Hydrol. Earth Syst. Sci. Discuss., 6, 3301–3333, 2009
www.hydrol-earth-syst-sci-discuss.net/6/3301/2009/

Hydrology and Earth System Sciences Discussions

Papers published in *Hydrology and Earth System Sciences Discussions* are under open-access review for the journal *Hydrology and Earth System Sciences*

Recycling of moisture in Europe: contribution of evaporation to variability in very wet and dry years

B. Bisselink and A. J. Dolman

Department of Hydrology & Geo-environmental Sciences, VU University, Amsterdam, The Netherlands

Received: 6 April 2009 – Accepted: 14 April 2009 – Published: 21 April 2009

Correspondence to: B. Bisselink (berny.bisselink@falw.vu.nl)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Evaporation is a key parameter in the regional atmospheric water cycle. Precipitation recycling is defined as the contribution of local evaporation in a region to the precipitation in the same region. In this work, we apply a dynamic precipitation recycling mode, which includes the moisture storage term, to calculate the warm season variability of the precipitation recycling over central Europe at a daily scale for 2003 (dry) and 2006 (wet).

For the central part of Europe advection is the most important contributor to precipitation. In dry spells in both years 2003 and 2006, when moisture of advective origin diminishes, the local evaporation becomes an important contributor to precipitation (negative feedback). In two periods (June 2003 and July 2006) where there is enough moisture storage in the soil to continue the evaporation the recycling is enhanced. In August 2003 the evaporation is affecting the recycling due the lack of water availability caused by the dryness of the preceding spring and summer season. According to a multi variance analyses the evaporation in 2003 is the most important factor to explain the variance in the recycling ratio. In 2006, the precipitable water and the moisture fluxes are more dominant and the evaporation becomes less important, except for the dry period in July.

Not only evaporation is important for recycling, but also a mechanism to trigger precipitation. In case studies we follow the path of an air column of days with one of the highest recycling. At the 2 days with enough moisture availability (28 May 2003 and 5 July 2006) we see long path length due to weak winds. Following the paths, the air is transported over land for a very long distance before it precipitates and has a lot of time to traverse the region and capture moisture of evaporative origin. However, we hypothesize that the precipitation falling at those days originates (partly) from oceanic sources, but the triggering of precipitation may itself be a result of enhanced instability induced by soils, which still have enough moisture storage. In this way, the evaporation is an important driver in the recycling ratio variability. For the case study of 10 August

2003, the atmosphere is too dry to generate precipitation with exception of the mountainous regions due orographical lifting. However, the impact of land-use change in future climate will have the most impact on the evaporation in dry spells dominated by persistent blocking systems.

1 Introduction

Land-atmosphere interactions play an important role in our climate system. Recently there has been an increasing interest in how future climate and/or land-use change may effect the evaporation and moreover land-atmosphere interactions (see the review paper by Seneviratne et al., 2009). It is important to identify and understand the underlying mechanisms which involve the land-surface and the overlying atmosphere. One of these mechanisms is the feedback process from local evaporation to local precipitation, called "recycling".

Numerous land-atmosphere interactions and recycling studies have been performed. Over the central US plains the dominant mechanism is a negative feedback that enhanced recycling during periods of lower precipitation, divergent moisture flux and reduced precipitable water (Zangvil et al., 2001; Ruiz-Barradas and Nigam, 2006; Dominguez and Kumar, 2008). Drier atmospheric conditions lead to higher sensible heat flux and boundary layer height that may promote precipitation (Findell and Eltahir, 2003; Ek and Holtslag, 2004).

A positive feedback mechanism is found in a large region extending from northwestern Mexico to the southwestern United States (Small, 2001; Dominguez et al., 2008). Bosilovich et al. (2003) concludes in their study with water vapour tracers that the wettest monsoons have the largest continental sources, while drier monsoons have less local sources of precipitation. Positive rainfall anomalies potentially enhance evapotranspiration and subsequent precipitation by decreasing boundary layer height, increasing moist static energy, and increasing instability (Betts et al., 1996; Eltahir, 1998). Schär et al. (1999) conducted several experiments to study the summertime

HESSD

6, 3301–3333, 2009

B. Bisselink and A. J. Dolman

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀◀ | ▶▶
◀ | ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

soil moisture-precipitation feedback mechanism over Europe. They found that the soil-precipitation feedback must rely on some indirect mechanism such as increased moist static stability, which allows wet soils to increase the potential for convective activity.

During extreme dry or wet periods the hydroclimatology of a large region can be abruptly changed. Several studies discussed the moisture sources over the United States during the 1988 drought and 1993 flood (Trenberth and Guillemot, 1996; Dirmeyer and Brubaker, 1999; Bosilovich and Schubert, 2001; Brubaker et al., 2001; Dominguez et al., 2006). They found that recycling was enhanced during the 1988 drought and considerable suppressed during the 1993 flood. In these dry and wet periods, land surface memory can provide some predictive potential. Findell and Eltahir (1997) have shown that knowledge of late spring/early summer soil moisture conditions can aid in the prediction of drought or flood years.

Most precipitation recycling studies that have been performed to define the role of land surface-atmosphere interactions focus on monthly or longer time scale. Long time scales however, mask key relationships between recycling and other variables involving the feedback process that occur at shorter time scales. Zangvil et al. (2004) introduced a model that can be used at a daily timescale. The drawback of this model is that it can only be used for days that have similar large-scale moisture characteristics, but their results show a clear need to analyze the recycling at shorter time scales.

In this study we apply a newly developed dynamical precipitation recycling model (Dominguez et al., 2006) to have a useful tool for relating precipitation recycling to daily meteorological processes. Bisselink and Dolman (2008) conclude that recycling only becomes important during periods of reduced total precipitation in central Europe. To study in more detail the differences between wet and dry years in moisture recycling, we selected the years, 2003 (dry and warm year with a dry pre-season) and 2006 (dry and warm in July with a wet pre-season) to assess the potential impacts on the evaporation and the recycling ratio. The difference in moisture availability in the pre-season can have impacts in the summer months because of the land surface moisture memory. In Europe, the risk of extreme heat waves like the one of summer 2003 is likely to increase in the future (Beniston, 2004; Meehl and Tebaldi, 2004; Schär et al., 2004; Stott et al., 2004; Vautard et al., 2007). It is therefore also important to investigate the contribution of the recycling in the feedback process in dry periods.

The paper is organized as follows. Section 2 presents the data used in this study. In Sect. 3 we give an overview of the climate in 2003 and 2006. Section 4 gives a description of the dynamical precipitation recycling model. The results and interpretations of the land-atmosphere interactions are presented in Sect. 5. Finally, the conclusions are presented in Sect. 6.

2 Data

The study area captures only land over the European continent (Fig. 1). We are interested in the recycling over land, which is the contribution of evaporation in an area to the precipitation in the same area. Evaporation from the ocean does not depend on the surface moisture budget, as the surface is always wet (Trenberth, 1999).

