{E_{c,t}}{E}. \tag{5.9}$$

The two metrics in Eqs. (5.8) and (5.9) both carry information about their relative contribution to moisture recycling as well as their relative contribution to total evaporation. To study the recycling efficiency of the individual partitioned fluxes we define the “continental evaporation recycling efficiency for interception”:

$$\varepsilon_{c,ii} = \frac{E_{c,i}}{E_i} \tag{5.10}$$

and the “continental evaporation recycling efficiency for transpiration”:

$$\varepsilon_{c,tt} = \frac{E_{c,t}}{E_t}. \tag{5.11}$$

LIFETIME OF CONTINENTAL MOISTURE RECYCLING

In Chapter 4 we calculated the local depletion and restoration time scales of atmospheric moisture, defined as the atmospheric moisture storage over precipitation and evaporation respectively (Eqs. 4.15, 4.16 and Fig. 4.4). Trenberth [1998] estimated the average time scale over land to be around 9 days. However meaningful, these time scales only provided local information , but did not indicate the actual time spent in the atmosphere by a recycled water particle. Therefore, we propose new metrics that describe the actual time spent in the atmosphere. We define the "lifetime of continental precipitation recycling" as

$$\tau_{\rho,\mathrm{c}} = N\left(P_\mathrm{c} \leftarrow E_\mathrm{c}\right), \tag{5.12}$$

where N stands for the time spent in the atmosphere, or in other words, the age of the water particle. The lifetime of continentally recycled precipitation $\tau_{\rho,\mathrm{c}}$ is a measure at the point where a water particle precipitates and stands for the average time spent between continental evaporation and continental precipitation, or in other words, the average age at the point where a water particle precipitates. Note that $\tau_{\rho,\mathrm{c}}$ only provides information on the recycled part of the precipitation and not on the total precipitation (see Eq. 5.4). Likewise we define the "lifetime of interception that recycles on land" as

$$\tau_{\varepsilon,\mathrm{c,i}} = N\left(E_\mathrm{c,i} \rightarrow P_\mathrm{c,i}\right) \tag{5.13}$$

and the "lifetime of transpiration that recycles on land":

$$\tau_{\varepsilon,\mathrm{c,t}} = N\left(E_\mathrm{c,t} \rightarrow P_\mathrm{c,t}\right). \tag{5.14}$$

Both metrics in Eq. (5.13) and (5.14) are defined at the place where evaporation occurs at the land surface (E_c in Eq. 5.7) and determine the average time an evaporated particle that recycles over land will spend in the atmosphere. For the calculation of these lifetimes we included water age tracers in our model (Section 2.5).

LOCAL RECYCLING AND THE LENGTH SCALES OF EVAPORATED WATER

Besides the continental recycling metrics, we are also interested in the feedback between evaporation and precipitation locally. For a certain predefined region (e.g., a grid cell) we can split evaporation as follows:

$$E = E_\mathrm{a} + E_\mathrm{r} = E_\mathrm{a,i} + E_\mathrm{a,t} + E_\mathrm{r,i} + E_\mathrm{r,t}, \tag{5.15}$$

where E_a is the part of the evaporation that is advected away from the grid cell and E_r is the regional recycling part (i.e., recycles within the same region). Subscripts "i" and "t" again denote interception (Eq. 5.2) and transpiration (Eq. 5.3) respectively. We can use this to define the "regional evaporation recycling efficiency for interception" as

$$\varepsilon_\mathrm{r,ii} = \frac{E_\mathrm{r,i}}{E_\mathrm{i}} \tag{5.16}$$

and the "regional evaporation recycling efficiency for transpiration" as

$$\varepsilon_\mathrm{r,tt} = \frac{E_\mathrm{r,t}}{E_\mathrm{t}}. \tag{5.17}$$

However, we should realise that Eqs. 5.16 and 5.17 are scale- and shape-dependent, which is problematic as the grid cells we are dealing with differ in scale and shape. In Section 4.2 we dealt with this problem by deriving equations, which converted the regional moisture recycling ratios to local length scales of the moisture recycling process. Analogously, the “local length scale of evaporation recycling for interception” can be found by:

$$\lambda_{\varepsilon,\mathrm{i}} = \frac{\Delta x}{\mathrm{W}\left(\frac{\exp\left(\frac{1}{\varepsilon_{\mathrm{r,ii}}-1}\right)}{\varepsilon_{\mathrm{r,ii}}-1}\right)+\frac{1}{1-\varepsilon_{\mathrm{r,ii}}}} \tag{5.18}$$

and the “local length scale of evaporation recycling for transpiration” can be found by:

$$\lambda_{\varepsilon,\mathrm{t}} = \frac{\Delta x}{\mathrm{W}\left(\frac{\exp\left(\frac{1}{\varepsilon_{\mathrm{r,tt}}-1}\right)}{\varepsilon_{\mathrm{r,tt}}-1}\right)+\frac{1}{1-\varepsilon_{\mathrm{r,tt}}}}. \tag{5.19}$$

Note that both $\lambda_{\varepsilon,\mathrm{i}}$ and $\lambda_{\varepsilon,\mathrm{t}}$ are defined by $\frac{Su_\mathrm{h}}{P}$ (Eq. 4.6), so they are only equal if evaporation from interception and transpiration occur simultaneously. However, in many cases they will occur at different times when the quantity $\frac{Su_\mathrm{h}}{P}$ is different [see e.g., Wang-Erlandsson et al., 2014]. As a result, $\lambda_{\varepsilon,\mathrm{i}}$ and $\lambda_{\varepsilon,\mathrm{t}}$ are likely to have different values and can be effectively used in revealing their relative importance for local moisture feedback.

5.3. RESULTS AND DISCUSSION

5.3.1. NEW IMAGE OF THE HYDROLOGICAL CYCLE OVER LAND

Figure 5.3 presents an image of the global hydrological cycle over land. In contrast to traditional images of the hydrological cycle [e.g., Chahine, 1992] we include a quantification of moisture recycling, partitioned evaporation and the lifetime of all these processes separately. Before precipitation falls on land, its average atmospheric residence time is about 10 days. We estimate that about 38 % of continental precipitation P is transformed into runoff Q and the remaining part evaporates by direct (purely physical) fluxes E_i and by the delayed (biophysical) flux E_t (see Part I). A portion of this land evaporation is advected to the oceans and precipitates there E_o. The remaining part recycles over land, but interestingly, interception $E_\mathrm{c,i}$ and transpiration $E_\mathrm{c,t}$ do so in different relative magnitudes. Of interception, 60 % ($E_\mathrm{c,i}/E_\mathrm{i}$) recycles, while transpiration recycles slightly less at 56 % ($E_\mathrm{c,t}/E_\mathrm{t}$). The lifetime in the atmosphere of evaporated water is on average more than a week, which is similar to a previous estimate of 9.2 days [Bosilovich et al., 2002]. The recycled part of evaporation, however, spends on average less than a week in the atmosphere on average. We can also observe that (the recycled part of) interception has a shorter lifetime in the atmosphere. Finally, global continental precipitation recycling P_c is estimated at 36 %, slightly less than the 40 % estimated in Chapter 3, which is due to the evaporation data being from STEAM instead of ERA-I. Globally averaged, the recycling efficiencies and atmospheric lifetimes are not very different for interception and transpiration, but locally these differences can be large, which we show in Sections 5.3.2 to 5.3.5, where we discuss the spatial patterns of the magnitudes and time scales of the recycling fluxes in the hydrological cycle.

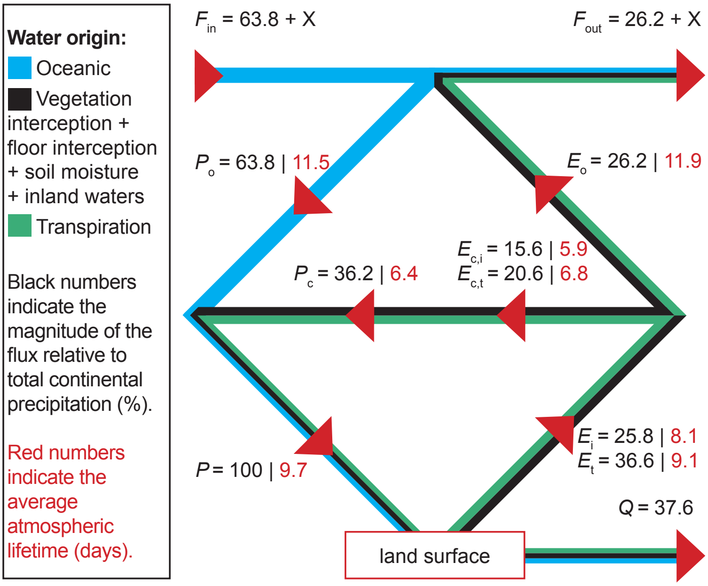
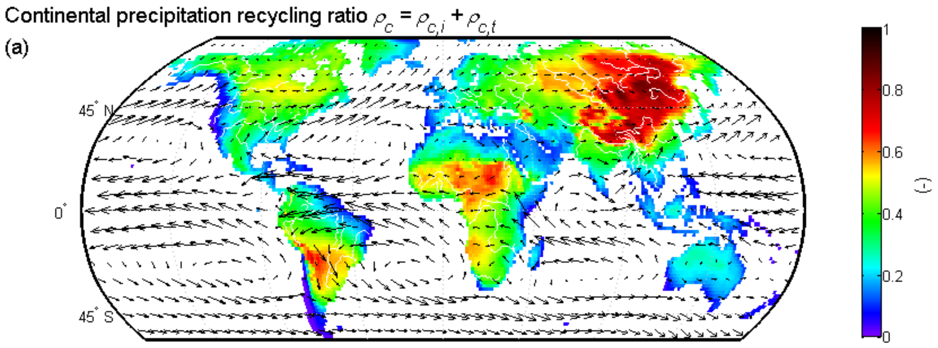


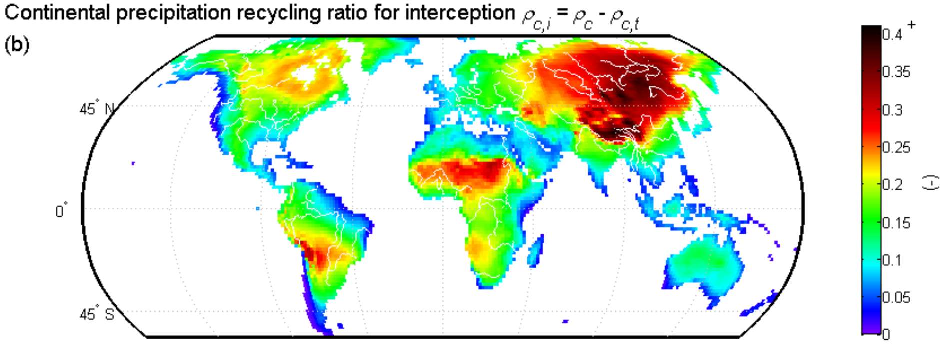
Figure 5.3: Global hydrological cycle over land. F_{in} is the atmospheric moisture of oceanic origin that crosses the ocean-land boundary and enters the atmosphere above land. F_{out} is the atmospheric moisture that leaves the ocean-land boundary towards the ocean. Thus, X represents the atmospheric moisture of oceanic origin that passes through the continental atmosphere, but never precipitates. The other symbols are explained in Section 5.3.1

5.3.2. CONTINENTAL MOISTURE RECYCLING

Figure 5.4 shows the annual average continental precipitation recycling ratios for total evaporation (Fig. 5.4a and Eq. 3.7), for interception (Fig. 5.4b and Eq. 5.5), and transpiration (Fig. 5.4c and Eq. 5.6). While interpreting the figure it should be remembered that “interception” includes evaporation from the vegetation, floor, soil and inland waters (Eq. 5.2). The areas that depend heavily on continental precipitation recycling are potentially susceptible to (upwind) changes in land use. Animations 2 to 4 (Supplement) illustrate how we obtained Fig. 5.4 with forward tracking runs of tagged terrestrial evaporation, interception and transpiration. They show the fraction of atmospheric moisture originating from terrestrial evaporation, interception and transpiration respectively, averaged for each day.

Precipitation recycling due to transpiration shows higher values (Fig. 5.4c) and is in the absolute sense more important than interception (Fig. 5.4b). Although the patterns of Fig. 5.4b and 5.4c are very similar, there are a few noteworthy differences, for which we can think of two reasons. First, dominance of one type of evaporative flux in a cer-


Continental precipitation recycling ratio $\rho_c = \rho_{c,i} + \rho_{c,t}$


Continental precipitation recycling ratio for interception $\rho_{c,i} = \rho_c - \rho_{c,t}$

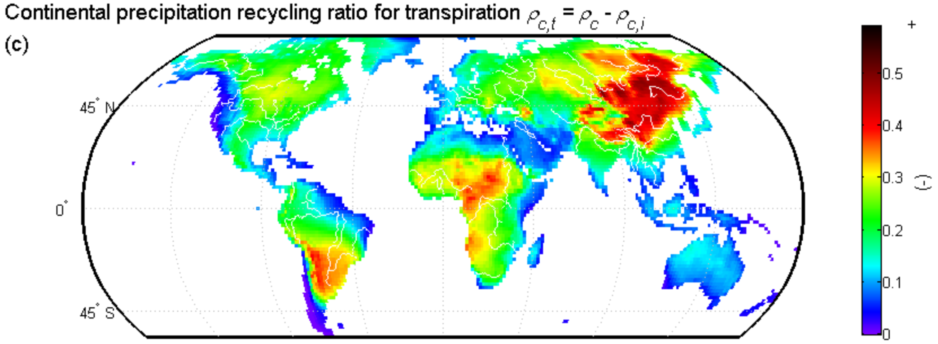

Continental precipitation recycling ratio for transpiration $\rho_{c,t} = \rho_c - \rho_{c,i}$

Figure 5.4: Continental precipitation recycling. **(a)** continental precipitation recycling ratio ρ_{c}, **(b)** continental precipitation recycling ratio for interception $\rho_{\text{c,i}}$, and **(c)** continental precipitation recycling ratio for transpiration $\rho_{\text{c,t}}$. The colour scale of (b) ends at 0.41, which is the global average fraction of direct evaporative fluxes (interception) and the colour scale of (c) ends at 0.59, which is the global average fraction of delayed evaporative flux (transpiration). The arrows in (a) indicate the vertically integrated moisture fluxes.