In our analysis of the warm season (1 April–30 September) for the years 2003 and 2006 we use daily variables from the Regional Atmospheric Climate Model (RACMO) at 50 km×50 km resolution (Lenderink et al., 2003). It's domain roughly stretches from 40° W to 50° E and from 30° N to 70° N. The area of interest (Fig. 1) is located in the center of the domain. ECMWF analyses are used to force the model from the lateral boundaries.

The precipitation and evaporation data are completely determined by model physics. Our results could be greatly influenced by the assumptions used in the model to calculate variables. In Sect. 6 we will discuss the change in recycling by the use of a different dataset. However, we believe that consistent data from the RACMO model is the best available for the analysis presented in this work. Van den Hurk et al. (2005) showed in a comparison between the modelled and observed average annual cycle of precipitation over the Rhine basin, that the average RACMO precipitation fall within the interannual variability of the observations. More details on the RACMO model can be found in Lenderink et al. (2003).

HESSD

6, 3301–3333, 2009

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀◀ | ▶▶
◀ | ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

3 Climate of 2003 and 2006

Figure 2a displays the average precipitation for 2003 and 2006. With the exception of January, April and October, the precipitation in 2003 is lower-than-average. In general, the months preceding the summer are very dry, but still in the range of the extreme values. However, drier than normal conditions start in February and after the very dry May and June, the rainfall deficit increases towards to 69 mm and persists until the end of the year with the exception of October. In contrast, most months in 2006 have a higher-than-average precipitation. Only January and June are significant drier than average. Before the start of the dry July month, the precipitation surplus exceeds of 32 mm. All precipitation values are within the range of the extreme values.

In 2003, the temperature (Fig. 2b) was exceptionally high from May right through to the end of August. In June and August, maximum temperature records were broken in many parts of Europe (Black et al., 2004). In July 2003, in contrast to June and August, temperatures were above normal, but not record-breaking (Schär et al., 2004; Rebetez et al., 2006). In the dry months, from May until August, the temperatures are much higher-than-average with the exception of the temperatures in July. The extreme temperatures and lack of precipitation in Europe from May to August 2003 were related to persistent anticyclonic conditions throughout the period (Black et al., 2004). Several studies show the critical role of the spring precipitation deficit to the summer temperatures (Della-Marta et al., 2007; Fischer et al., 2007; Vautard et al., 2007). In August 2003, the lack of precipitation and the associated depletion of soil moisture results in more sensible heat, inhibiting cloudiness and further increasing daytime temperature (Black et al., 2004).

In contrast, in 2006, most of the months are colder than average. In June and July the temperatures are higher-than-average. At the end of June a persistent anticyclonic situation favours the advection of dry and warm air (Rebetez et al., 2008). The temperature of August is lower than the lowest extreme value. Moreover, August is colder than any other month in 1981–2000.

Bisselink and Dolman (2008) conclude that recycling only becomes important during periods of reduced total precipitation in central Europe at a monthly time scale. For this reason, we selected the years 2003 and 2006 with at least one dry period, but with a different pre-season. We expect the difference in moisture availability in the pre-season to have important consequences for the evaporation and moreover the recycling in the rest of the season.

4 Precipitation recycling

The recycling ratio is calculated with the dynamical precipitation recycling model of Dominguez et al. (2006). The dynamical precipitation recycling model is derived from the vertically integrated water vapour balance equation:

$$\frac{\partial w}{\partial t} + \nabla \cdot \left[Q_\lambda, Q_\varphi\right] = E - P \quad (1)$$

where the precipitation (P) and the evaporation (E) are averaged directly from the RACMO data and the variables w, Q_λ and Q_ϕ are estimated from the data (see Table 1 for the precise mathematical definitions). The dynamical precipitation recycling model makes the assumption that the atmosphere is well-mixed. This means that the ratio of advected to evaporated water vapour in the atmospheric column is equal to the ratio of advected precipitation to recycled precipitation ($P_{\text{adv}}/P_r = w_{\text{adv}}/w_r$). Above most land regions the assumption of a well-mixed atmosphere is justified (Eltahir and Bras, 1996). However, according to Bosilovich (2003) the percent contribution of local water is greater in the lower troposphere and less in the middle and upper troposphere. Burde (2006) modifies the condition of a well-mixed atmosphere when the mixing of the atmosphere is incomplete with an empirical parameter. In a subsequent study Burde et al. (2006) applies that method to the Amazon basin, where part of the evaporation may be returned to the regional air/soil interface by "fast recycling". This refers to local showers yielding rain before all cloud water is mixed with the total precipitable water in the average tropospheric column above the region. The regional recycling ratio values for the Amazon basin estimated by the modified model are significantly higher than the values provided by the unmodified model, because of the fast recycling. Over the central United States the effects of incomplete vertical mixing do not produce significant effects in recycling. We believe that our results are not significantly affected by the assumption of a well-mixed atmosphere in Europe, because the "fast recycling" in central Europe is unlikely to be as effective as in the Amazon.

The local recycling ratio ρ is defined as the ratio of precipitation in a grid cell that originates from evaporation within a region to the total precipitation in that cell $\rho=P_r/P$ or w_r/w with the well mixed atmosphere assumption. After substituting the definition of the local recycling ratio, Eq. (1) will transform in a partial differential equation. With a lagrangian coordinate system ($\chi=x-ut$, $\xi=y-vt$, $\tau=t$), the evaporation as $\varepsilon(\chi,\xi,\tau)$ and the precipitable water as $\omega(\chi,\xi,\tau)$, the expression of the local recycling ratio $R(\chi,\xi,\tau)$ can now be calculated with of Eq. (1). This coordinate system enables us to follow these paths of the advected moisture flow backward in time, starting at the dots in Fig. 1, with the moisture-weighted wind velocities (Q_λ/w and Q_ϕ/w). Time-averaged fields are used as input for the calculation of the recycling ratios. We calculate the ratio from evaporative origin to total moisture within the column throughout the trajectory at every 6-h time step of the RACMO data, and integrate it from the time the column enters the region until the water precipitates:

$$R(\chi,\xi,\tau) = 1 - \exp\left[-\int_0^\tau \frac{\varepsilon(\chi,\xi,\tau)}{\omega(\chi,\xi,\tau)}\partial\tau'\right] \quad (2)$$

The value of R can be transformed back again onto the original coordinate system and the value of the local recycling ratio ρ be determined for every grid cell. Be aware, that the ρ is scale dependent with a logarithmic relationship between the recycling ration and spatial scale (Dominguez et al., 2006 and Bisselink and Dolman, 2008). To obtain the regional recycling ratio rr, which is the fraction of recycled to total precipitation within a region, we sum the local recycling ratios in all grid cells weighted by the amount of precipitation falling in each gridcell within the region (Eltahir and Bras, 1994). The advantage of the dynamical precipitation recycling model is that it explicitly incorporates the moisture storage $(\partial w/\partial t)$ term. We now have a tool to perform temporal and spatial analyses of the process of precipitation recycling on a daily timescale. A more detailed description of the dynamical precipitation recycling model can be found in Dominguez et al. (2006).