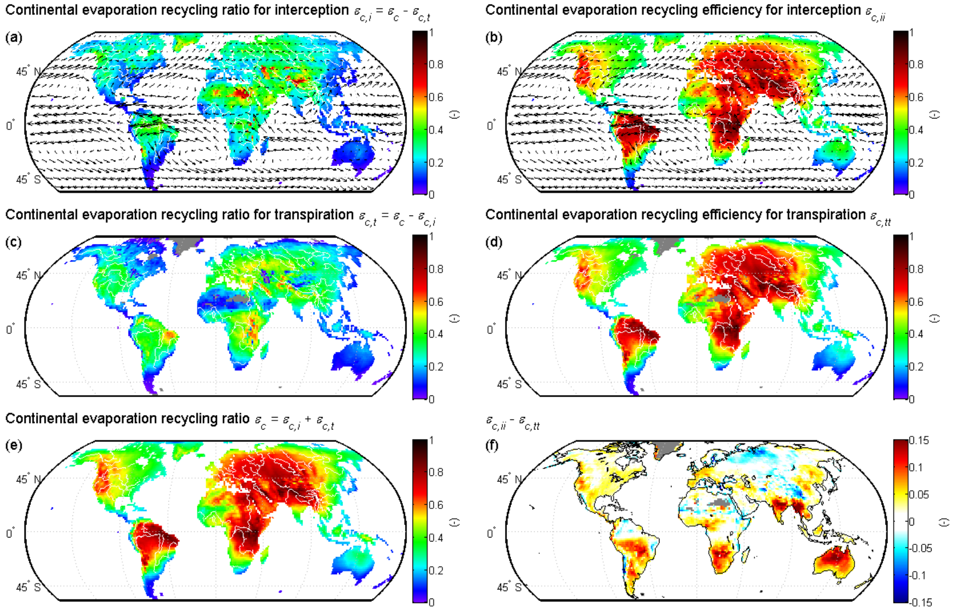


Figure 5.5: Continental evaporation recycling. **(a)** continental evaporation recycling ratio for interception $\varepsilon_{\mathrm{c,i}}$,**(b)** continental evaporation recycling efficiency for interception $\varepsilon_{\mathrm{c,ii}}$, **(c)** continental evaporation recycling ratio for transpiration $\varepsilon_{\mathrm{c,t}}$, **(d)** continental evaporation recycling efficiency for transpiration $\varepsilon_{\mathrm{c,tt}}$, **(e)** continental evaporation recycling ratio ε_{c}, and **(f)** $\varepsilon_{\mathrm{c,ii}} - \varepsilon_{\mathrm{c,tt}}$. Grey values on land indicate no data, due to the fact that the evaporative flux in question is zero. The arrows in (a) and (b) indicate the vertically integrated moisture fluxes.

tain area. Second, dominance of one type of evaporative flux during a certain part of the year with different prevailing winds. For example, in South America, the “hot spot” of interception recycling is situated more to the north compared to the “hot spot” of transpiration recycling. This is explained by high interception in the Amazonian rainforest (Fig. 5.1a), compared to transpiration being high throughout the continent (Fig. 5.1b), and by transpiration being more dominant during winter when the atmospheric flow is more directed to the south.

The complementary process of precipitation recycling is evaporation recycling. The different metrics corresponding to continental evaporation recycling (Eqs. 5.8 to 5.11) are shown in Fig. 5.5. Regions with high evaporation recycling are important source regions for sustaining downwind precipitation. Figures 5.5a and 5.5c contain information about where the respective evaporative fluxes are important as well as to which regions they supply the moisture. The sum of Figs. 5.5a and 5.5c leads to Fig. 5.5e. The evaporation recycling efficiencies (Figs. 5.5b and 5.5d) just contain information about the likelihood of a particle to recycle after continental evaporation. From Fig. 5.5f it can be seen that in most regions of the world evaporated interception (Fig. 5.5b and 5.1a) is more likely to return as precipitation over land than transpiration (Fig. 5.5d and 5.1b). This is especially the case in regions with a relatively small continental mass (in relation the prevalent winds) and distinct wet and dry seasons, such as southern Africa, India and Australia, where transpiration in the dry season is relatively likely to return to the ocean.

In the regions Congo and north-eastern Amazon, the continental evaporation recycling efficiencies are high (Figs. 5.5b and d) and the differences between relative interception and transpiration recycling are practically zero (Fig. 5.5f), which indicates that whatever evaporates is equally likely to return to the continent. This indicates strong local recycling, or at least evaporative fluxes that contribute to precipitation elsewhere on the continent, throughout the year. However, Fig. 5.5f also indicates some regions in Eurasia where transpiration is more likely to return to the continent (in blue). This can probably be explained by the fact that in these areas almost all evaporation in winter comes from interception (Fig. 5.2c), which, for a large part, is subsequently advected over and away from the relatively dry continent (Fig. 5.2a). In other words, the moisture coming from interception has less opportunity to recycle, whereas transpiration is present only in the wetter summer season and has more opportunity to recycle.

5.3.3. ATMOSPHERIC LIFETIME

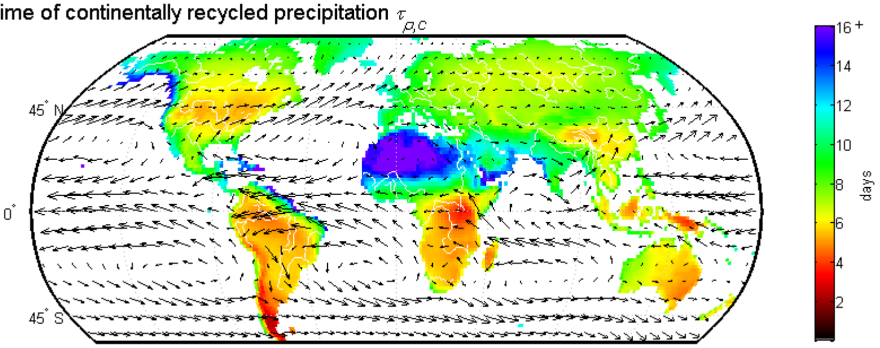
Figure 5.6 shows the time spent in the atmosphere by the moisture that recycles over land. Figure 5.6a indicates the time that continentally evaporated moisture has spent in the atmosphere until it precipitates (Eq. 5.12). In other words, it is the time component of Fig. 5.4a. Note that in places where ρ_c (Fig. 5.4a) is low, the corresponding regions in Fig. 5.6a contain little information. Figures 5.6b (Eq. 5.13) and 5.6c (Eq. 5.14) indicate the time it takes before direct (interception, soil moisture and inland waters) and delayed (transpiration) evaporative fluxes return to the terrestrial land surface.

Figures 5.6b and 5.6c are the time components of Figs. 5.5b and 5.5d. We can see that in general the direct evaporative fluxes (Fig. 5.6b) remain in the atmosphere for a shorter period of time compared to transpiration (Fig. 5.6c). We can explain this by the fact that the terrestrial time scales of the direct evaporative fluxes are much shorter than those of transpiration [Wang-Erlandsson et al., 2014, Figs. 4 and 5]. The differences between Figs. 5.6b and 5.6c are less strong in the very wet tropical regions around the equator, as well as in the Andes and Himalaya mountains. This is probably caused by the absence of distinctively different precipitation triggering mechanisms throughout the year. On the other hand, we see several regions where the atmospheric lifetime of interception recycling (Fig. 5.6b) is much lower than that of transpiration recycling (Fig. 5.6c). Many of these regions correspond with those identified in Fig. 5.5f (e.g., southern Africa, India and Australia). However, in contrast to Fig. 5.5f, the lifetime of interception recycling is also shorter in northern Eurasia, which is probably due to the fact that Figure 5.6 just considers the recycled part of the precipitation.

Not surprisingly, Fig. 5.6 shows that the recycling process in the tropics is faster (~3–6 days) than in the more temperate zones (~4–12 days). Interestingly, however, recycled precipitation (Fig. 5.6a) in North America has spent less time in the atmosphere than in Eurasia. We think that this could be explained by a fraction of evaporation in North America that passes over the Atlantic Ocean in summer and precipitates in Europe, which obviously increases the average atmospheric residence time. This phe-

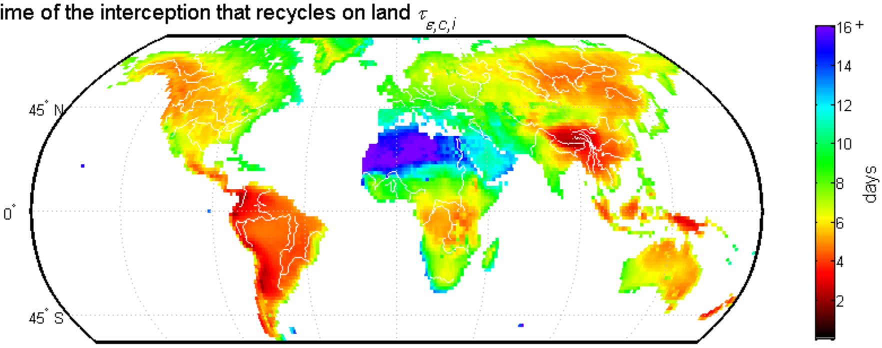
Lifetime of continentally recycled precipitation $\tau_{\rho,c}$

(a)



Lifetime of the interception that recycles on land $\tau_{\varepsilon,c,i}$

(b)



Lifetime of the transpiration that recycles on land $\tau_{\varepsilon,c,t}$

(c)

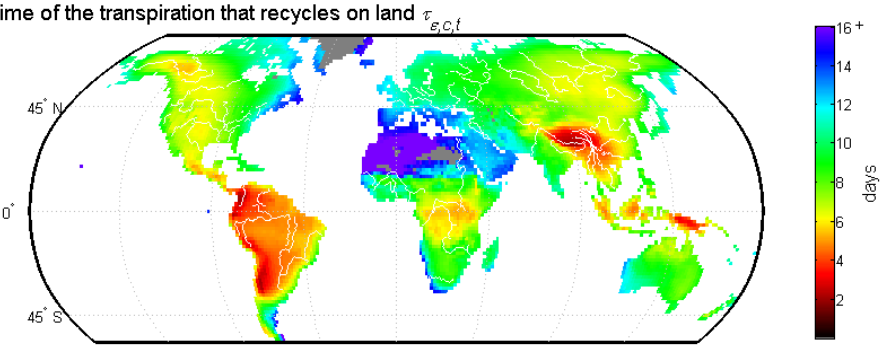


Figure 5.6: Atmospheric lifetimes of continental moisture recycling. **(a)** lifetime of continentally recycled precipitation $\tau_{\rho,\mathrm{c}}$ (defined at the point of precipitation), **(b)** lifetime of the interception that recycles on land $\tau_{\varepsilon,\mathrm{c,i}}$ (defined at the point of evaporation), and **(c)** lifetime of the transpiration that recycles on land $\tau_{\varepsilon,\mathrm{c,t}}$ (defined at the point of evaporation). Grey values on land indicate no data, due to the fact that the evaporative flux in question is zero. The arrows in (a) indicate the vertically integrated moisture fluxes.

nomenon can also be observed from Animations 3 and 4 (Supplement). It seems that transpiration (Animation 4 and Fig. 5.6c) is a slightly larger contributor to this cross-continental transport than the direct evaporative fluxes (Animation 3 and Fig. 5.6b).

5.3.4. LOCAL LENGTH SCALES

We assess local moisture recycling strength using local length scales of evaporation recycling (Eqs. 5.18 and 5.19), which are a scale- and shape-independent metrics. Figures 5.7b and 5.7c show the length scales of evaporation recycling for interception and transpiration respectively, where the importance of local evaporation for precipitation is indicated by a lower value. Note that the arrows in the graph now indicate the moisture fluxes in the bottom part of the atmosphere only (Eq. 2.5) as this is where the fast recycling takes place. If the values are similar over a large area they provide a proxy for the distance an evaporated water particle travels, before returning to the land surface. (e.g., < 2000 km in sub-Saharan Africa), despite a possible underestimation due to local moisture not reaching the fast moving, upper layers of the atmosphere. In the world's deserts there is obviously very little precipitation, and the probability of an evaporated particle returning locally is very low given the high local length scales. Ignoring the deserts, Fig. 5.7b indicates that direct evaporation on most of the globe has a length scale of less than 2500 km, which corresponds to ~2 % recycling within 100 km.

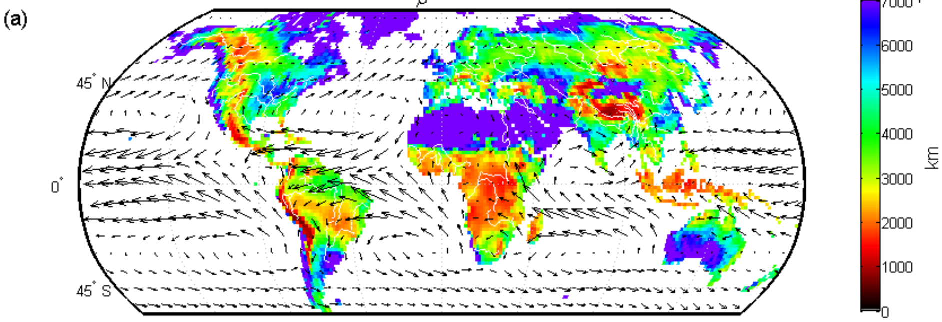
We have already seen that interception in general has a higher probability to recycle over land (Figs. 5.3 and 5.5) and returns to the land surface more quickly (Figs. 5.3 and 5.6). Consistent with this, the length scale of interception recycling (Fig. 5.7b) is much shorter compared to that of transpiration recycling (Fig. 5.7c). The difference in length scales between interception and transpiration is quite striking, especially in the temperate zones. This is similar to the findings in Fig. 5.6, but seems more pronounced. The typical time scale of a wet spell is 1-5 days [Zolina et al., 2013], while evaporation from interception has a time scale at the surface in the order of hours [Wang-Erlandsson et al., 2014, Figs 4c, 4d, 5c and 5d] and transpiration has a time scale in the order of weeks to months [Wang-Erlandsson et al., 2014, Figs. 4a and 5a]. Since interception takes place only during wet spells and transpiration takes place regardless, it follows that interception recycling is much more local than transpiration recycling.

5.3.5. SEASONALITY OF MOISTURE RECYCLING METRICS

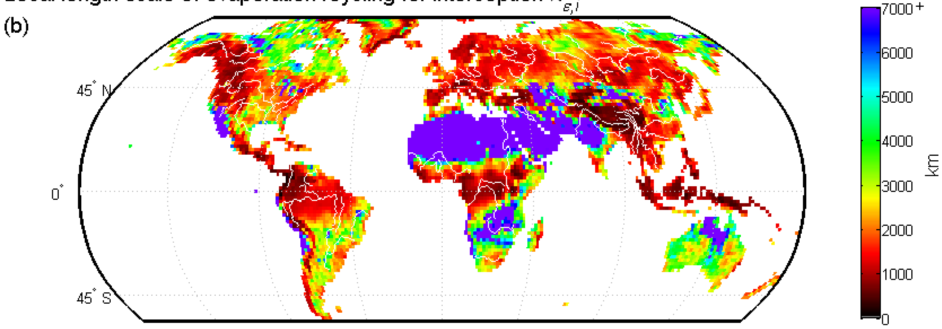
A selection of moisture recycling metrics for the months of January and July is shown in Fig. 5.8. In summer, the land is warmer than the ocean and continental precipitation recycling ratios are higher, whereas is winter this is the opposite (Fig. 5.8a–d). Looking at the Northern Hemisphere's temperate and polar climate zones, the lifetimes and length scales in winter (Fig. 5.8e, g, i and k) are in most places shorter than in summer (Fig. 5.8f, h, j and l). This means that evaporation in winter generally returns to the land surface more quickly than in summer. However, evaporation in winter is much lower (Fig. 5.2) and is thus a less important contributor to precipitation than in summer (Fig. 5.8a–d). In the tropics and subtropics, the moisture recycling metrics are driven more by monsoonal periods, with stronger feedback, i.e., shorter atmospheric lifetimes (Fig. 5.8e–h) and shorter length scales (Fig. 5.8i–l) during the monsoon season.

The different roles of interception and transpiration in the hydrological cycle become

Local length scale of precipitation reycling λ_ρ



Local length scale of evaporation reycling for interception $\lambda_{\varepsilon,i}$



Local length scale of evaporation reycling for transpiration $\lambda_{\varepsilon,t}$

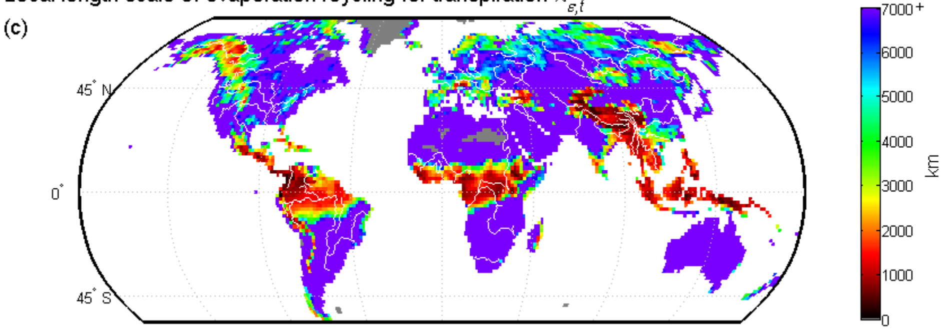


Figure 5.7: Local length scales of the moisture recycling process. **(a)** length scale of precipitation recycling λ_ρ, **(b)** length scale of evaporation recycling for interception $\lambda_{\varepsilon,\mathrm{i}}$, and **(c)** length scale of evaporation recycling for transpiration $\lambda_{\varepsilon,\mathrm{t}}$. Grey values on land indicate no data, due to the fact that the evaporative flux in question is zero. Note that lower values indicate higher moisture feedback strength. The arrows in (a) indicate the moisture fluxes in the lowest part of the atmosphere (approximately the lowest 2 km of the atmosphere at standard pressure, (Eq. 2.5).

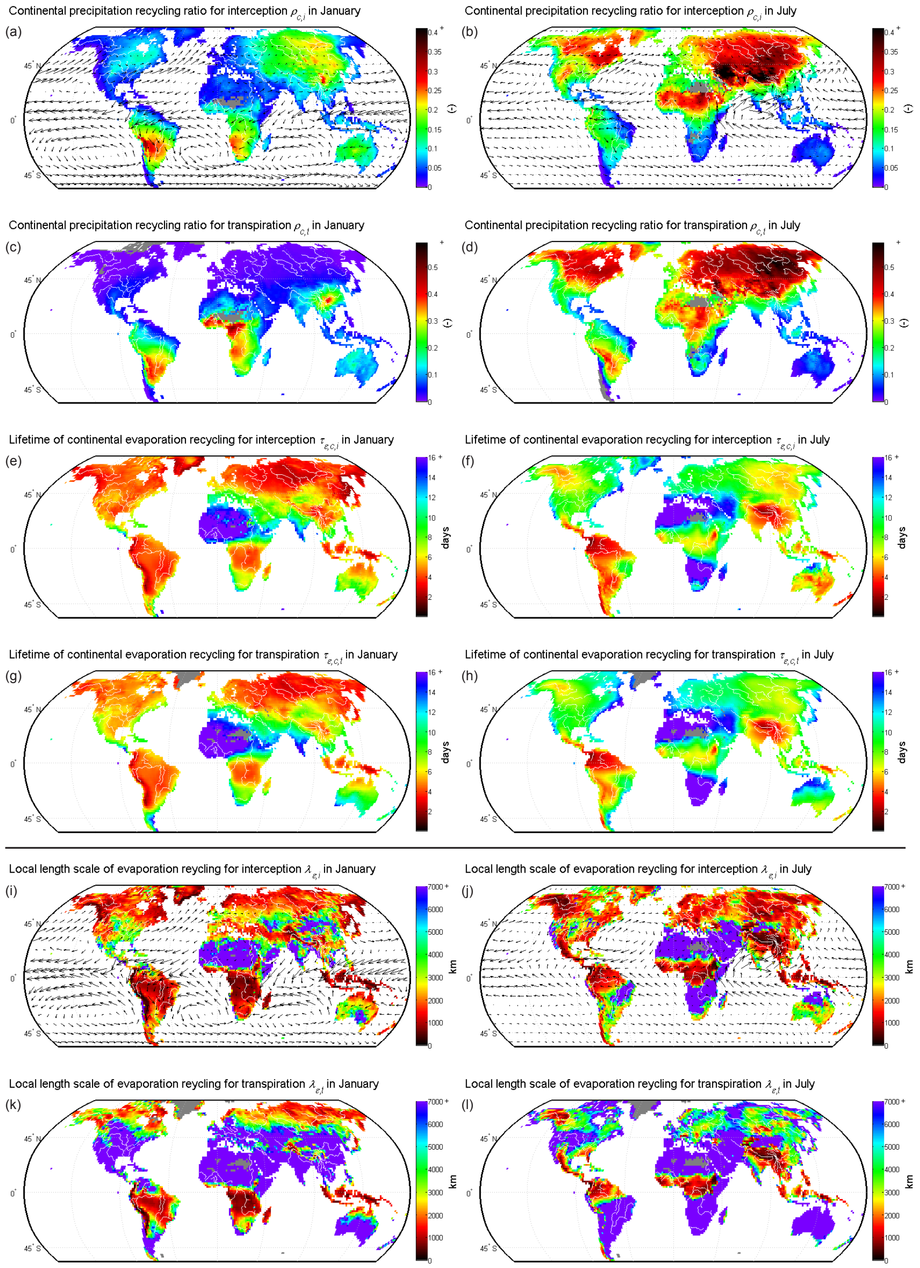


Figure 5.8: Moisture recycling metrics for January (left column) and July (right column). The arrows in (a) and (b) indicate the vertically integrated moisture fluxes, which are most relevant for panels (a)–(h). The arrows in (i) and (j) indicate the moisture flux only in approximately the lowest 2 km of the atmosphere, which is most relevant for panels (i)–(l).

evident when we compare January and July (Fig. 5.8), relative to the annual averages (Figs. 5.4 to 5.7). For example, it is clear that in the Northern Hemisphere's temperate and polar zones in January, evaporation from interception is the principal moisture recycling mechanism (Fig. 5.8a vs. 5.8c, and Fig. 5.8i vs. 5.8k). This is explained by the near absence of transpiration (Fig. 5.2e). However, near absence of transpiration is not a necessity for interception to be the principal recycling mechanism, which we can see from Australia and South Africa in January (summer). This is probably explained by the relatively small dimensions of these land masses which cause transpiration outside of a wet spell to get advected to the oceanic atmosphere more often than evaporated interception.

Whereas transpiration can compensate for a reduction of interception in the wet season, the opposite is not true, making transpiration dependent regions more vulnerable. For example, coastal West Africa in January and the La Plata basin in July are predominantly dependent on recycled moisture from transpiration. For both these regions, this transpiration recycling dependence is in a period with little rainfall (Fig. 5.2a and b). However, this rainfall could be important for dry season farming and drinking water supply, making these regions susceptible to local and remote land-use changes. These regions are particularly threatened by upwind deforestation, which could therefore lead to reduced precipitation in West Africa and the La Plata basin [see also Keys et al., 2014; Zemp et al., 2014] in general, but particularly during their respective dry seasons.

5.4. CONCLUSIONS

The objective of this paper was to assess the role of the different components of evaporation in the hydrological cycle over continents. We have used the atmospheric moisture tracking model WAM-2layers to track direct (purely physical) and delayed (biophysical) evaporative fluxes, as computed by STEAM [Wang-Erlandsson et al., 2014]. By direct evaporative fluxes we mean the water evaporated from vegetation interception, floor interception, soil moisture, and inland waters. Interception is what largely dominates direct evaporation [Wang-Erlandsson et al., 2014, Fig. 2]. By delayed evaporative flux we mean transpiration.

We can summarise our findings about the different roles of interception and transpiration in the hydrological cycle as follows: 1) 60 % of direct evaporation returns to the land surface, whereas this is 56 %, and thus slightly less, for transpiration, 2) the residence time of direct evaporation in the atmosphere is 8 days (6 for the recycling part only) and 9 days for transpiration, and 3) the local length scale of interception recycling is on average much shorter than the length scale of transpiration recycling. We attribute these results to the fact that interception has a small storage reservoir and therefore occurs mostly during wet spells. Transpiration, on the other hand, draws from a large storage reservoir and can occur during dry periods as well during which evaporated moisture is more likely to be advected over large distances.

These results are particularly useful from a landscape resilience perspective. Regions that receive precipitation from continentally recycled evaporation are vulnerable to upwind land-use changes [e.g., Dekker et al., 2007; Schaefli et al., 2012]. However, a region that receives precipitation originating from interception is more resilient to land-use changes in their source region than a region that depends on transpiration. A land-use change could for example reduce interception capacity, but during a wet period this is likely to be compensated by other evaporative fluxes. Regions that receive precipitation from continentally recycled transpiration are less resilient to land-use changes in their source region, especially if a region's precipitation depends on transpiration in the dry season. Because when vegetation is removed, the mechanism to retain and draw moisture from the root zone is lost as well, and total evaporation will be significantly reduced.

Our results suggest that the effect of land-use change on moisture recycling is very different during wet and dry seasons, and also during summer and winter, indicating that seasonality is important to consider when analysing effects of land-use change. During the wet season, increased or decreased interception could amplify or attenuate the local moisture recycling signal. Still, we conclude that land-use change needs to be drastic to influence the evaporative fluxes in a way that this signal would have continental scale influence. During the dry season, land-use change (in particular deforestation), could lead to reduced transpiration, which reduces moisture recycling, and as such could have a domino effect on precipitation downwind.

6

WATERSHEDS OF THE ATMOSPHERE

Water is the driving force of all nature.

Leonardo Da Vinci

It is well known that rivers connect upstream and downstream ecosystems within watersheds. Here we describe the concept of atmospheric watersheds to show how precipitation depends on upwind evaporation and how evaporation sustains precipitation downwind. The biggest sources and sinks are generally found close to the region of interest. However, for West Africa it is shown that, outside the rainy season, more distant sources, of in particular transpiration, are very important for the hydrological cycle as well.

This chapter is based on:

Keys, P. W., R. J. van der Ent, L. J. Gordon, H. Hoff, R. Nikoli, and H. H. G. Savenije, *Analyzing precipitationsheds to understand the vulnerability of rainfall dependent regions*, Biogeosciences, **9**, 733–746, 2012.

Van der Ent, R. J., and H. H. G. Savenije, *Oceanic sources of continental precipitation and the correlation with sea surface temperature*, Water Resources Research, **49**, 3993–4004, 2013.

Van der Ent, R. J., L. Wang-Erlandsson, P. W. Keys, and H. H. G. Savenije, *Contrasting roles of interception and transpiration in the hydrological cycle – Part 2: Moisture recycling*, Earth System Dynamics Discussions, **5**, 281–326, 2014.

6.1. INTRODUCTION

Surface watersheds, delineated by topography, are considered the physical boundaries for managing surface water resources, including the management of upstream activities that influence downstream water flows [e.g., Rockström et al., 2009a]. Spatial boundaries for the origin of precipitation have been suggested in previous work [e.g., Dirmeyer et al., 2009a], and terrestrial evaporation has been identified as a significant source of precipitation for some areas globally (e.g., Chapter 3). Additionally, recent analyses of land-cover changes indicate that human-induced land-cover changes can significantly alter the volume of evaporated moisture in the atmosphere [e.g., Boucher et al., 2004; Gordon et al., 2005; Rost et al., 2008; Van der Ent et al., 2012; Wang-Erlandsson et al., 2014].

The aim of this chapter is to integrate this knowledge into the concept of atmospheric watersheds. First, we define the “precipitationshed” as the upwind atmosphere and surface that contributes evaporation to a specific location’s precipitation. Second, we define the “evaporationshed” as the downwind atmosphere and surface that receives precipitation from a specific location’s evaporation.

Understanding the connection between upwind land cover and downwind precipitation may help to identify both risks and opportunities associated with land-cover changes. This is particularly relevant for societies based on rain-fed agriculture, because they already operate at the margins of productivity, so even a small decline in precipitation could have disproportionately large consequences for agricultural yields [Rockström et al., 2009a].

6.2. METHODS: THE CONCEPT OF ATMOSPHERIC WATERSHEDS

In this chapter we use the conceptual framework of precipitationsheds and evaporationsheds to illustrate how land-use change in one region could affect evaporation, moisture recycling and hence precipitation, in a geographically separate region. The definitions of these atmospheric watersheds include both the oceanic and terrestrial land surface. In order to use these concepts as tools to study the susceptibility to land-use changes it is most relevant to consider the terrestrial part of the atmospheric watershed. Nonetheless, the oceanic part could be interesting as well, for example, in the light of globally increasing sea surface temperatures and their relation to continental precipitation [see e.g., Gimeno et al., 2010; Xie et al., 2010; Ma and Xie, 2012; Van der Ent and Savenije, 2013].

The precipitationshed (Fig. 6.1) is for precipitation dependent ecosystems what the surface watershed is for surface water dependent ecosystems, and it is defined as the upwind atmosphere and upwind oceanic and terrestrial land surface that contributes evaporation to a specific location’s precipitation (e.g., rainfall). An important distinction with a surface watershed is that precipitationshed boundaries are not deterministic but probabilistic. In other words, they do not have fixed and deterministic boundaries, but depend rather on a threshold of contribution, on the period of integration, and the moment in time.

An evaporationshed (Fig. 6.2) is defined as the downwind oceanic and terrestrial surface that receives precipitation from a specific region’s evaporation. Just like the pre-

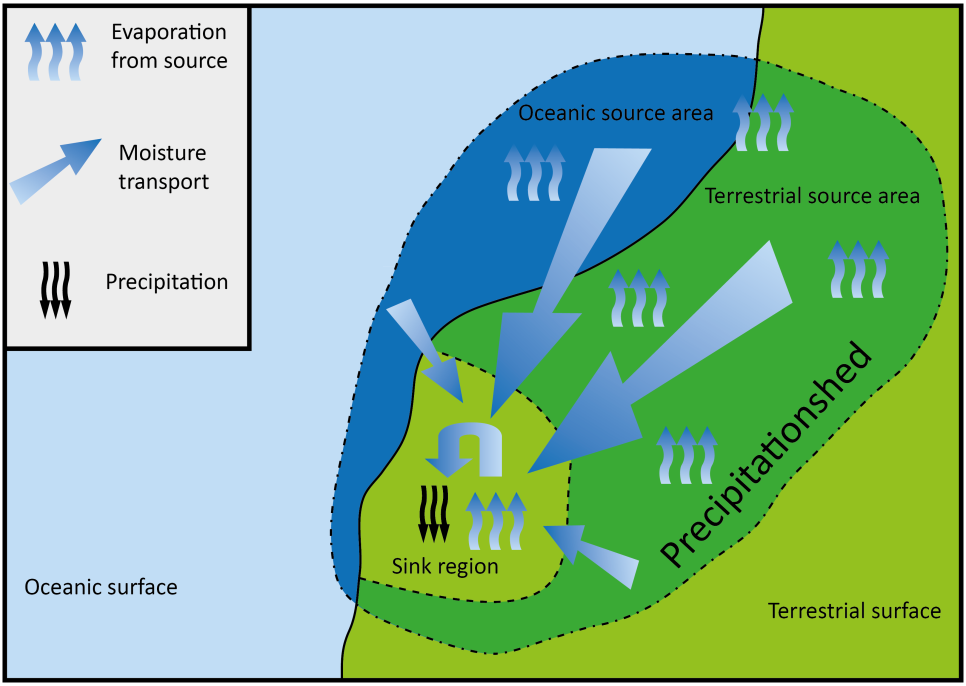


Figure 6.1: Conceptual image of a precipitationshed, with precipitation in the sink region originating from both terrestrial and oceanic sources of evaporation.

cipitationshed, the evaporationshed has probabilistic boundaries. For visualisation or management purposes, however, it can be desirable to draw a single boundary. It is important to realise that this requires a user-defined threshold of contribution to be chosen, which influences the size and shape of the atmospheric watershed [see e.g., Keys et al., 2012, Figs. 2 and S1]. Such a threshold fully depends on the purpose of the study. We suggest that either an absolute boundary with dimension $\mathrm{L\,T^{-1}}$ or a relative boundary should be chosen. To obtain, e.g., the "50 %-relative evaporationshed" of region Z, one has to rank the grid cells by the fraction of their precipitation that they received from Z and proceed to until the sum of these values equals 50 % of the evaporation in Z. A precipitationshed can be easiest obtained through the tracking of precipitation backward in time through the atmosphere, whereas an evaporationshed is obtained through forward tracking of evaporated moisture until the point of precipitation.