5 Results – Precipitation recycling in 2003 and 2006

5.1 Daily recycling ratios

Figure 3 presents the 11-day running mean of the daily regional recycling ratio (*rr*), recycled precipitation (*Pr*) and the evaporation (*E*) for 2003 (Fig. 3a) and 2006 (Fig. 3b). The recycling ratio is generally around 0.15 in 2003 (Fig. 3a) with periods of high recycling at the end of May/beginning of June and in the first half of August. By multiplying the recycling ratio with the precipitation we have an estimate of the recycled precipitation (*Pr*). The recycled precipitation peaks in the second half of May with values of 0.4 mm/day and in July with values of 0.35 mm/day. There is a negative correlation coefficient of −0.16 between the daily regional recycling ratio and the daily total precipitation (passes 95% significance). After the first rains recede in May, the evaporation reaches it's highest value after a rapid increase in April and May. At this point the recycling ratio also peaks. This is the beginning of a warm and very dry month resulting in a lack of soil moisture and a further decrease of the evaporation. In July, after the rain from the beginning of the month, enough moisture is available to keep the evaporation at a stable level but the water availability becomes a limited factor now. After the rains recede in July, the recycling ratio increase and reaches the second peak in the first half of August. The evaporation is negatively affecting the recycling in this period due the lack of water availability caused by the dryness of the preceding spring and summer season. The beginning of August is a very warm and dry period. From mid-August until the end of September, we see a rapid decrease of the evaporation and the recycling. Throughout the warm season the evaporation is synchronous with the recycling ratio.

In 2006 (Fig. 3b), the recycling ratio has an average value of 0.15 with a peak of 0.24 in the beginning of May and a peak of 0.30 at mid-July. The recycled precipitation has several peaks during the season with peaks between 0.4 and 0.6 mm/day. The daily regional recycling ratio and the daily total precipitation have a negative correlation coefficient of −0.06 (not significant). After the rains in May, the evaporation start to increase and reaches it's maximum at the end of June. The evaporation remains more or less at the same level because there is enough moisture to evaporate. After the rains recede, the recycling ratio reaches it's maximum. This period is a warm and dry period. At the end of July a different regime starts to dominate the continent with a cold and wet weather pattern. From this moment the recycling remains low until the end of September.

In both, 2003 and 2006, we see a peak in recycling in the dry periods. This is in good agreement with the findings of Bisselink and Dolman (2008) in their recycling calculations at a monthly scale. However, the interannual variability of the recycling is different between the years. The recycling and evaporation peak in 2006 is later in the season than in 2003. In 2003 the evaporation and the recycling peaks earlier in the season due to the dry pre-season. The second peak in recycling is lower than when the evaporation was not limited.

Figure 4 shows the 11-day running mean of the precipitable water (w) and the zonal and meridional moisture fluxes, Q_ϕ and Q_λ respectively for 2003 (Fig. 4a) and 2006 (Fig. 4b) to investigate how these variables are related to the recycling ratio. In general, the zonal moisture flux is positive and the meridional moisture flux is negative in 2003 (Fig. 4a), which means moisture transport from the west and north respectively. We see the peaks in the recycling ratio when the zonal and meridional moisture flux decrease to zero (Fig. 3a). The peaks in the recycling ratio follow the decrease in the moisture fluxes. The precipitable water is generally around 20 mm in 2003 with a peak of 29 mm at the end of July before the warm period in August. There is a negative correlation coefficient of −0.25 between the daily regional recycling ratio and the daily precipitable water (passes 95% significance).

In 2006 (Fig. 4b) the zonal moisture flux has high peaks, which give an explanation for the rainfall in May and in August. Again the recycling ratio (Fig. 3b) follows the decrease in moisture flux. The precipitable water is generally around 21 mm with a peak of 29 mm at the end of June when we see a peak in precipitation of recycled origin and a maximum in evaporation. There is a negative correlation coefficient of −0.31 between the daily regional recycling ratio and the daily precipitable water (passes 95% significance). In both 2003 and 2006, recycling becomes important when the moisture from advective origin is small. When the moisture fluxes are small, the air will have a longer residence time in the study area to capture moisture from evaporative origin.

The recycling is calculated with the dynamical precipitation recycling model and is dependent on evaporation, precipitable water, moisture fluxes and precipitation. With a simple analysis of variance, ANOVA F-test, we decompose the total variation present in the recycling ratio in terms of variation due to evaporation, precipitable water and the zonal and meridional moisture fluxes that can cause this variation. The F-test's null hypothesis assumes no significant impact of changed evaporation, precipitable water, moisture fluxes and precipitation on the recycling ratio. To reject the null hypothesis at the 99% confidence level, the F-value must exceed 6.63. For 2003, the ANOVA support the conclusion that there is sufficient evidence that the recycling ratio is ruled by evaporation (F=19.10), precipitable water (F=14.84) and the zonal moisture flux (F=12.45). For 2006, the precipitable water (F=34.99), the zonal moisture flux (F=25.05) and the evaporation (F=17.67) provide a causal factor in explaining the recycling ratio. In 2003 the evaporation is the most important factor to explain the variance in the recycling ratio. In 2006, a wetter year, the precipitable water is the most important factor. Thus, we find that in dry years the evaporation becomes more important. Years of high precipitation will generally have higher evaporation and precipitation and recycling are generally negative correlated. It is expected that the F-test for evaporation will not be significant in extreme wet years (wetter than 2006).

5.2 Spatial variability

In order to gain an understanding of the spatial distribution of the variables that modulate the recycling, we again focus our attention on the year 2003 and 2006. Figure 5 and Fig. 6 show the average of the daily local recycling ratio (ρ), evaporation (E) and precipitation (P) for the years 2003 and 2006, respectively. In general, we expect that the eastern part of the study area has the highest recycling ratio. In central Europe the westerly circulation is dominant and the eastern part of the study area corresponds to the longest paths of moisture.

At the end of May and in the beginning of June (Fig. 5) a high pressure cell starts to dominate the synoptic situation of the study area. The moisture flux is almost stagnant with little advection. The air in the study area will have a longer residence time and have more time to capture moisture of evaporative origin. Consequently, we see a peak in the recycling ratio. The evaporation is high in the entire region, while the precipitation is very low. From this point on, the evaporation decreases throughout the rest of the season with the exception of the beginning of August. A second peak in the recycling ratio in the first part of August is preceded by rainfall in July in the west part of the study area. During periods of high recycling and evaporation, the total precipitation is very low due the presence of a high pressure cell. Consequently, the recycled precipitation will be low in periods of low total precipitation. However, the evaporation is a major contributor to precipitation in periods of high recycling.