6.3. RESULTS AND DISCUSSION

6.3.1. PRECIPITATION SOURCES OF WEST AFRICA

WEST AFRICA'S PRECIPITATIONSHED

We choose to investigate the sources for precipitation in West Africa in more detail. Large parts of West Africa, the Sahel in particular, are dependent on rain-fed agriculture, which

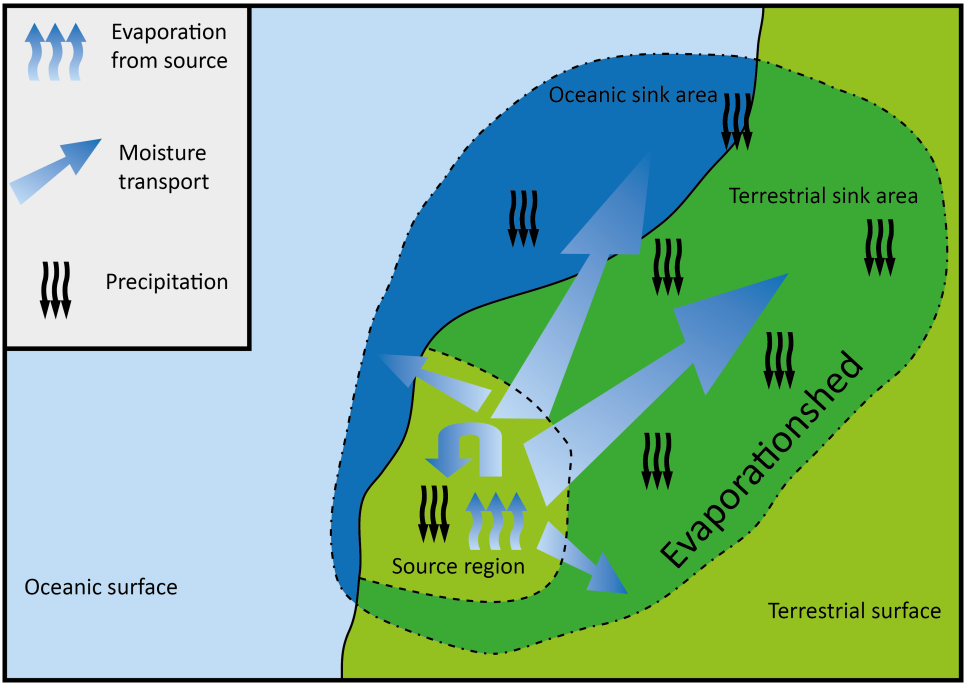


Figure 6.2: Conceptual image of an evaporationshed, with evaporation in the source region ending up on both terrestrial and oceanic sink regions as precipitation.

makes West Africa susceptible to changes in precipitation, moisture recycling, and thus upwind land-use change. Figure 6.3 depicts the spatial distribution of the yearly average evaporative sources for precipitation in West Africa, which is termed the precipitationshed. It should be noted that only direct evaporative contributions are represented. Figure 6.3a and b represent two different methods for visualizing and bounding the precipitationshed. Figure 6.3a depicts the absolute precipitationshed, emphasizing the grid cells that contribute the largest absolute amount of evaporation to sink region precipitation. Figure 6.3b depicts the relative precipitationshed, emphasizing those grid cells from which the largest relative amounts of their evaporation contribute to sink region precipitation. We choose not to assign a specific boundary to the precipitationshed, but the colour scales indicate how such a boundary could be assigned. For example, the combination of all black, red and green grid cells in Fig. 6.3b would represent to "47 %-relative precipitationshed".

The strongest absolute source of precipitation in West Africa comes from within the region, especially the south (Fig. 6.3a). Oceanic contributions come from different directions: Atlantic Ocean, Mediterranean, Red Sea and Indian Ocean. However, a significant moisture contribution comes from terrestrial sources, with the African continent itself being the most important. Some of southern Europe's evaporation ends up in West Africa as well. This also provides an explanation for the long lifetimes of evaporated moisture

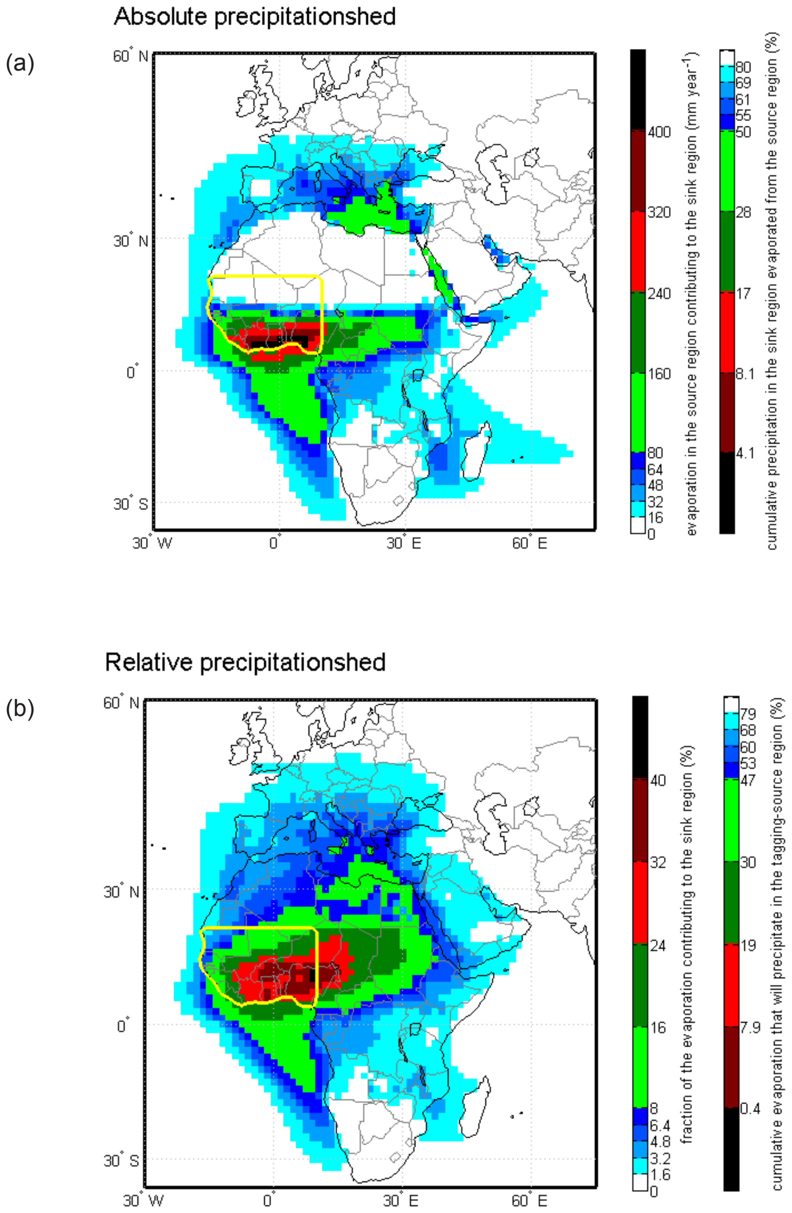


Figure 6.3: Evaporative sources for precipitation in West Africa. **(a)** Yearly average absolute precipitationshed of West Africa. **(b)** Yearly average relative precipitationshed of West Africa. The left colour scale indicates the evaporative contribution each grid cell has to the sink region (yellow box). The right colour scale indicates which percentage of the precipitation in the yellow box is cumulatively contributed by the corresponding colours. For example, the light green grid cells in (a) generate $50 - 28 = 22\,\%$ of the precipitation in the yellow box.

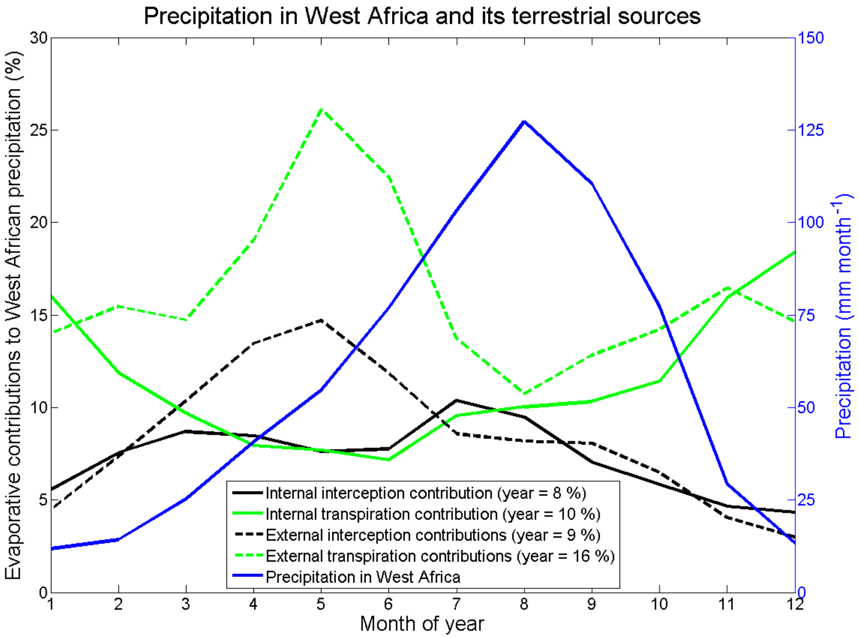


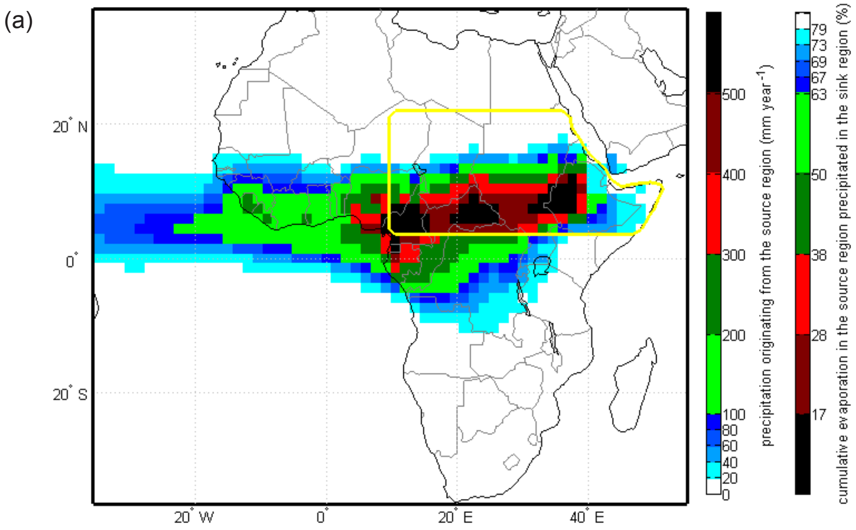
Figure 6.4: Seasonal precipitation in the sink region (yellow box Fig. 6.3) and its evaporative sources split out by internal vs. external, and interception vs. transpiration. The oceanic sources are not shown, but contribute the remaining percentages to West Africa's precipitation.

in southern Europe (Fig. 5.6b and c). The source regions found in Fig. 6.3a are in line with previous research in this region [e.g, Druyan and Koster, 1989; Gong and Eltahir, 1996; Nieto et al., 2006; Dirmeyer et al., 2009a; Goessling and Reick, 2013a], but it is hard to be specific as all these studies used slightly different sink regions. The moisture tracking model used here, WAM-2layers, assigns a relatively more important role to the Atlantic compared to our previously used WAM-1layer [Van der Ent et al., 2010; Keys et al., 2012]. With the use of WAM-2layers our results are more in line with those found by Goessling and Reick [2013a], who employed an online 3-D moisture tracking method.

SEASONAL DEPENDENCE ON DIFFERENT SOURCES

Figure 6.4 shows the seasonal variation in precipitation and its terrestrial evaporative sources split up into internal vs. external and interception vs. transpiration. In the beginning of the year, when there is little precipitation in the region; transpiration from within West Africa as well as more remote sources of transpiration are most important contributors. However, during the onset of the monsoon (April–June), remote sources, and specifically transpiration sources become increasingly important. This is also the period where southern Europe's transpiration contribution to West African precipitation is largest (peaking at 5 % in June, not shown). From March until the peak of the monsoon

Absolute evaporationshed



Relative evaporationshed

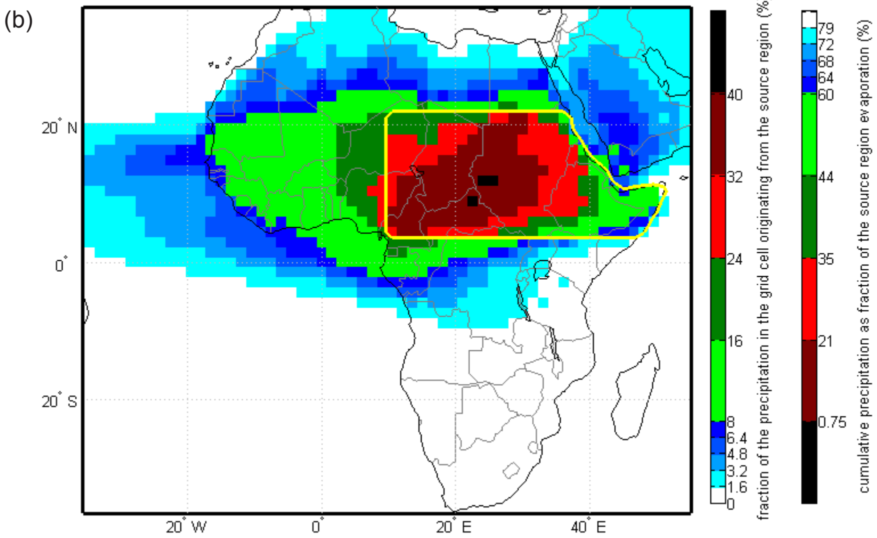


Figure 6.5: Precipitation sinks for evaporation in East Africa. **(a)** Yearly average absolute evaporationshed of East Africa. **(b)** Yearly average relative evaporationshed of East Africa. The left colour scale indicates the precipitation each grid cell receives from the source region (yellow box). The right colour scale indicates which percentage of the evaporation in the yellow box is cumulatively received by the corresponding colours. For example, the dark green grid cells in (a) receive 50 – 38 = 12 % of the evaporation in the yellow box.

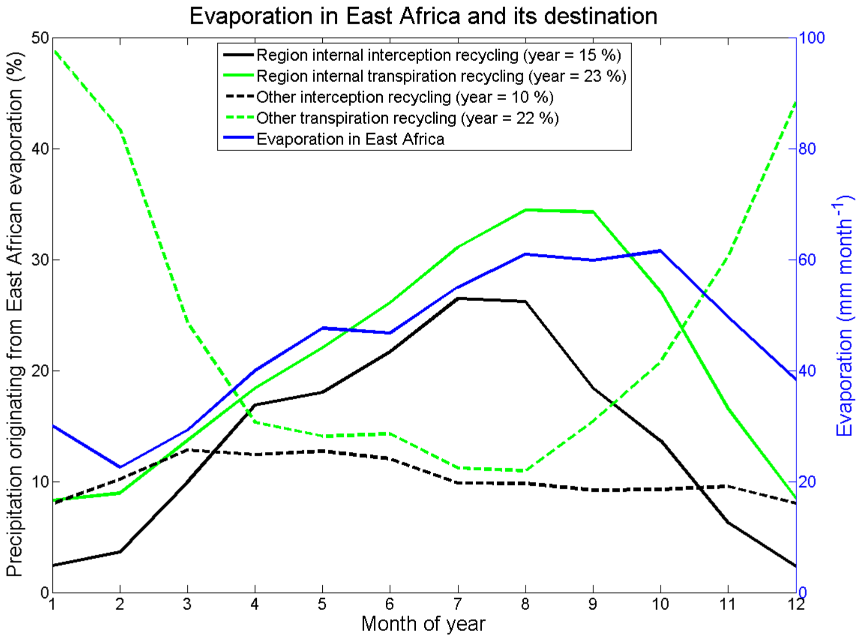


Figure 6.6: Seasonal evaporation in the source region (yellow box Fig. 6.5) and its precipitation sinks split out by internal vs. external and interception vs. transpiration. The oceanic sinks are not shown, but receive the remaining percentages of East Africa's evaporation.

in August, the contribution to rainfall from regional interception is about equal to that from regional transpiration. In the decline of the monsoon both internal and external transpiration recycling become more important again, whereas the share of interception recycling reduces. These results fit well into the picture that monsoonal rainfall in West Africa is associated with a strong linkage to soil moisture anomalies [Koster et al., 2004; Van den Hurk and Van Meijgaard, 2009; Taylor et al., 2011], but that precipitation in the northern part of the region has a strong correlation to sea surface temperature in the Mediterranean as well [Rowell, 2003; Van der Ent and Savenije, 2013].

6.3.2. FATE OF EAST AFRICA'S EVAPORATION

EAST AFRICA'S EVAPORATIONSHED

Figure 6.5 depicts the spatial distribution of the yearly average fate of evaporation from East Africa, which is termed the evaporationshed. It can be seen that this region supplies moisture mainly to the south-west towards the Congo and West Africa. In fact much of the evaporation from East Africa ends up in the sink region of Fig. 6.3. From Figs. 6.3a and 6.5a it appears that a considerable part of the moisture over Africa recycles more than once. In Figs. 6.3b and 6.5b the Sahel and Sahara pop up as regions that contribute relatively large amounts of their evaporation to precipitation in West Africa, but in an absolute sense this is very little (Figs. 6.3a and 6.5a). The high relative contributions, however, nicely illustrate that land and water management practices in East Africa, aimed at conserving water and increasing evaporation, may have a positive effect on downwind precipitation in West Africa.

SEASONAL INFLUENCE ON DIFFERENT REGIONS

The seasonal variation of the fate of the evaporation from East Africa can be seen in Fig. 6.6. Yearly averaged, 40 % of all evaporation recycles as terrestrial precipitation. Particularly striking is the transpiration in the dry season, of which most is transported out of East Africa but still returns as precipitation on the continent rather than the ocean. The internal evaporation recycling peaks in the rainy season, with transpiration being slightly dominant throughout the year. During the onset of the rainy season, however, internal interception recycling is closer to the line of transpiration. Transpiration, on the other hand, is relatively more important during the rainy season's decline, which may indicate that transpiration contributes in keeping the land wet for a longer period.

6.4. CONCLUSIONS

We have introduced and developed the concept of precipitationsheds and evaporationsheds. These atmospheric watersheds highlight the sources and sinks of atmospheric moisture for specific regions. While the absolute precipitationshed (Fig. 6.3a) is useful for identifying the regions that currently contribute the most evaporation to sink region precipitation, the relative precipitationshed (Fig. 6.3b) is useful for understanding where land-use changes would be particularly important to alter precipitation in the sink region. Likewise, the absolute evaporationshed (Fig. 6.5a) identifies the regions that currently receive most precipitation from the source region, whereas the relative evaporationshed (Fig. 6.5b) is useful for understanding which areas are expected to be influenced most by altered evaporation in the source region.

Our results further suggest that food security in some parts of the world, such as West Africa, could be very sensitive to distant land-use change. As such, the Earth's biophysical system is interlinked with its social systems. The precipitationshed and evaporationshed concepts may be useful from a policy perspective and could make a first order assessment for large scale land-use policies. For example, we think that these atmospheric watershed concepts may aid proactive assessments of the long-distance effects of major land-use change such as through REDD (Reducing Emissions from Deforestation and Forest Degradation).

7

CONCLUSIONS, IMPLICATIONS AND OUTLOOK

It is not the strongest of the species that survives, nor the most intelligent that survives. It is the one that is the most adaptable to change.

Charles Darwin

This chapter is based on:

Van der Ent, R. J., A. M. J. Coenders-Gerrits, R. Nikoli, and H. H. G. Savenije, *The importance of proper hydrology in the forest cover-water yield debate: commentary on Ellison et al. Global Change Biology, 18, 806–820*, Global Change Biology, **18**, 2677–2680, 2012.

Van der Ent, R. J., L. Wang-Erlandsson, P. W. Keys, and H. H. G. Savenije, *Contrasting roles of interception and transpiration in the hydrological cycle – Part 2: Moisture recycling*, Earth System Dynamics Discussions, **5**, 281–326, 2014.

7.1. CONCLUSIONS

Land evaporation plays a major role in the hydrological cycle over continents as on average more than half of it returns as precipitation over land. For this process of continental moisture recycling several regions play a crucial role in providing atmospheric moisture by evaporation: western North America, northern Amazon, eastern Africa, Europe, western Asia and India. Other regions are strongly dependent on continentally recycled moisture for their precipitation: north-eastern North America, western Amazon, La Plata, West Africa, Sahel and large parts of eastern Asia. In the tropics or in mountainous terrain the length scale of moisture recycling can be as low as 500 to 2000 km, and the time scale less than 5 days. In temperate zones local recycling is less important; the length scale is typically 3000 to 5000 km and the time scale around 10 days. Interception and transpiration have contrasting roles in the hydrological cycle. While interception mainly works as an intensifier of the local hydrological cycle during wet spells, transpiration remains active during dry spells and is transported over much larger distances downwind where it can act as a significant source of moisture. The concepts of the precipitationshed and evaporationshed can be effectively used as tools to study the moisture recycling effect of land-use changes in specific regions of interest.

7.2. IMPLICATIONS

The question remains how this knowledge could be implemented in policy making. From a water and land management perspective it would be ideal if we were able to predict exactly the effect of land-use change on the regional as well as the continental hydrological cycle. Such an attempt was, for example, made by Werth and Avissar [2002] for Amazonian deforestation with a climate model, but unfortunately different climate models are likely to provide different answers leading to large uncertainty [e.g., Pitman et al., 2009]. In our opinion, the uncertainty involved in estimating the effects of deforestation is even more reason to be extremely reserved with further deforestation.

Observations already show a general decrease (with some edge effects) in precipitation over forest-to-non-forest transitions due to deforestation in the Amazon basin [Knox et al., 2011]. Our results suggest that reduced moisture recycling could propagate the decline in precipitation further downwind. Bagley et al. [2014] showed how the northern part of the Amazon, which is wet all year round, depends on recycled moisture and as such is vulnerable to deforestation. Our results suggest that deforestation in this northern part would mainly lead to reduced interception recycling. Potentially, other evaporative fluxes may compensate for the reduction in interception evaporation [Wang-Erlandsson et al., 2014], and other well-managed vegetation would not necessarily lead to dramatic rainfall reductions. For the southern part of the Amazon and the link with the La Plata basin, however, deforestation could be a much bigger problem, as reduced transpiration recycling could lead to a drier dry season. It must be noted, however, that the magnitude of the reduced moisture recycling effect depends on the land use that replaces the forest. Irrigated agriculture or open water could theoretically maintain high evaporation rates as well, but most other land-use types will not be able to produce high evaporation rates during the dry season.

Such potential effects of forest to agriculture conversion make the already difficult task of sustainably producing enough food for a growing population [Rockström et al., 2012] even more challenging. On the other hand, the fact that evaporation in some places in the world is very likely to recycle over the continent also provides opportunities. Our results for Africa, for example, suggest that large-scale implementation of water harvesting, water conservation, small reservoirs and agro-forestry [Reij and Smaling, 2008; Makurira et al., 2010; Van de Giesen et al., 2010] in West Africa, but mainly in East Africa (upwind), could have positive effects on the rainfall and thus water resources of the continent.

7.3. OUTLOOK

Current efforts are ongoing to include moisture recycling in water accounting and water footprint studies [e.g., Hoekstra and Chapagain, 2007; Karimi et al., 2013; Berger et al., 2014]. This gives a first order assessment of the importance of evaporation to sustain precipitation locally and further downwind. For future studies, however, we expect that coupled land-biosphere-atmosphere models will be increasingly used for predicting climate impacts due to land-use changes. On the other hand, we must not forget the tremendous uncertainty in the process understanding and parameterisation underlying these models [e.g., Pielke et al., 2011]. It is not uncommon for different models to predict different outputs for temperature [e.g., Brovkin et al., 2013], but especially precipitation [e.g., Pitman et al., 2012], and fundamental issues are still debated, such as the partitioning of evaporation [Jasechko et al., 2013; Coenders-Gerrits et al., 2014]. More clarity should be gained on the scale over which various mechanisms of land-atmosphere feedback act. Whereas this thesis showed that on the continental scale moisture recycling is often important, on the local scale this could be different. For example, Taylor et al. [2011] showed, based on satellite observations over the Sahel, that rainfall in this area preferably occurs over dry soils. Interestingly, a possible explanation for this can be found in the interplay between wet and dry soils. A wet area can lower the condensation level [e.g., Van den Hurk and Van Meijgaard, 2009], but the convection associated with more sensible heat over the dry area can actually trigger the rainfall.

It is therefore of utmost importance to continue efforts aimed at gaining fundamental understanding of different biogeophysical and biogeochemical effects of, for example, removing forest cover [see also Bonan, 2008] and their consequences for the hydrological cycle at different scales. For instance, it is known that young trees transpire more [e.g., Forrester et al., 2010], but the effect of this on moisture recycling has yet to be studied. Another issue requiring attention of further research is that recent studies have shown that increased atmospheric carbon dioxide reduces transpiration [De Boer et al., 2011; Keenan et al., 2013]. Our work shows that this will likely reduce moisture recycling and precipitation in some regions, making them more vulnerable to droughts, but this clearly needs more quantification.

This thesis stresses the fact that the land surface has a large potential to influence the hydrological cycle which in some places on Earth may outweigh the signal of sea surface temperatures or increased carbon-dioxide. Quantification of exact regional and planetary thresholds [Rockström et al., 2009b] of tolerable land-use change before drastic precipitation changes are expected are, however, difficult to provide. This is because the results presented in this thesis only allow for a first order estimate of land-use change impacts, because very drastic land-use change affects the energy balance and wind patterns as well [e.g., Kleidon et al., 2000; Baidya Roy and Avissar, 2002; Dallmeyer and Claussen, 2011; Goessling and Reick, 2011; Bowring et al., 2014]. Nonetheless, the results of this thesis may help future coupled land–atmosphere research to interpret whether the findings are the result of moisture recycling or other climatic processes. As such, this work is useful for providing a larger context to future regional studies examining the impact of land-use change on the hydrological cycle.

REFERENCES

Bagley, J. E., Desai, A. R., Dirmeyer, P. A., and Foley, J. A.: Effects of land cover change on moisture availability and potential crop yield in the world's breadbaskets, Environmental Research Letters, 7, 014 009, 2012.

Bagley, J. E., Desai, A. R., Harding, K. J., Snyder, P. K., and Foley, J. A.: Drought and Deforestation: Has Land Cover Change Influenced Recent Precipitation Extremes in the Amazon?, Journal of Climate, 27, 345–361, 2014.

Baidya Roy, S. and Avissar, R.: Impact of land use/land cover change on regional hydrometeorology in Amazonia, Journal of Geophysical Research, 107, LBA4–1–LBA4–12, 2002.

Bastiaanssen, W. G. M., Cheema, M. J. M., Immerzeel, W. W., Miltenburg, I. J., and Pelgrum, H.: Surface energy balance and actual evapotranspiration of the transboundary Indus Basin estimated from satellite measurements and the ETLook model, Water Resources Research, 48, W11 512, 2012.

Benton, G. S.: The Role of the Atmosphere in the Hydrologic Cycle, Weatherwise, 2, 99–103, 1949.

Berger, M., van der Ent, R., Eisner, S., Bach, V., and Finkbeiner, M.: Water Accounting and Vulnerability Evaluation (WAVE): Considering Atmospheric Evaporation Recycling and the Risk of Freshwater Depletion in Water Footprinting, Environmental Science & Technology, 2014.

Berrisford, P., Dee, D., Fielding, K., Fuentes, M., Kållberg, P. W., Kobayashi, S., and Uppala, S. M.: The ERA-Interim archive, http://www.ecmwf.int/research/era/do/get/era-interim, ERA report series 1, European Centre for Medium Range Weather Forecasts, 2009.

Bierkens, M. F. P. and Van den Hurk, B. J. J. M.: Groundwater convergence as a possible mechanism for multi-year persistence in rainfall, Geophysical Research Letters, 34, 2007.

Bisselink, B. and Dolman, A. J.: Precipitation recycling: Moisture sources over Europe using ERA-40 data, Journal of Hydrometeorology, 9, 1073–1083, 2008.

Bisselink, B. and Dolman, A. J.: Recycling of moisture in Europe: contribution of evaporation to variability in very wet and dry years, Hydrology and Earth System Sciences, 13, 1685–1697, 2009.

Bonan, G. B.: Forests and Climate Change: Forcings, Feedbacks, and the Climate Benefits of Forests, Science, 320, 1444–1449, 2008.

Bosilovich, M. G.: On the vertical distribution of local and remote sources of water for precipitation, Meteorology and Atmospheric Physics, 80, 31–41, 2002.

Bosilovich, M. G. and Chern, J. D.: Simulation of water sources and precipitation recycling for the MacKenzie, Mississippi, and Amazon River basins, Journal of Hydrometeorology, 7, 312–329, 2006.

Bosilovich, M. G. and Schubert, S. D.: Water vapor tracers as diagnostics of the regional hydrologic cycle, Journal of Hydrometeorology, 3, 149–165, 2002.

Bosilovich, M. G., Sud, Y., Schubert, S. D., and Walker, G. K.: GEWEX CSE sources of precipitation using GCM water vapor tracers, GEWEX News, 12, 1, 6, 7, 12, 2002.

Boucher, O., Myhre, G., and Myhre, A.: Direct human influence of irrigation on atmospheric water vapour and climate, Climate Dynamics, 22, 597–603, 2004.

Bowring, S. P. K., Miller, L. M., Ganzeveld, L., and Kleidon, A.: Applying the concept of "energy return on investment" to desert greening of the Sahara/Sahel using a global climate model, Earth System Dynamics, 5, 43–53, 2014.

Brovkin, V., Boysen, L., Arora, V. K., Boisier, J. P., Cadule, P., Chini, L., Claussen, M., Friedlingstein, P., Gayler, V., van den Hurk, B. J. J. M., Hurtt, G. C., Jones, C. D., Kato, E., de Noblet-Ducoudré, N., Pacifico, F., Pongratz, J., and Weiss, M.: Effect of Anthropogenic Land-Use and Land-Cover Changes on Climate and Land Carbon Storage in CMIP5 Projections for the Twenty-First Century, Journal of Climate, 26, 6859–6881, 2013.

Brubaker, K. L., Entekhabi, D., and Eagleson, P. S.: Estimation of continental precipitation recycling, Journal of Climate, 6, 1077–1089, 1993.

Budyko, M. I.: Climate and Life, Academic Press, New York, 1974.

Burde, G. I.: Bulk recycling models with incomplete vertical mixing. Part I: Conceptual framework and models, Journal of Climate, 19, 1461–1472, 2006.

Burde, G. I. and Zangvil, A.: The estimation of regional precipitation recycling. Part I: Review of recycling models, Journal of Climate, 14, 2497–2508, 2001a.

Burde, G. I. and Zangvil, A.: The estimation of regional precipitation recycling. Part II: A new recycling model, Journal of Climate, 14, 2509–2527, 2001b.