The season of 2006 starts with high recycling ratio at the end of April and beginning of May. At the end of April it is clearly seen that the recycling ratio and precipitation are negative correlated. In this period a Siberian anticyclone is widespread over almost the entire continent. The pressure gradient over the continent is very low with low moisture advection and high recycling ratios. The high evaporation rates in the second half of June are followed by high recycling ratios in July. From the end of July a different regime starts to dominate with considerable moisture advection from the ocean which remains until the end of the season and suppress the recycling ratio.

HESSD
6, 3301–3333, 2009

B. Bisselink and A. J. Dolman

5.3 Case studies

So far we discussed the dynamics of the recycling using spatially averaged data and the spatial distribution of the variables. In the next figures we present an analysis for 3 selected days show one of the highest recycling ratios. We will discuss the role of moisture recycling as an important processes in land-atmosphere interactions.

In the situation of 28 May 2003, the areas of highest recycling are confined to the west of a line from southwest to northeast (Fig. 7a). The areas of intense evaporation however, are in the areas where the recycling is low (Fig. 7b). Precipitation falls in a line from southwest to northeast where colder and warmer air converge (Fig. 7c). Selected paths for the region of highest recycling ratios are plotted in Fig. 7d. The paths are defined by the u and v velocities (the zonal and meridional moisture flux divided by the total precipitable water). Throughout the trajectory we calculate the ratio of moisture from evaporative origin to total moisture within the column, and integrate it from the time the column enters the region until the water precipitates. The spatial variability of evaporation translates into different ε/ϖ ratios throughout the paths. In general, evaporation becomes important in the recycling process when moisture of advective origin diminishes. The air has more time to traverse the region and capture moisture of evaporative origin. Following the paths in the precipitation zone, we see that trajectory enter the region from the east and one from the south. The air mass coming from the east has a dry origin but picks up moisture throughout its trajectory before it precipitates. The origin of the air mass coming from the south, belonging to a low pressure system east of Spain, contains already moisture. However, the air is first transported north and later to the south and is able to pick up moisture before its precipitates. In this precipitation event evaporation significantly contributes to the moisture content. However, it is questionable if the precipitation event had occurred when the moisture source was not from oceanic origin.

At 5 July 2006, the areas of the highest recycling ratio are located in central Europe where an anticyclone with less pressure gradient dominates the synoptic situation

HESSD

6, 3301–3333, 2009

(Fig. 8a). In the southwest part of the region the winds are already increasing which decrease the recycling ratio. The evaporation is intense in the east part of the study area (Fig. 8b) and precipitation is falling in the area of high recycling (Fig. 8c). In Fig. 8d two paths of the region of highest precipitation are plotted. Following the trajectory, we see that winds enter the region from the west, origin from the ocean, and east. However, in both paths the air is transported over land for a very long distance before it precipitates. The air has considerable time to traverse the region and capture moisture of evaporative origin and then contribute significantly to the precipitation.

In the situations of 28 May 2003 and 5 July 2006 enough moisture storage is available and a mechanism to trigger precipitation. The precipitation falling at those days originates (partly) from oceanic sources, but the triggering of precipitation may itself be a result of enhanced instability induced by soils, which still have enough moisture storage. In this way, the evaporation is an important driver in the recycling ratio variability and the generation of rainfall in dry periods. Both days in the case study are in warm periods where the sensible heat flux is getting more dominant. Some studies hypothesize that enhanced sensible heat can lead to higher boundary layer to promote precipitation (Findell and Eltahir, 2003; Ek and Holtslag, 2004). Ek and Holtslag (2004) showed that this is only valid in situations with weak atmospheric instability above the boundary layer.

In August 2003, evaporation is limited because of the preceded warm period. The synoptic situation of 10 August 2003 (Fig. 9) is dominated by an anticyclone above Scandinavia associated with clockwise air movement. Logically, the highest recycling ratios are southwest of the study area (Fig. 9a) while the areas of intense evaporation are more north (Fig. 9b). In the rest of the region the evaporation is very low. The precipitation rate is very low, except for the mountainous region due orographic lifting (Fig. 9c). The strong high pressure system is typically accompanied by subsidence, clear skies, warm-air advection from the east and prolonged hot conditions at the surface. We hypothesize that the air is too dry to generate precipitation with exception of mountainous areas. The air at 10 August (Fig. 9d) enters the region from the north

HESSD
6, 3301–3333, 2009

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◄ | ►
◄ | ►
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

and is then transported to the west, because of the anticyclonic wind. The evaporation in the region is low and doesn't significantly contribute to the moisture content with exception of mountainous regions.

6 Concluding remarks

In this work, we applied a dynamical recycling model that does incorporate time dependent moisture storage, and therefore the model can be used to study recycling ratios at a daily time scale. One of the limitations of the model is that we use the assumption of a well-mixed atmosphere. Moreover, the model remains scale dependent and therefore results must be interpreted with some caution.

Our study uses daily variables from RACMO with the domain roughly stretches from 40° W to 50° E and from 30° N to 70° N. The analysis is focused on the warm season (1 April–30 September) for the years 2003 and 2006. Bisselink and Dolman (2008) conclude that recycling only becomes important during periods of reduced total precipitation in central Europe at a monthly time scale. However they were unable to look into the differences between very wet and dry years in detail. In this study we selected the years 2003 and 2006 for further analysis. The warm season of 2003 is characterized with a dry pre-season and two heat wave periods, in June and August. The summer of 2006 also has a heat wave period, but the season started with higher-than-average precipitation. We are interested in the potential impacts on the evaporation and the recycling ratio in both 2003 and 2006. The difference in moisture availability in the pre-season can have impacts in the summer months because of the potential of the land surface moisture memory to impact precipitation.

The results presented in this study are dependent upon the quality of the data. The precipitation and evaporation data are completely determined by model physics, and therefore rely on the assumption made in the model. Precipitation and evaporation are the most critical variables. In order to evaluate the recycling ratios obtained with RACMO, we tested our results by estimating the recycling ratios and the variables using

HESSD

6, 3301–3333, 2009

Recycling of moisture in Europe

B. Bisselink and A. J. Dolman

the ECMWF operational data set. The recycling ratios using the ECMWF dataset are very similar to those obtained with the RACMO model for 2003. For 2006 the recycling ratios using ECMWF data are slightly higher than the RACMO estimated due to higher precipitation and evaporation rates. We believe that the results presented here are not affected by this difference, because the recycling is enhanced in dry periods.

The analysis reveals that, over central Europe, the recycling ratios are negative correlated to precipitation, precipitable water and the moisture fluxes for both years 2003 and 2006. However, the negative correlation to precipitation in 2006 is not significant. We hypothesize that for the central part of Europe local evaporation becomes an important contributor to precipitation when moisture of advective origin, the largest contributor to precipitation, diminishes. According the ANOVA F-test the evaporation in 2003 is the most important factor to explain the variance in the recycling ratio. In 2006, a wetter year, the precipitable water and the moisture fluxes are more dominant and the evaporation becomes less important, except for the dry period in July. Notice that, the amount of recycled precipitation that falls during periods of low recycling ratios (when precipitation is high) is higher than during periods of high recycling. In other words, in a wetter year (2006) the recycled precipitation will be higher than in a dry year (2003). However, when the moisture fluxes diminish (in dry periods) the most important mechanism is a negative feedback where evaporation continues to feed moisture into the overlying atmosphere and contribute to rainfall.

As precipitation decreases, evaporation will continue if there is enough moisture storage in the soil. Not only evaporation is important for recycling, but also a mechanism to trigger precipitation. In May/June 2003 and July 2006, when moisture of advective origin is diminished and the recycling is high, enough moisture storage is available and the evaporation peaks in these months. In the case study of 28 May 2003 and 5 July 2006 recycling promotes precipitation. In both days the winds are weak in this period due the presence of an anticyclone and the sensible heat flux is an important source of energy to the atmospheric boundary layer. Following the paths, the air is transported over land for a very long distance before it precipitates and has enough time to traverse

HESSD
6, 3301–3333, 2009

B. Bisselink and A. J. Dolman

the region and capture moisture of evaporative origin. However, we hypothesize that the precipitation falling at those days originates (partly) from oceanic sources, but the triggering of precipitation may itself be a result of enhanced instability induced by soils, which still have enough moisture storage. In this way, the evaporation is an important driver in the recycling ratio variability.

For the case study of 10 August 2003, the domain was under a strong high pressure system, which is typically accompanied by subsidence, clear skies, warm-air advection from the east and prolonged hot conditions at the surface. The evaporation is affecting the recycling in this period due the lack of water availability caused by the dryness of the preceding spring and summer season. We hypothesize that the air is too dry to generate precipitation in these cases with exception of the mountainous regions due orographical lifting.

Summarizing, our analysis reveals that, over central Europe, precipitation originates largely from oceanic sources and that the contribution of evaporation is limited. However, as the moisture fluxes diminish the air has more time to traverse the region and capture moisture from evaporative origin. Bisselink and Dolman (2008) concluded that evaporation is a limiting factor for the occurrence of precipitation of recycled origin. Here, at a daily time scale, we hypothesize that in dry spells (also in wet years) the recycling plays a significant role in triggering of precipitation, even if the total amount of precipitation is small. An important factor is that the soil moisture storage is not limited. In extreme dry years, like 2003, the lack of moisture availability will be more an issue than in a dry spell of wet years (2006). In Europe, the risk of extreme heat waves like the one of summer 2003 is likely to increase in the future (Beniston, 2004; Meehl and Tebaldi, 2004; Schär et al., 2004; Stott et al., 2004; Vautard et al., 2007). For this reason, it is important to know the impact of land-use change will have the most impact on the evaporation in these dry spells dominated by persistent blocking systems.

Acknowledgements. This work was carried out within the framework of the ACER project under the Dutch National Research Program "Climate Changes Spatial Planning." The RACMO data was generously provided by E. van Meijgaard and B. van den Hurk.

References

Beniston, M.: The 2003 heat wave in Europe. A shape of things to come?, Geophys. Res. Lett., 31, L02202, doi:10.1029/2003GL018857, 2004.

Betts, A. K., Ball, J. H., Beljaars, A. C. M., Miller, M. J., and Viterbo, P. A.: The land surface-atmosphere interaction: A review based on observational and global modeling perspectives, J. Geophys. Res., 101, 7209–7225, 1996.

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

Black, E., Blackburn, M., Harrison, G., Hoskins, B., and Methven, J.: Factors contributing to the summer 2003 European heatwave, Weather, 59, 217–223, 2004.

Bosilovich, M. G.: On the vertical distribution of local and remote sources of water for precipitation, Meteorol. Atmos. Phys., 80, 31–41, 2003.

Bosilovich, M. G. and Schubert, S. D.: Precipitation recycling over the central United States diagnosed from the GEOS-1 data assimilation system, J. Hydrometeorol., 2, 26–35, 2001.

Bosilovich, M. G., Sud, Y. C., Schubert, S. D., and Walker, G. K.: Numerical simulation of the large-scale North American monsoon water sources, J. Geophys. Res., 108 (D16), 8614, doi:10.10292002JD003095, 2003.

Brubaker, K. L., Dirmeyer, P. A., Sudradjat, A., Levy, B. S., and Bernal, F.: A 36-yr climatological description of the evaporative sources of warm-season precipitation in the Mississippi River basin, J. Hydrometeorol., 2, 537–557, 2001.

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

Burde, G. I.: Bulk recycling models with incomplete vertical mixing. Part I: Review of recycling models, J. Climate, 19, 1461–1472, 2006.

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

HESSD

6, 3301–3333, 2009

Della-Marta, P. M., Haylock, M. R., Luterbacher, J., and Wanner, H.: Doubled length of western European summer heat waves since 1880, J. Geophys. Res., 112, D15103, doi:10.1029/2007JD008510, 2007.
Della-Marta, P. M., Luterbacher, J., vonWeissenfluh, H., Xoplaki, E., Brunet, M., and Wanner, H.: Summer heat waves over western Europe 1880-2003, their relationship to large-scale forcings and predictability, Clim. Dynam., 29, 251–275, 2007.
Dirmeyer, P. A. and Brubaker, K. L.: Contrasting evaporative moisture sources during the drought of 1988 and the flood of 1993, J. Geophys. Res., 104(D16), 19383–19397, 1999.
Dominguez, F. and Kumar, P.: Precipitation recycling variability and ecoclimatological stability – A study using NARR data. Part I: Central U.S. plains ecoregion, J. Climate, 5165–5186, 2008.
Dominguez, F., Kumar, P., Liang, X., and Ting, M.: Impact of atmospheric moisture storage on precipitation recycling, J. 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, J. Climate, 5187–5203, 2008.
Ek, M. and Holtslag, A. M. M.: Influence of soil moisture on boundary layer cloud development, J. Hydrometeorol., 5, 86–99, 2004.
Eltahir, E. A. B.: A Soil Moisture-Rainfall Feedback Mechanism, 1. Theory and Observations, Water Resour. Res., 34, 765–776, 1998.
Eltahir, E. A. B. and Bras, R. L.: Precipitation recycling in the Amazon basin, Q. J. Roy. Meteor. Soc., 120, 861–880, 1994.
Eltahir, E. A. B. and Bras, R. L.: Precipitation recycling, Rev. Geophys., 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 Resour. Res., 33, 725–735, 1997.
Findell, K. L. and Eltahir, E. A. B.: Atmospheric controls on soil moisture-boundary layer interactions. Part I: Framework development, J. Hydrometeorol., 4, 552–569, 2003.
Fischer, E. M., Seneviratne, S. I., Lüthi, D., and Schär, C.: Contribution of land-atmosphere coupling to recent European summer heat waves, Geophys. Res. Lett., 34, L06707, doi:10.1029/2006GL029068, 2007.
Lenderink, G., van den Hurk, B., van Meijgaard, E., van Ulden, A. P., and Cuijpers, J. H.: Simulation of present-day climate in RACMO2: first results and model developments, KNMI Technical Report 252, 24 pp., 2003.