Burde, G. I., Gandush, C., and Bayarjargal, Y.: Bulk recycling models with incomplete vertical mixing. Part II: Precipitation recycling in the Amazon basin, Journal of Climate, 19, 1473–1489, 2006.

Chahine, M. T.: The hydrological cycle and its influence on climate, Nature, 359, 373–380, 1992.

Coenders-Gerrits, A. M. J., Van der Ent, R. J., Bogaard, T. A., Wang-Erlandsson, L., Hrachowitz, M., and Savenije, H. H. G.: Uncertainties in transpiration estimates, Nature, 506, E1–E2, 2014.

Corless, R. M., Gonnet, G. H., Hare, D. E. G., Jeffrey, D. J., and Knuth, D. E.: On the Lambert W function, Advances in Computational Mathematics, 5, 329–359, 1996.

Dallmeyer, A. and Claussen, M.: The influence of land cover change in the Asian monsoon region on present-day and mid-Holocene climate, Biogeosciences, 8, 1499–1519, 2011.

De Boer, H. J., Lammertsma, E. I., Wagner-Cremer, F., Dilcher, D. L., Wassen, M. J., and Dekker, S. C.: Climate forcing due to optimization of maximal leaf conductance in subtropical vegetation under rising CO2, Proceedings of the National Academy of Sciences, 108, 4041–4046, 2011.

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

Dekker, S. C., Rietkerk, M., and Bierkens, M. F. P.: Coupling microscale vegetation–soil water and macroscale vegetation–precipitation feedbacks in semiarid ecosystems, Global Change Biology, 13, 671–678, 2007.

Dirmeyer, P. A. and Brubaker, K. L.: Contrasting evaporative moisture sources during the drought of 1988 and the flood of 1993, Journal of Geophysical Research, 104, 19 383–19 397, 1999.

Dirmeyer, P. A. and Brubaker, K. L.: Characterization of the global hydrologic cycle from a back-trajectory analysis of atmospheric water vapor, Journal of Hydrometeorology, 8, 20–37, 2007.

Dirmeyer, P. A., Koster, R. D., and Guo, Z. C.: Do global models properly represent the feedback between land and atmosphere?, Journal of Hydrometeorology, 7, 1177–1198, 2006.

Dirmeyer, P. A., Brubaker, K. L., and DelSole, T.: Import and export of atmospheric water vapor between nations, Journal of Hydrology, 365, 11–22, 2009a.

Dirmeyer, P. A., Schlosser, C. A., and Brubaker, K. L.: Precipitation, recycling, and land memory: An integrated analysis, Journal of Hydrometeorology, 10, 278–288, 2009b.

Dirmeyer, P. A., Wei, J., Bosilovich, M. G., and Mocko, D. M.: Comparing Evaporative Sources of Terrestrial Precipitation and Their Extremes in MERRA Using Relative Entropy, Journal of Hydrometeorology, 15, 102–116, 2014.

Dominguez, F. and Kumar, P.: Precipitation recycling variability and ecoclimatological stability - A study using NARR Data. Part I: Central U.S. plains ecoregion, Journal of Climate, 21, 5165–5186, 2008.

Dominguez, F., Kumar, P., Liang, X. Z., and Ting, M.: Impact of atmospheric moisture storage on precipitation recycling, Journal of Climate, 19, 1513–1530, 2006.

Dominguez, F., Kumar, P., and Vivoni, E. R.: Precipitation recycling variability and ecoclimatological stability - A study using NARR data. Part II: North American monsoon region, Journal of Climate, 21, 5187–5203, 2008.

Dominguez, F., Villegas, J. C., and Breshears, D. D.: Spatial extent of the North American Monsoon: Increased cross-regional linkages via atmospheric pathways, Geophysical Research Letters, 36, 2009.

Draxler, R. R. and Hess, G. D.: Description of the HYSPLIT 4_modeling system of trajectories, dispersion, and deposition, Australian Meteorological Magazine, 47, 295–308, 1998.

Draxler, R. R. and Rolph, G. D.: HYSPLIT (HYbrid Single-Particle Lagrangian Integrated Trajectory) Model, NOAA Air Resources Laboratory, Silver Spring, MD, http://ready.arl.noaa.gov/HYSPLIT.php, access 30 January 2014, 2014.

Druyan, L. M. and Koster, R. D.: Sources of Sahel Precipitation for Simulated Drought and Rainy Seasons, Journal of Climate, 2, 1438–1446, 1989.

Dufournet, Y. and Russchenberg, H. W. J.: Towards the improvement of cloud microphysical retrievals using simultaneous Doppler and polarimetric radar measurements, Atmosperic Measurement Techniques, 4, 2163–2178, 2011.

Eltahir, E. A. B. and Bras, R. L.: Precipitation recycling in the Amazon Basin, Quarterly Journal of the Royal Meteorological Society, 120, 861–880, 1994.

Eltahir, E. A. B. and Bras, R. L.: Precipitation recycling, Reviews of Geophysics, 34, 367–378, 1996.

Findell, K. L. and Eltahir, E. A. B.: An analysis of the soil moisture-rainfall feedback, based on direct observations from Illinois, Water Resources Research, 33, 725–735, 1997.

Findell, K. L., Gentine, P., Lintner, B. R., and Kerr, C.: Probability of afternoon precipitation in eastern United States and Mexico enhanced by high evaporation, Nature Geoscience, 4, 434–439, 2011.

Fitzmaurice, J.: A critical Analysis of Bulk Precipitation Recycling Models, Ph.D. thesis, Massachusetts Institute of Technology, 2007.

Forrester, D. I., Collopy, J. J., and Morris, J. D.: Transpiration along an age series of Eucalyptus globulus plantations in southeastern Australia, Forest Ecology and Management, 259, 1754–1760, 2010.

Froehlich, K., Gibson, J. J., and Aggarwal, P.: Deuterium excess in precipitation and its climatological significance, International Atomic Energy Agency, C&S Papers Series 13/P, Vienna, 54–66, 2001.

Froehlich, K., Kralik, M., Papesch, W., Rank, D., Scheifinger, H., and Stichler, W.: Deuterium excess in precipitation of Alpine regions - Moisture recycling, Isotopes in Environmental and Health Studies, 44, 61–70, 2008.

Gangoiti, G., Gómez-Domenech, I., Sáez de Cámara, E., Alonso, L., Navazo, M., Iza, J., García, J. A., Ilardia, J. L., and Millán, M. M.: Origin of the water vapor responsible for the European extreme rainfalls of August 2002: 2. A new methodology to evaluate evaporative moisture sources, applied to the August 11-13 central European rainfall episode, Journal of Geophysical Research, 116, D21 103, 2011.

Gat, J. R. and Matsui, E.: Atmospheric water balance in the Amazon basin: An isotopic evapotranspiration model, Journal of Geophysical Research, 96, 13 179–13 188, 1991.

Gimeno, L., Drumond, A., Nieto, R., Trigo, R. M., and Stohl, A.: On the origin of continental precipitation, Geophysical Research Letters, 37, L13 804, 2010.

Gimeno, L., Stohl, A., Trigo, R. M., Dominguez, F., Yoshimura, K., Yu, L., Drumond, A., Durán-Quesada, A. M., and Nieto, R.: Oceanic and Terrestrial Sources of Continental Precipitation, Reviews of Geophysics, 50, RG4003, 2012.

Goessling, H. F. and Reick, C. H.: What do moisture recycling estimates tell us? Exploring the extreme case of non-evaporating continents, Hydrology and Earth System Sciences, 15, 3217–3235, 2011.

Goessling, H. F. and Reick, C. H.: On the "well-mixed" assumption and numerical 2-D tracing of atmospheric moisture, Atmospheric Chemistry and Physics, 13, 5567–5585, 2013a.

Goessling, H. F. and Reick, C. H.: Continental moisture recycling as a Poisson process, Hydrology and Earth System Sciences, 17, 4133–4142, 2013b.

Gong, C. and Eltahir, E.: Sources of moisture for rainfall in west Africa, Water Resources Research, 32, 3115–3121, 1996.

Gordon, L. J., Steffen, W., Jönsson, B. F., Folke, C., Falkenmark, M., and Johannessen, A.: Human modification of global water vapor flows from the land surface, Proceedings of the National Academy of Sciences of the United States of America, 102, 7612–7617, 2005.

Gordon, L. J., Peterson, G. D., and Bennett, E. M.: Agricultural modifications of hydrological flows create ecological surprises, Trends in Ecology and Evolution, 23, 211–219, 2008.

Henderson-Sellers, A., McGuffie, K., and Zhang, H.: Stable isotopes as validation tools for global climate model predictions of the impact of Amazonian deforestation, Journal of Climate, 15, 2664–2677, 2002.

Hoekstra, A. Y. and Chapagain, A. K.: Water footprints of nations: Water use by people as a function of their consumption pattern, Water Resources Management, 21, 35–48, 2007.

Jasechko, S., Sharp, Z. D., Gibson, J. J., Birks, S. J., Yi, Y., and Fawcett, P. J.: Terrestrial water fluxes dominated by transpiration, Nature, 496, 347–350, 2013.

Joussaume, S., Sadourny, R., and Vignal, C.: Origin of precipitating water in a numerical simulation of the July climate, Ocean-Air Interactions, 1, 43–56, 1986.

Karimi, P., Bastiaanssen, W. G. M., and Molden, D.: Water Accounting Plus (WA+) - a water accounting procedure for complex river basins based on satellite measurements, Hydrology and Earth System Sciences, 17, 2459–2472, 2013.

Keenan, T. F., Hollinger, D. Y., Bohrer, G., Dragoni, D., Munger, J. W., Schmid, H. P., and Richardson, A. D.: Increase in forest water-use efficiency as atmospheric carbon dioxide concentrations rise, Nature, 499, 324–327, 2013.

Keys, P. W., Van der Ent, R. J., Gordon, L. J., Hoff, H., Nikoli, R., and Savenije, H. H. G.: Analyzing precipitationsheds to understand the vulnerability of rainfall dependent regions, Biogeosciences, 9, 733–746, 2012.

Keys, P. W., Barnes, E., Van der Ent, R. J., and Gordon, L.: Natural variability of moisture recycling using a precipitationshed framework, in preparation, 2014.

Kleidon, A., Fraedrich, K., and Heimann, M.: A Green Planet Versus a Desert World: Estimating the Maximum Effect of Vegetation on the Land Surface Climate, Climatic Change, 44, 471–493, 2000.

Knoche, H. R. and Kunstmann, H.: Tracking atmospheric water pathways by direct evaporation tagging: A case study for West Africa, Journal of Geophysical Research, under review, 2013.

Knox, R., Bisht, G., Wang, J., and Bras, R.: Precipitation Variability over the Forest-to-Nonforest Transition in Southwestern Amazonia, Journal of Climate, 24, 2368–2377, 2011.

Koster, R., Jouzel, J., Suozzo, R., Russell, G., Broecker, W., Rind, D., and Eagleson, P.: Global sources of local precipitation as determined by the NASA/GISS GCM, Geophysical Research Letters, 13, 121–124, 1986.

Koster, R. D., Dirmeyer, P. A., Guo, Z., Bonan, G., Chan, E., Cox, P., Gordon, C. T., Kanae, S., Kowalczyk, E., Lawrence, D., Liu, P., Lu, C. H., Malyshev, S., McAvaney, B., Mitchell, K., Mocko, D., Oki, T., Oleson, K., Pitman, A., Sud, Y. C., Taylor, C. M., Verseghy, D., Vasic, R., Xue, Y., and Yamada, T.: Regions of strong coupling between soil moisture and precipitation, Science, 305, 1138–1140, 2004.

Kunstmann, H. and Jung, G.: Influence of soil-moisture and land use change on precipitation in the Volta Basin of West Africa, International Journal of River Basin Management, 5, 9–16, 2007.

Kurita, N., Yoshida, N., Inoue, G., and Chayanova, E. A.: Modern isotope climatology of Russia: A first assessment, Journal of Geophysical Research, 109, D03 102, 2004.

Lettau, H., Lettau, K., and Molion, L. C.: Amazonia's hydrological cycle and the role of atmospheric recycling in assessing deforestation effects, Montly Weather Review, 107, 227–238, 1979.

Lintner, B. R., Gentine, P., Findell, K. L., D'Andrea, F. D., Sobel, A. H., and Salvucci, G. D.: An Idealized Prototype for Large-Scale Land-Atmosphere Coupling, Journal of Climate, 26, 2379–2389, 2013.

Liu, Z., Tian, L., Yao, T., and Yu, W.: Seasonal deuterium excess in Nagqu precipitation: Influence of moisture transport and recycling in the middle of Tibetan Plateau, Environmental Geology, 55, 1501–1506, 2008.

Lorenz, C. and Kunstmann, H.: The Hydrological Cycle in Three State-of-the-art Reanalyses: Intercomparison and Performance Analysis, Journal of Hydrometeorology, 13, 1397–1420, 2012.

Ma, J. and Xie, S.-P.: Regional Patterns of Sea Surface Temperature Change: A Source of Uncertainty in Future Projections of Precipitation and Atmospheric Circulation, Journal of Climate, 26, 2482–2501, 2012.

Makarieva, A. M. and Gorshkov, V. G.: Biotic pump of atmospheric moisture as driver of the hydrological cycle on land, Hydrology and Earth System Sciences, 11, 1013–1033, 2007.

Makurira, H., Savenije, H. H. G., and Uhlenbrook, S.: Modelling field scale water partitioning using on-site observations in sub-Saharan rainfed agriculture, Hydrology and Earth System Sciences, 14, 627–638, 2010.

Marengo, J. A.: On the hydrological cycle of the Amazon basin; a historical review and current state-of-the-art, Revista Brasileira de Meteorologica, 21, 1–19, 2006.

McDonald, J. E.: The evaporation precipitation fallacy, Weather, 17, 168–179, 1962.

Mohamed, Y. A., Van den Hurk, B. J. J. M., Savenije, H. H. G., and Bastiaanssen, W. G. M.: Hydroclimatology of the Nile: Results from a regional climate model, Hydrology and Earth System Sciences, 9, 263–278, 2005.

Molion, L. C. B.: A climatonomic study of the energy and moisture fluxes of the Amazon basin with consideration on deforestation, Ph.D. thesis, University of Wisconsin, 1975.

Mueller, B., Hirschi, M., Jimenez, C., Ciais, P., Dirmeyer, P. A., Dolman, A. J., Fisher, J. B., Jung, M., Ludwig, F., Maignan, F., Miralles, D., McCabe, M. F., Reichstein, M., Sheffield, J., Wang, K. C., Wood, E. F., Zhang, Y., and Seneviratne, S. I.: Benchmark products for land evapotranspiration: LandFlux-EVAL multi-dataset synthesis, Hydrology and Earth System Sciences, 17, 3707–3720, 2013.

Nieto, R., Gimeno, L., and Trigo, R. M.: A Lagrangian identification of major sources of Sahel moisture, Geophysical Research Letters, 33, L18 707, 2006.

Njitchoua, R., Sigha-Nkamdjou, L., Dever, L., Marlin, C., Sighomnou, D., and Nia, P.: Variations of the stable isotopic compositions of rainfall events from the Cameroon rain forest, Central Africa, Journal of Hydrology, 223, 17–26, 1999.

Numaguti, A.: Origin and recycling processes of precipitating water over the Eurasian continent: Experiments using an atmospheric general circulation model, Journal of Geophysical Research, 104, 1957–1972, 1999.

Oki, T. and Kanae, S.: Global hydrological cycles and world water resources, Science, 313, 1068–1072, 2006.

Overeem, A., Leijnse, H., and Uijlenhoet, R.: Country-wide rainfall maps from cellular communication networks, Proceedings of the National Academy of Sciences of the United States of America, 110, 2741–2745, 2013.

Pang, H., He, Y., Zhang, Z., Lu, A., and Gu, J.: The origin of summer monsoon rainfall at New Delhi by deuterium excess, Hydrology and Earth System Sciences, 8, 115–118, 2004.