Meehl, G. A. and Tebaldi, C.: More intense, more frequent, and longer lasting heat waves in the 21st century, Science, 305, 994–997, 2004.
Rebetez, M., Dupont, O., and Giroud, M.: An analysis of the July 2006 heatwave extent in Europe compared to the record year of 2003, Theor. Appl. Climatol., 95, 1–7, 2009.
Rebetez, M., Mayer, H., Dupont, O., Schindler, D., Gartner, K., Kropp, J., and Menzel, A.: Heat and drought 2003 in Europe: a climate synthesis, Ann. For. Sci., 63, 569–577, 2006.
Ruiz-Barradas, A. and Nigam, S.: Great Plains hydroclimate variability: The view from North American Regional Re-analysis, J. Climate, 19, 3004–3010, 2006.
Seneviratne, S. I., Corti, T., Davin, E. L., Hirschi, M., Lehner, I., and Teuling, A. J.: Investigating soil moisture-climate interactions in a changing climate: A review, submitted, Earth-Sci. Rev., 2009.
Schär C., Lüthi D., Beyerle U., and Heise, E.: The Soil–Precipitation Feedback: A Process Study with a Regional Climate Model, J. Climate, 12, 722–741, 1999.
Schär, C., Vidale, P. L., Lüthi, D., Frei, C., Häberli, C., Liniger, M., and Appenzeller, C.: The role of increasing temperature variability in European summer heat waves, Nature, 427, 332–336, 2004.
Small, E. E.: The influence of soil moisture anomalies on variability of the North American monsoon system, Geophys. Res. Lett., 28, 139–142, 2001.
Stott, P. A., Stone, D. A., and Allen, M. R.: Human contribution to the European heatwave of 2003, Nature, 432, 610–614, 2004.
Trenberth, K. E.: Atmospheric moisture recycling: Role of advection and local evaporation, J. Climate, 12, 1368–1381, 1999.
Trenberth, K. E. and Guillemot, C. J.: Physical processes involved in the 1988 drought and 1993 floods in North America, J. Climate, 9, 1288–1298, 1996.
Van den Hurk, B., Hirschi, M., Schär, C., Lenderink, G., van Meijgaard, E., van Ulden, A., Rockel, B., Hagemann, S., Graham, P., Kjellström, E., and Jones R.: Soil control on runoff response to climate change in regional climate model simulations, J. Climate, 17, 3536–3551, 2005.
Vautard, R., Yiou, P., D'Andrea, F., de Noblet, N., Viovy, N., and Cassou, C.: Summertime European heat and drought waves induced by wintertime Mediterranean rainfall deficit, Geophys. Res. Lett., 34, L07711, doi:10.1029/2006GL028001, 2007.
Zangvil, A., Portis, D. H., and Lamb, P. J.: Investigation of the large-scale atmospheric moisture field over the midwestern United States in relation to summer precipitation. Part I: Relation-

ship between moisture budget components on different time scales, J. Climate, 14, 582–597, 2001.
Zangvil, A., Portis, D. H., and Lamb, P. J.: Investigation of the large-scale atmospheric moisture field over the Midwestern United States in relation to summer precipitation. Part II: Recycling of local evapotranspiration and association with soil moisture and crop yields, J. Climate, 17, 3283–3301, 2004.

Table 1. Derived variables from the RACMO model where q, u and v are the specific humidity and zonal and meridional wind components, respectively.

Variable	Description	Equation
Q_λ	Vertically integrated average zonal moisture flux	$Q_\lambda = \int_0^{p_s} qu \frac{dp}{g}$
Q_φ	Vertically integrated average meridional moisture flux	$Q_\varphi = \int_0^{p_s} qv \frac{dp}{g}$
w	Precipitable water	$w = \int_0^{p_s} q \frac{dp}{g}$

HESSD
6, 3301–3333, 2009

Recycling of moisture in Europe

B. Bisselink and A. J. Dolman

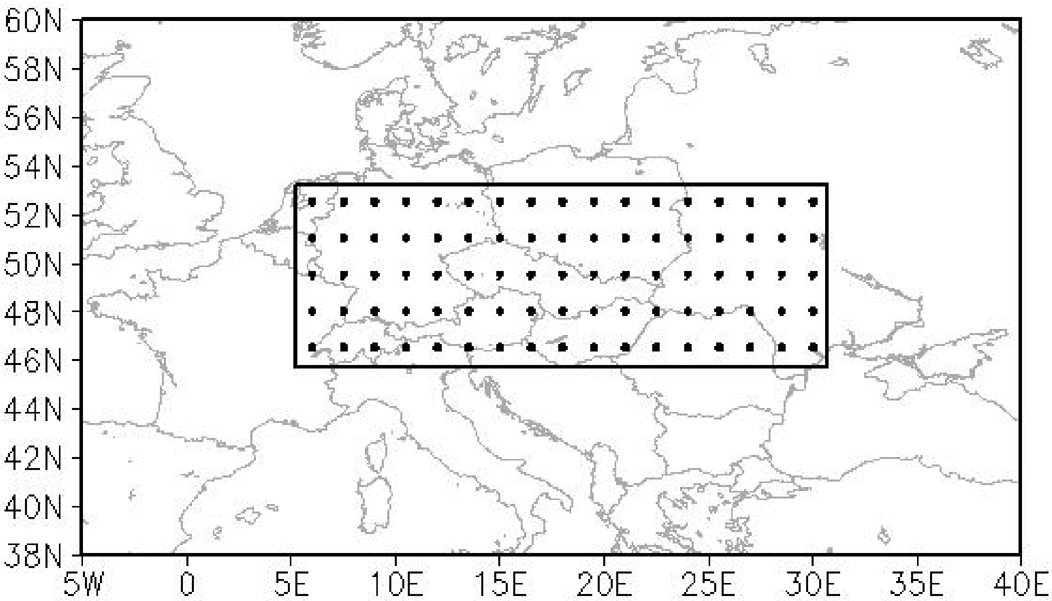

Fig. 1. Area of interest (48.75–53.25° N; 5.25–11.25° E). The dots represent the starting point of the backward trajectory calculation.