Pielke, R. A., Pitman, A., Niyogi, D., Mahmood, R., McAlpine, C., Hossain, F., Goldewijk, K. K., Nair, U., Betts, R., Fall, S., Reichstein, M., Kabat, P., and de Noblet, N.: Land use/land cover changes and climate: modeling analysis and observational evidence, Wiley Interdisciplinary Reviews: Climate Change, 2, 828–850, 2011.

Pielke Sr, R. A., Adegoke, J., Beltrán-Przekurat, A., Hiemstra, C. A., Lin, J., Nair, U. S., Niyogi, D., and Nobis, T. E.: An overview of regional land-use and land-cover impacts on rainfall, Tellus, Series B: Chemical and Physical Meteorology, 59, 587–601, 2007.

Pitman, A. J., de Noblet-Ducoudré, N., Cruz, F. T., Davin, E. L., Bonan, G. B., Brovkin, V., Claussen, M., Delire, C., Ganzeveld, L., Gayler, V., van den Hurk, B. J. J. M., Lawrence, P. J., van der Molen, M. K., Müller, C., Reick, C. H., Seneviratne, S. I., Strengers, B. J., and Voldoire, A.: Uncertainties in climate responses to past land cover change: First results from the LUCID intercomparison study, Geophysical Research Letters, 36, L14 814, 2009.

Pitman, A. J., de Noblet-Ducoudré, N., Avila, F. B., Alexander, L. V., Boisier, J. P., Brovkin, V., Delire, C., Cruz, F., Donat, M. G., Gayler, V., van den Hurk, B., Reick, C., and Voldoire, A.: Effects of land cover change on temperature and rainfall extremes in multi-model ensemble simulations, Earth System Dynamics, 3, 213–231, 2012.

Reij, C. P. and Smaling, E. M. A.: Analyzing successes in agriculture and land management in Sub-Saharan Africa: Is macro-level gloom obscuring positive micro-level change?, Land Use Policy, 25, 410–420, 2008.

Rios-Entenza, A. and Miguez-Macho, G.: Moisture recycling and the maximum of precipitation in spring in the Iberian Peninsula, Climate Dynamics, 42, 3207–3231, 2013.

Risi, C., Noone, D., Frankenberg, C., and Worden, J.: The role of continental recycling in intra-seasonal variations of continental moisture as deduced from model simulations and water vapor isotopic measurements, Water Resources Research, 49, 4136–4156, 2013.

Rockström, J., Falkenmark, M., Karlberg, L., Hoff, H., Rost, S., and Gerten, D.: Future water availability for global food production: The potential of green water for increasing resilience to global change, Water Resources Research, 45, W00A12, 2009a.

Rockström, J., Steffen, W., Noone, K., Persson, A., Chapin III, F. S., Lambin, E. F., Lenton, T. M., Scheffer, M., Folke, C., Schellnhuber, H. J., Nykvist, B., de Wit, C. A., Hughes, T., van der Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P. K., Costanza, R., Svedin, U., Falkenmark, M., Karlberg, L., Corell, R. W., Fabry, V. J., Hansen, J., Walker, B., Liverman, D., Richardson, K., Crutzen, P., and Foley, J. A.: A safe operating space for humanity, Nature, 461, 472–475, 2009b.

Rockström, J., Falkenmark, M., Lannerstad, M., and Karlberg, L.: The planetary water drama: Dual task of feeding humanity and curbing climate change, Geophysical Research Letters, 39, L15 401, 2012.

Rost, S., Gerten, D., and Heyder, U.: Human alterations of the terrestrial water cycle through land management, Advances in Geosciences, 18, 43–50, 2008.

Rowell, D. P.: The Impact of Mediterranean SSTs on the Sahelian Rainfall Season, Journal of Climate, 16, 849–862, 2003.

Salati, E., Dall'olio, A., Matsui, E., and Gat, J. R.: Recycling of water in the Amazon Basin: an isotopic study, Water Resources Research, 15, 1250–1258, 1979.

Savenije, H. H. G.: New definitions for moisture recycling and the relationship with land-use changes in the Sahel, Journal of Hydrology, 167, 57–78, 1995a.

Savenije, H. H. G.: Does moisture feedback affect rainfall significantly?, Physics and Chemistry of the Earth, 20, 507–513, 1995b.

Savenije, H. H. G.: The runoff coefficient as the key to moisture recycling, Journal of Hydrology, 176, 219–225, 1996.

Savenije, H. H. G.: The importance of interception and why we should delete the term evapotranspiration from our vocabulary, Hydrological Processes, 18, 1507–1511, 2004.

Schaefli, B., van der Ent, R. J., Woods, R., and Savenije, H. H. G.: An analytical model for soil-atmosphere feedback, Hydrology and Earth System Sciences, 16, 1863–1878, 2012.

Schär, C., Lüthi, D., Beyerle, U., and Heise, E.: The soil-precipitation feedback: A process study with a regional climate model, Journal of Climate, 12, 722–741, 1999.

Seneviratne, S. I., Lüthi, D., Litschi, M., and Schär, C.: Land-atmosphere coupling and climate change in Europe, Nature, 443, 205–209, 2006.

Serreze, M. C. and Etringer, A. J.: Precipitation characteristics of the Eurasian Arctic drainage system, International Journal of Climatology, 23, 1267–1291, 2003.

Shukla, J. and Mintz, Y.: Influence of Land-Surface Evapotranspiration on the Earth's Climate, Science, 215, 1498–1501, 1982.

Sodemann, H., Schwierz, C., and Wernli, H.: Interannual variability of Greenland winter precipitation sources: Lagrangian moisture diagnostic and North Atlantic Oscillation influence, Journal of Geophysical Research, 113, D03 107, 2008.

Sodemann, H., Wernli, H., and Schwierz, C.: Sources of water vapour contributing to the Elbe flood in August 2002—A tagging study in a mesoscale model, Quarterly Journal of the Royal Meteorological Society, 135, 205–223, 2009.

Spracklen, D. V., Arnold, S. R., and Taylor, C. M.: Observations of increased tropical rainfall preceded by air passage over forests, Nature, 489, 282–285, 2012.

Stohl, A. and James, P.: A Lagrangian analysis of the atmospheric branch of the global water cycle. Part II: Moisture transports between earth's ocean basins and river catchments, Journal of Hydrometeorology, 6, 961–984, 2005.

Stohl, A., Forster, C., Frank, A., Seibert, P., and Wotawa, G.: Technical note: The Lagrangian particle dispersion model FLEXPART version 6.2, Atmospheric Chemistry and Physics, 5, 2461–2474, 2005.

Szeto, K. K.: Moisture recycling over the Mackenzie basin, Atmosphere - Ocean, 40, 181–197, 2002.

Taylor, C. M., Gounou, A., Guichard, F., Harris, P. P., Ellis, R. J., Couvreux, F., and De Kauwe, M.: Frequency of Sahelian storm initiation enhanced over mesoscale soil-moisture patterns, Nature Geoscience, 4, 430–433, 2011.

Taylor, C. M., de Jeu, R. A. M., Guichard, F., Harris, P. P., and Dorigo, W. A.: Afternoon rain more likely over drier soils, Nature, 489, 423–426, 2012.

Tian, L., Yao, T., Sun, W., Stievenard, M., and Jouzel, J.: Relationship between δD and δ^{18}O in precipitation on north and south of the Tibetan Plateau and moisture recycling, Science in China, Series D: Earth Sciences, 44, 789–796, 2001.

Tian, L., Yao, T., MacClune, K., White, J. W. C., Schilla, A., Vaughn, B., Vachon, R., and Ichiyanagi, K.: Stable isotopic variations in west China: A consideration of moisture sources, Journal of Geophysical Research, 112, D10 112, 2007.

Trenberth, K. E.: Atmospheric moisture residence times and cycling: Implications for rainfall rates and climate change, Climatic Change, 39, 667–694, 1998.

Trenberth, K. E.: Atmospheric moisture recycling: Role of advection and local evaporation, Journal of Climate, 12, 1368–1381, 1999.

Trenberth, K. E.: Changes in precipitation with climate change, Climate Research, 47, 123–138, 2011.

Trenberth, K. E., Branstator, G. W., Karoly, D., Kumar, A., Lau, N.-C., and Ropelewski, C.:

Progress during TOGA in understanding and modeling global teleconnections associated with tropical sea surface temperatures, Journal of Geophysical Research, 103, 14 291–14 324, 1998.

Trenberth, K. E., Smith, L., Qian, T. T., Dai, A., and Fasullo, J.: Estimates of the global water budget and its annual cycle using observational and model data, Journal of Hydrometeorology, 8, 758–769, 2007.

Tuinenburg, O. A., Hutjes, R. W. A., Jacobs, C. M. J., and Kabat, P.: Diagnosis of local land-atmosphere feedbacks in India, Journal of Climate, 24, 251–266, 2011.

Tuinenburg, O. A., Hutjes, R. W. A., and Kabat, P.: The fate of evaporated water from the Ganges basin, Journal of Geophysical Research, 117, D01 107, 2012.

Van de Giesen, N., Liebe, J., and Jung, G.: Adapting to climate change in the Volta Basin, West Africa, Current Science, 98, 1033–1037, 2010.

Van den Hurk, B., Doblas-Reyes, F., Balsamo, G., Koster, R. D., Seneviratne, S. I., and Camargo, Helio, J.: Soil moisture effects on seasonal temperature and precipitation forecast scores in Europe, Climate Dynamics, 38, 349–362, 2012.

Van den Hurk, B. J. J. M. and Van Meijgaard, E.: Diagnosing Land–Atmosphere Interaction from a Regional Climate Model Simulation over West Africa, Journal of Hydrometeorology, 11, 467–481, 2009.

Van der Ent, R. J.: Interactive comment on “Continental moisture recycling as a Poisson process” by H. F. Goessling and C. H. Reick, Hydrology and Earth System Sciences Discussions, 10, C1441–C1446, 2013.

Van der Ent, R. J. and Savenije, H. H. G.: Length and time scales of atmospheric moisture recycling, Atmospheric Chemistry and Physics, 11, 1853–1863, 2011.

Van der Ent, R. J. and Savenije, H. H. G.: Oceanic sources of continental precipitation and the correlation with sea surface temperature, Water Resources Research, 49, 3993–4004, 2013.

Van der Ent, R. J., Savenije, H. H. G., Schaefli, B., and Steele-Dunne, S. C.: Origin and fate of atmospheric moisture over continents, Water Resources Research, 46, W09 525, 2010.

Van der Ent, R. J., Coenders-Gerrits, A. M. J., Nikoli, R., and Savenije, H. H. G.: The importance of proper hydrology in the forest cover-water yield debate: commentary on Ellison et al. (2012) Global Change Biology, 18, 806–820, Global Change Biology, 18, 2677–2680, 2012.

Van der Ent, R. J., Tuinenburg, O. A., Knoche, H. R., Kunstmann, H., and Savenije, H. H. G.: Should we use a simple or complex model for moisture recycling and atmospheric moisture tracking?, Hydrology and Earth System Sciences, 17, 4869–4884, 2013.

Van der Ent, R. J., Wang-Erlandsson, L., Keys, P. W., and Savenije, H. H. G.: Contrasting roles of interception and transpiration in the hydrological cycle – Part 2: Moisture recycling, Earth System Dynamics Discussions, 5, 281–326, 2014.

Wang-Erlandsson, L., van der Ent, R. J., Gordon, L., and Savenije, H. H. G.: Contrasting roles of interception and transpiration in the hydrological cycle – Part 1: Simple

Terrestrial Evaporation to Atmosphere Model, Earth System Dynamics Discussions, 5, 203–279, 2014.

Wei, J., Dirmeyer, P. A., Wisser, D., Bosilovich, M. G., and Mocko, D. M.: Where does the irrigation water go? An estimate of the contribution of irrigation to precipitation using MERRA, Journal of Hydrometeorology, 14, 275–289, 2012.

Werth, D. and Avissar, R.: The local and global effects of Amazon deforestation, Journal of Geophysical Research, 107, 8087, 2002.

Wolfram|Alpha: Wolfram Alpha LLC, http://www.wolframalpha.com (access 10 August 2010), 2010.

Xie, S.-P., Deser, C., Vecchi, G. A., Ma, J., Teng, H., and Wittenberg, A. T.: Global Warming Pattern Formation: Sea Surface Temperature and Rainfall*, Journal of Climate, 23, 966–986, 2010.

Yoshimura, K., Oki, T., Ohte, N., and Kanae, S.: Colored moisture analysis estimates of variations in 1998 Asian monsoon water sources, Journal of the Meteorological Society of Japan, 82, 1315–1329, 2004.

Yu, W., Yao, T., Tian, L., Ma, Y., Kurita, N., Ichiyanagi, K., Wang, Y., and Sun, W.: Stable isotope variations in precipitation and moisture trajectories on the western Tibetan Plateau, China, Arctic, Antarctic, and Alpine Research, 39, 688–693, 2007.

Zemp, D. C., Schleussner, C. F., Barbosa, H. M. J., Van der Ent, R. J., Donges, J. F., Heinke, J., Sampaio, G., and Rammig, A.: On the importance of cascading moisture recycling in South America, Atmosperic Chemistry and Physics Discussions, 14, 17 479–17 526, 2014.

Zolina, O., Simmer, C., Belyaev, K., Gulev, S. K., and Koltermann, P.: Changes in the Duration of European Wet and Dry Spells during the Last 60 Years, Journal of Climate, 26, 2022–2047, 2013.

SUMMARY

A NEW VIEW ON THE HYDROLOGICAL CYCLE OVER CONTINENTS

Where does precipitation come from? It is not easy to answer this question because of the complex and energy-intensive processes that bring moisture to a certain location and cause moisture to precipitate highly heterogeneously in space and variable over time. Part of the precipitation comes from so-called “moisture recycling”, which is moisture from land evaporation that returns to the land surface as precipitation. It is widely accepted that land-atmosphere interactions play a crucial role in the global climate, but the importance of moisture recycling specifically had, before the research presented in this thesis, not yet been fully quantified. It is, however, important to do so as the magnitude of moisture recycling can be used as an indicator for the susceptibility of our water resources to local and remote land-use change. The main research question of this thesis is: “How important is land evaporation in the hydrological cycle over continents?”

Chapter 2 presents the offline Eulerian numerical atmospheric moisture tracking model WAM-2layers (Water Accounting Model-2layers), which is being used throughout the thesis. The underlying principle of this model is simply the water balance. WAM-2layers can be used to track tagged moisture on both the regional and global scale, and both forward and backward in time. The focus of this thesis is the moisture recycling over continents and therefore a near global grid is used, which includes all continents except Antarctica. The ERA-Interim reanalysis, from which evaporation, precipitation, humidity and wind speed is used, is the main data source for input to the tracking model. WAM-2layers provides a fast computation of large scale atmospheric moisture tracking while the two layers ensure that problems such as wind shear are still adequately dealt with.

Chapter 3 presents new definitions for continental moisture recycling. The continental precipitation recycling ratio identifies regions that are dependent on upwind evaporation and the continental evaporation recycling ratio identifies the importance of evaporation to sustain downwind precipitation. Global maps showing the spatial distribution of two ratios are presented and together they provide a new way to describe continental scale moisture feedback within the hydrological cycle. It is estimated that on average 40 % of all terrestrial precipitation is derived from continental sources and 57 % of all terrestrial evaporation returns as precipitation to continents. Mountain ranges can play an important role in continental moisture recycling by either “blocking” moisture from entering the continent or by “capturing” the moisture from the atmosphere to enhance recycling. Overall, this chapter demonstrates the important role of global wind patterns, topography and land cover in continental moisture recycling patterns and the distribution of global water resources.