HESSD

6, 3301–3333, 2009

Recycling of moisture in Europe

B. Bisselink and A. J. Dolman

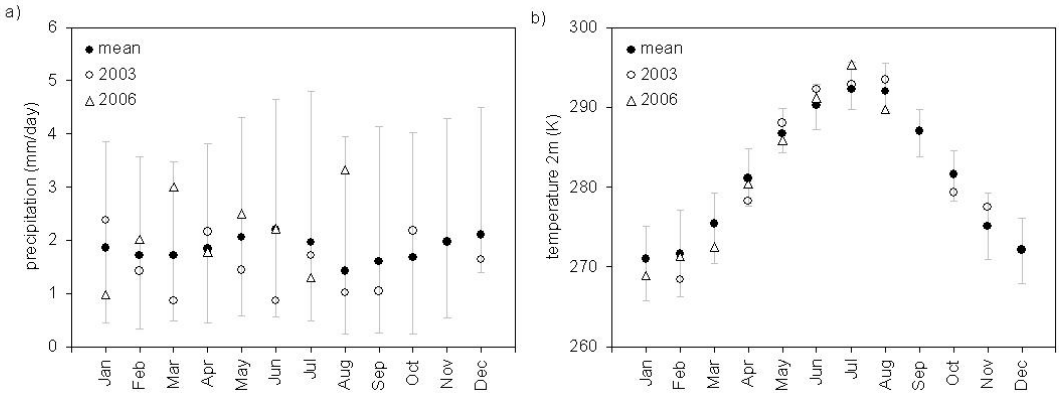

Fig. 2. (a) Precipitation (mm/day) and **(b)** 2 m temperature (K) averaged over 48.75–53.25° N; 5.25–11.25° E. The filled circles represents the RACMO average monthly values for the period 1981–2000 with corresponding extreme values; the open circles represent the monthly values for 2003 and the triangles represent the monthly values for 2006 (until August).

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

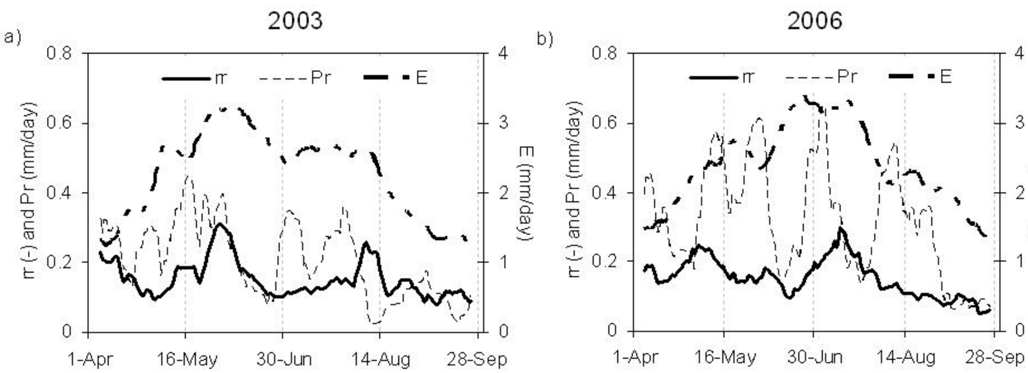

Fig. 3. Time series of the April–September RACMO 11-day running mean of the daily regional recycling ratio (*rr*), recycled precipitation (*Pr*) and the evaporation (*E*) for 2003 **(a)** and 2006 **(b)**.

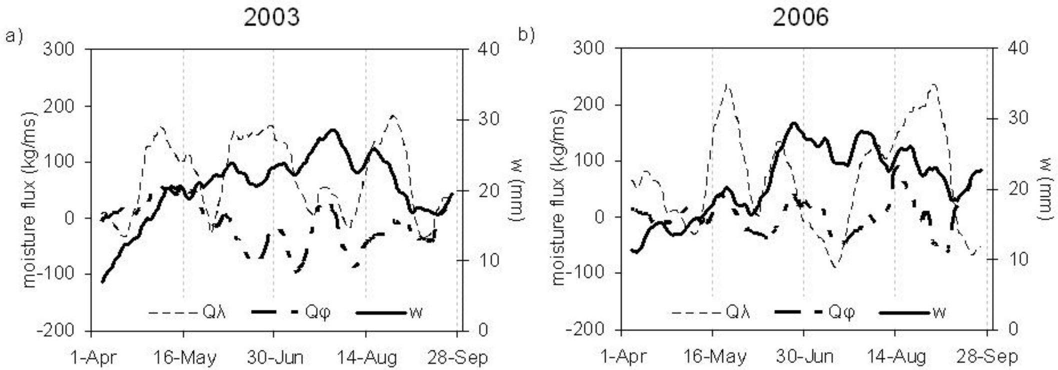

Fig. 4. Time series of the April–September RACMO 11-day running mean of the regional precipitable water (w), zonal moisture flux (Q_λ) and the meridional moisture flux (Q_ϕ) for 2003 **(a)** and 2006 **(b)**.

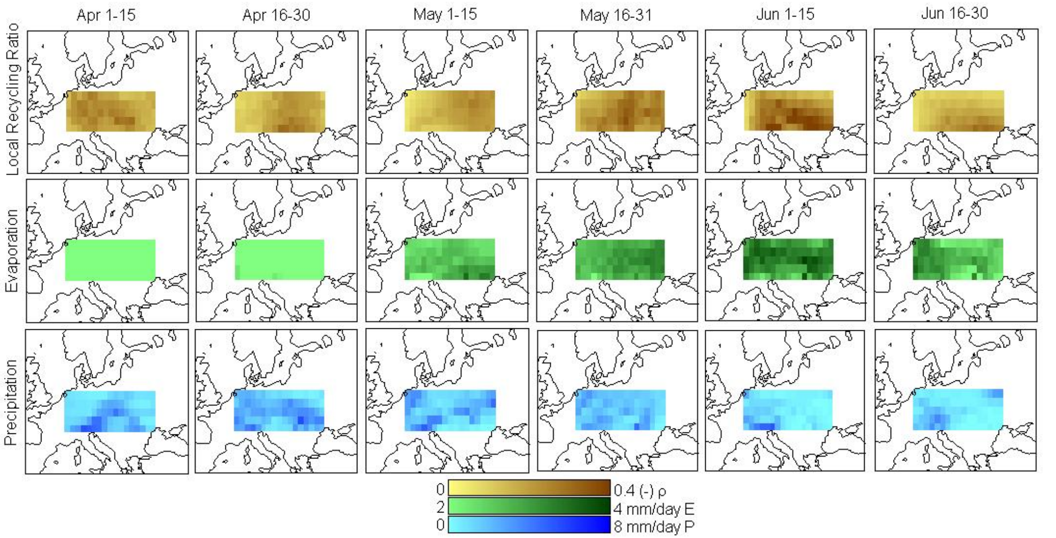

Fig. 5. Average daily local recycling ratio $\rho(-)$, evaporation E (mm/day) and precipitation P (mm/day) of 2003. The 15-day panels go from beginning of April to the end of September.