Chapter 4 presents a novel approach to quantify the spatial and temporal scale of moisture recycling, independent of the size and shape of the region under study. As such, this approach overcomes the previously existing problem of scale- and shape-dependency of regional moisture recycling ratios. It is shown that in the tropics or in mountainous terrain the local length scale of recycling can be as low as 500 to 2000 km. In temperate climates the length scale is typically between 3000 to 5000 km whereas it amounts to more than 7000 km in desert areas. The local time scale of recycling ranges from 3 to 20 days, with the exception of deserts, where it is much longer. Analysis of both the length and times scales identifies several hot spots of high local moisture recycling, in particular, in and around mountainous areas. It is also found that local moisture recycling plays a much more important role in summer than in winter.

Chapter 5 present a new image of that global hydrological cycle over land, which, in contrast to traditional images of the hydrological cycle includes a quantification of moisture recycling, partitioned evaporation and the lifetime of all these processes separately. It is demonstrated that evaporated interception is more likely to return as precipitation on land than transpired moisture. On average, direct evaporation (essentially interception) is found to have an atmospheric residence time of 8 days, while transpiration typically resides 9 days in the atmosphere. Interception recycling has a much shorter local length scale than transpiration recycling, thus interception generally precipitates closer to its evaporative source than transpiration, which is particularly pronounced outside the tropics. The results suggest that the effect of land-use change on moisture recycling is very different during wet and dry seasons, and also during summer and winter, indicating that seasonality is important to consider when analysing effects of land-use change. During the wet season, increased or decreased interception could amplify or attenuate the local moisture recycling signal, but land-use change needs to be drastic to influence the evaporative fluxes in a way that this signal would have continental scale influence. During the dry season, land-use change (in particular deforestation), could lead to reduced transpiration, hence reduced moisture recycling, and therefore a drier dry season.

Chapter 6 describe the concept of atmospheric watersheds. Precipitationsheds show how precipitation depends on upwind evaporation and evaporationsheds show how evaporation sustains precipitation downwind. The biggest sources and sinks are generally found close to the region of interest. However, for West Africa it is shown that, outside the rainy season, more distant sources, of in particular transpiration, are very important for the hydrological cycle as well. As such, this chapter illustrates how land-use change in one region alters evaporation and moisture recycling, and hence, influences precipitation, in a geographically separate region.

It is concluded that land evaporation plays a major role in the hydrological cycle over continents as on average more than half of it returns as precipitation over land. Strong local moisture feedback is generally found in very wet regions, or in regions where it is enhanced by topography. Interception and transpiration are found to have contrasting roles in the hydrological cycle. While interception mainly works as an intensifier of the local hydrological cycle during wet spells, transpiration remains active during dry spells and is transported over much larger distances downwind where it can act as a significant source of moisture. The concepts of the precipitationshed and evaporationshed can be effectively used as tools to study the moisture recycling effect of land-use changes in specific regions of interest.

The results of this thesis suggest that reduced evaporation due to a change in land use can lead to reduced precipitation downwind. It must be noted, however, that the magnitude of the reduced moisture recycling effect depends on the nature of the land-use change. As a conversion of forest to agriculture may lead to reduced precipitation downwind, this make the already difficult task of sustainably producing enough food for a growing population even more challenging. On the other hand, the fact that evaporation in some places in the world is very likely to recycle over the continent also provides opportunities. In Africa, for example, large-scale implementation of water harvesting and water conservation techniques could have positive effects on the rainfall and thus water resources of the continent. Overall, this thesis contributes to an increased understanding of the global hydrological over continents, and provides important context to future local and regional land-use change impact studies.

SAMENVATTING

EEN NIEUWE KIJK OP DE HYDROLOGISCHE CYCLUS OVER CONTINENTEN

Waar komt neerslag vandaan? Het is niet makkelijk deze vraag te beantwoorden vanwege de complexe en energie-intensieve processen die waterdamp naar een bepaalde locatie brengen en die ervoor zorgen dat deze waterdamp heterogeen in plaats en variabel over de tijd valt als neerslag. Een deel van de neerslag is afkomstig van zogenaamde "waterdamprecycling", waaronder waterdamp wordt verstaan die afkomstig is van landverdamping en ook weer terugvalt op het landoppervlak als neerslag. Het is alom geaccepteerd dat land-atmosfeerinteracties een cruciale rol spelen in het globale klimaat, maar het belang van waterdamprecycling was, alvorens het in dit proefschrift gepresenteerde onderzoek, nog niet volledig gekwantificeerd. Het is echter belangrijk dit te doen, omdat de omvang van waterdamprecycling kan worden gebruikt als een indicator voor de vatbaarheid van onze waterbronnen voor lokale en verweggelegen landgebruiksveranderingen. De hoofdonderzoeksvraag van dit proefschrift is: "Hoe belangrijk is landverdamping in the hydrologische cyclus over continenten?"

Hoofdstuk 2 presenteert het offline Euleriaanse numerieke atmosferische waterdampvolgmodel WAM-2layers (Water Accounting Model-2layers) dat in het gehele proefschrift wordt gebruikt. Het onderliggende principe van dit model is simpelweg de waterbalans. WAM-2layers kan zowel op regionale als op globale schaal worden gebruikt om gelabelde waterdamp zowel voorwaarts als terugwaarts in de tijd te volgen. De focus van dit proefschrift is waterdamprecycling over continenten en daarom wordt een nagenoeg globaal coördinatenstelsel gebruikt dat alle continenten behalve Antarctica omvat. De ERA-Interim reanalysis, waarvan verdamping, neerslag, luchtvochtigheid en windsnelheid worden gebruikt, is de belangrijkste gegevensbron voor de input van het waterdampvolgmodel. WAM-2layers voorziet in een snelle computatie van het volgen van atmosferische waterdamp op grote schaal, terwijl de twee lagen ervoor zorgen dat er met problemen zoals windschering adequaat wordt omgegaan.

Hoofdstuk 3 presenteert nieuwe begrippen voor continentale waterdamprecycling. Het continentale neerslagrecyclingverhoudingsgetal identificeert gebieden die afhankelijk zijn van bovenwindse verdamping en het continentale verdampingverhoudingsgetal identificeert het belang van verdamping om benedenwindse neerslag te onderhouden. Globale kaarten die de ruimtelijke distributie van deze twee verhoudingsgetallen weergeven worden gepresenteerd en tezamen bieden ze een nieuwe manier om de terugkoppeling van waterdamp in de hydrologische cyclus op continentale schaal te beschrijven. Bergketens kunnen een belangrijke rol spelen voor continentale waterdamprecycling door ofwel het "blokkeren" van waterdamp van het binnengaan van het continent dan wel het "afvangen" van waterdamp van de atmosfeer waardoor recycling wordt versterkt. In zijn algemeen demonstreert dit hoofdstuk de belangrijk rol van globale windpatronen, topografie en bodembedekking voor de continentale waterdampsrecyclingpatronen en de verdeling van globale waterbronnen.

Hoofdstuk 4 presenteert een nieuwe methode om de ruimtelijke en temporele schaal van waterdamprecycling te kwantificeren, onafhankelijk van de grootte en vorm van het gebied wat wordt bestudeerd. Het blijkt dat in de tropen of in bergachtige gebieden de lokale lengteschaal van recycling zo laag kan zijn als 500 tot 2000 km. In gematigde klimaten is de lengteschaal typisch tussen de 3000 en 5000 km, terwijl dit meer dan 7000 km is in woestijngebieden. De lokale tijdschaal van recycling ligt tussen de 3 en de 20 dagen met uitzondering van woestijnen waar dit veel langer is. Analyse van zowel de lengte- als tijdschalen leidt tot de identificatie van verscheidene hotspots met hoge lokale waterdamprecycling, met name in en rond bergachtige gebieden. Het blijkt ook dat lokale waterdamprecycling in de zomer een veel belangrijkere rol speelt dan in de winter.

Hoofdstuk 5 presenteert een nieuwe afbeelding van de globale hydrologische cyclus over land die, in tegenstelling to traditionele afbeeldingen van de hydrologische cyclus, een kwantificatie van waterdamprecycling, gepartitioneerde verdamping en de levensduur van al deze processen apart omvat. Er wordt gedemonstreerd dat het waarschijnlijker is voor verdampte interceptie om weer terug te vallen als neerslag op het land dan dat dit is voor getranspireerde waterdamp. Gemiddeld genomen blijkt directe verdamping (in weze interceptie) een verblijftijd in de atmosfeer te hebben van 8 dagen, terwijl tranpiratie typisch 9 dagen in de atmosfeer verblijft. Interceptierecycling heeft een veel korte lokale lengteschaal vergeleken met transpiratierecycling en dit is met name te zien buiten de tropen. De resultaten suggereren dat de effecten van landgebruiksverandering op waterdamprecycling zeer verschillend zijn tijdens natte en droge seizoenen, en ook tijdens zomer en winter, hetgeen aangeeft dat seizoensgebondenheid belangrijk is om te beschouwen wanneer de effecten van landgebruiksveranderingen worden geanalyseerd. Tijdens het natte seizoen zou verhoogde of verlaagde interceptie het lokale waterdampsrecyclingsignaal kunnen versterken of verzwakken, maar landgebruiksveranderingen moeten drastisch zijn om de verdampingsfluxen zo te beïnvloeden dat dit signaal invloed heeft op continentale schaal. Tijdens het droge seizoen zou landgebruiksverandering (met name ontbossing) kunnen leiden tot verminderde transpiratie, dus minder waterdamprecycling en daarom een drogere droge tijd.

Hoofdstuk 6 beschrijft het concept van atmosferische stroomgebieden. Precipitationsheds laten zien in welke mate neerslag afhankelijk is van bovenwindse verdamping en evaporationsheds laten zien hoe verdamping benedenwindse neerslag onderhoudt. De grootste bron- en afhankelijkheidsgebieden blijken over het algemeen dichtbij het interessegebied te worden gevonden. Echter, voor West-Afrika geldt dat buiten het regenseizoen verderweggelegen bronnen, van met name transpiratie, ook erg belangrijk zijn voor de hydrologische cyclus. Als zodanig illustreert dit hoofdstuk hoe langebruiksverandering in de ene regio, verdamping en waterdamprecycling verandert en daarmee de neerslag van geografisch gescheiden regio beïnvloedt.

Er wordt geconcludeerd dat landverdamping een zeer belangrijke rol vervult in the hydrologische cyclus over continenten, omdat meer dan de helft weer retourneert als neerslag op land. Sterke lokale terugkoppeling van waterdamp wordt over het algemeen gevonden in hele natte gebieden of in gebieden waar dit wordt versterkt door topografie. Interceptie en transpiratie blijken een contrasterende rol te vervullen in de hydrologische cycle. Ofschoon interceptie voornamelijk fungeert als een versterker van de hydrologische cyclus tijdens een natte periode, blijft transpiratie ook actief tijdens droge periodes en wordt het getransporteerd over veel langere afstanden, alwaar het kan fungeren als belangrijk bron van waterdamp. De concepten van de precipitationshed en de evaporationshed zijn gereedschappen die effectief toegepast kunnen worden om de effecten van landgebruiksveranderingen in specifieke gebieden te bestuderen.

De resultaten van dit proefschrift suggereren dat verminderde verdamping, als gevolg van veranderd landgebruik, benedenwinds kan leiden tot verminderde neerslag. Hierbij moet echter wel aangetekend worden dat de sterkte van het effect van verminderde waterdamprecycling afhangt van de aard van de landgebruiksverandering. Doordat een conversie van bos naar landbouw benedenwinds zou kunnen leiden tot verminderde neerslag wordt de reeds ingewikkelde taak om op een duurzame manier genoeg voedsel te produceren nog uitdagender. Aan de andere kant biedt het feit dat verdamping in sommige gebieden op deze wereld zeer waarschijnlijk recycled over het continent ook mogelijkheden. In Afrika bijvoorbeeld zou grootschalige implementatie van regenwateropvangsystemen en technieken om water vast te houden positieve effecten kunnen hebben op de regen en daarmee de waterbronnen voor het continent. In zijn totaliteit draagt dit proefschrift bij een verhoogd begrip van de globale hydrologische cyclus over continenten en verschaft het belangrijke context voor toekomstige lokale en regionale studies die het effect van landgebruiksverandering onderzoeken.

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EDUCATION

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LIST OF PUBLICATIONS

1. **Van der Ent, R. J.**, H. H. G. Savenije, B. Schaefli, and S. C. Steele-Dunne, *Origin and fate of atmospheric moisture over continents*, Water Resources Research, **46**, W09525, 2010.
2. **Van der Ent, R. J.**, and H. H. G. Savenije, *Length and time scales of atmospheric moisture recycling*, Atmospheric Chemistry and Physics, **11**, 1853–1863, 2011.
3. Keys, P. W., **R. J. van der Ent**, L. J. Gordon, H. Hoff, R. Nikoli, and H. H. G. Savenije, *Analyzing precipitationsheds to understand the vulnerability of rainfall dependent regions*, Biogeosciences, **9**, 733–746, 2012.
4. Schaefli, B., **R. J. van der Ent**, R. Woods, and H. H. G. Savenije, *An analytical model for soil-atmosphere feedback*, Hydrology and Earth System Sciences, **16**, 1863–1878, 2012.
5. **Van der Ent, R. J.**, A. M. J. Coenders-Gerrits, R. Nikoli, and H. H. G. Savenije, *The importance of proper hydrology in the forest cover-water yield debate: commentary on Ellison et al. Global Change Biology, 18, 806–820*, Global Change Biology, **18**, 2677–2680, 2012.
6. **Van der Ent, R. J.**, and H. H. G. Savenije, *Oceanic sources of continental precipitation and the correlation with sea surface temperature*, Water Resources Research, **49**, 3993–4004, 2013.
7. **Van der Ent, R. J.**, O. A. Tuinenburg, H. R. Knoche, H. Kunstmann, and H. H. G. Savenije, *Should we use a simple or complex model for moisture recycling and atmospheric moisture tracking?*, Hydrology and Earth System Sciences, **17**, 4869–4884, 2013.
8. Coenders-Gerrits, A. M. J., **R. J. van der Ent**, T. A. Bogaard, L. Wang-Erlandsson, M. Hrachowitz, and H. H. G. Savenije, *Uncertainties in transpiration estimates*, Nature, **506**, E1-E2, 2014.
9. Berger, M., **R. van der Ent**, S. Eisner, V. Bach, and M. Finkbeiner, *Water Accounting and Vulnerability Evaluation (WAVE): Considering Atmospheric Evaporation Recycling and the Risk of Freshwater Depletion in Water Footprinting*, Environmental Science & Technology, **8**, 2014.

10. Wang-Erlandsson, L., **R. J. van der Ent**, L. J. Gordon, and H. H. G. Savenije, *Contrasting roles of interception and transpiration in the hydrological cycle – Part 1: Simple Terrestrial Evaporation to Atmosphere Model*, Earth System Dynamics Discussions, **5**, 203–279, 2014.

11. **Van der Ent, R. J.**, L. Wang-Erlandsson, P. W. Keys, and H. H. G. Savenije, *Contrasting roles of interception and transpiration in the hydrological cycle – Part 2: Moisture recycling*, Earth System Dynamics Discussions, **5**, 281–326, 2014.

12. Keys, P. W., E. A. Barnes, **R. J. van der Ent**, and L. J. Gordon, *Variability of moisture recycling using a precipitationshed framework*, Hydrology and Earth System Sciences Discussions, **11**, 5143–5178, 2014.

13. Zemp, D. C., C. F. Schleussner, H. M. J. Barbosa, **R. J. van der Ent**, J. F. Donges, J. Heinke, G. Sampaio, and A. Rammig, *On the importance of cascading moisture recycling in South America*, Atmosperic Chemistry and Physics Discussions, **14**, 17479–17526, 2014.