HESSD
6, 3301–3333, 2009

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◂ ▸
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

HESSD

6, 3301–3333, 2009

Recycling of moisture in Europe

B. Bisselink and A. J. Dolman

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◄◄ | ►►
◄ | ►
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

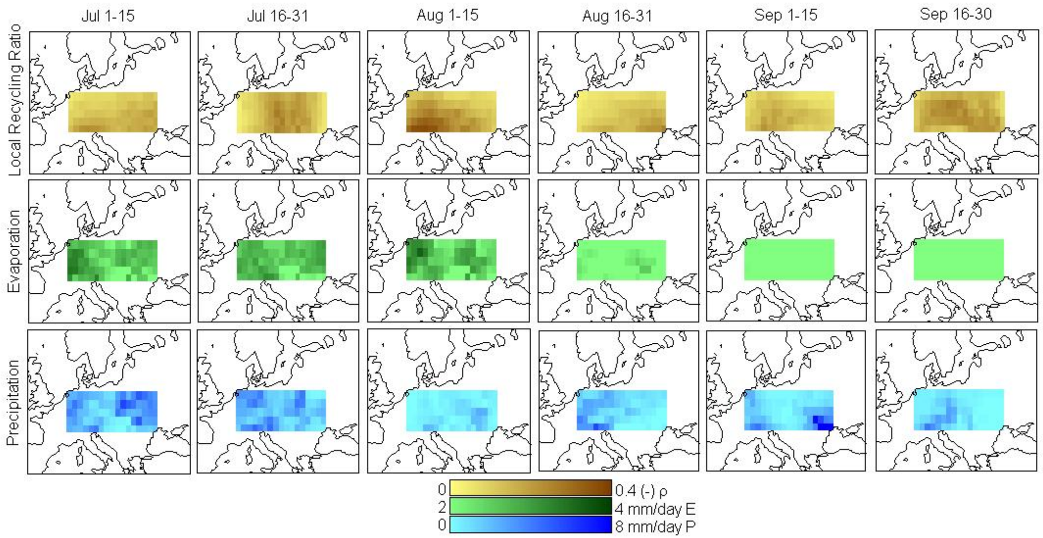

Fig. 5. Continued.

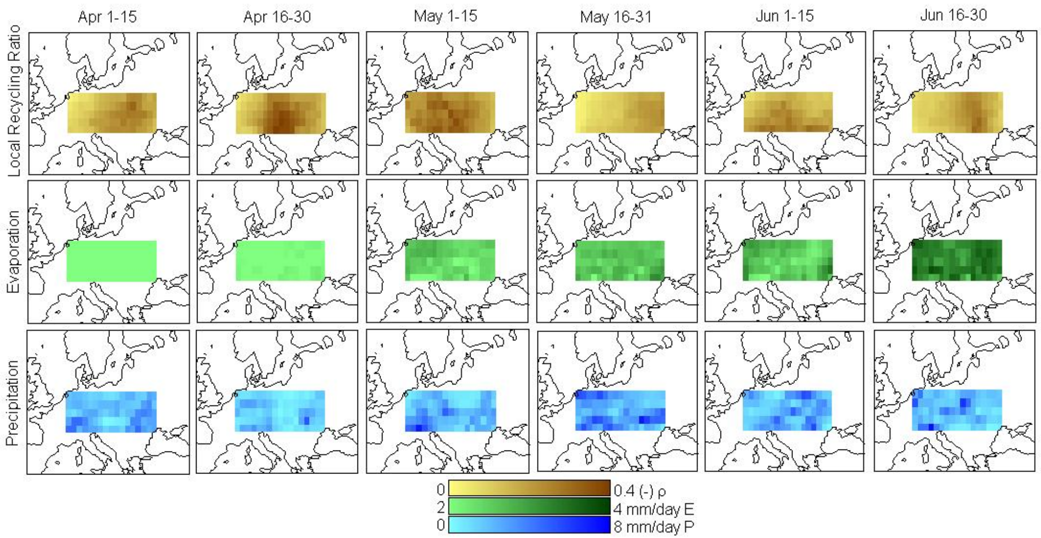

Fig. 6. Same as in Fig. 5 but for 2006.

HESSD
6, 3301–3333, 2009

Recycling of moisture in Europe

B. Bisselink and A. J. Dolman

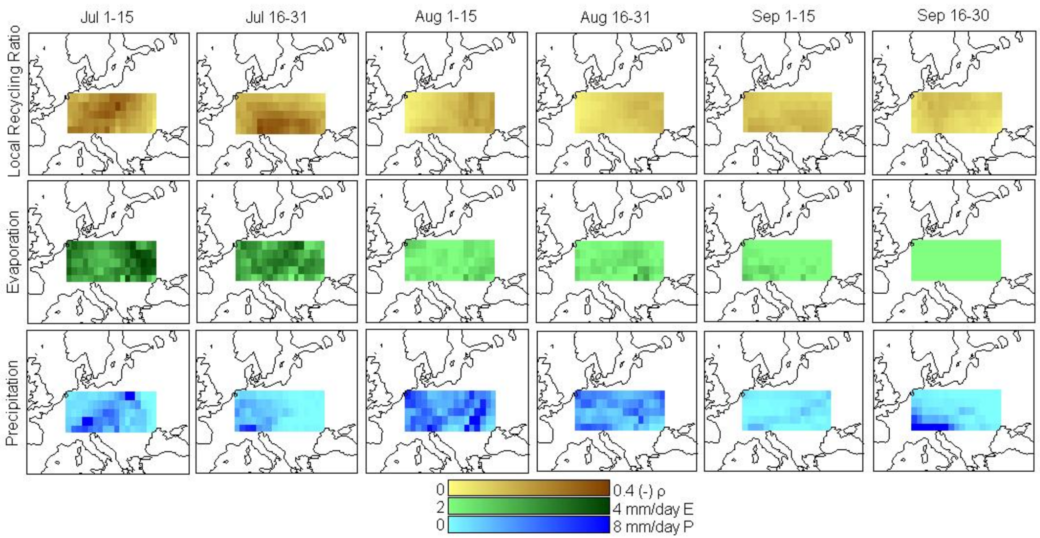

Fig. 6. Continued.

HESSD
6, 3301–3333, 2009

Recycling of moisture in Europe

B. Bisselink and A. J. Dolman

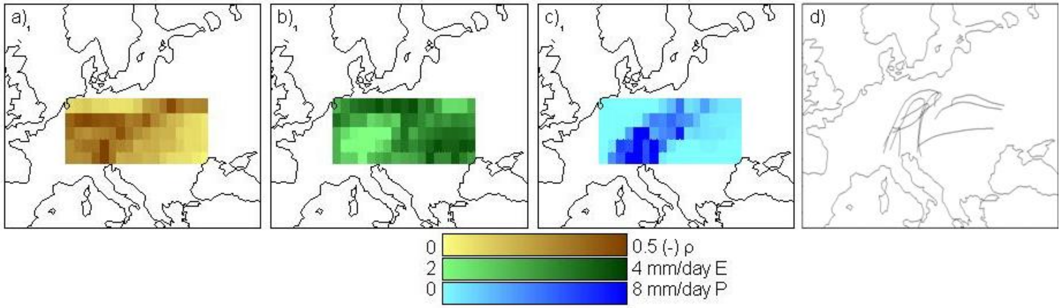

Fig. 7. 28 May 2003 **(a)** local recycling ratio ρ **(b)** evaporation E **(c)** precipitation P and **(d)** selected paths to show the origin of moisture for the regions of high recycling and precipitation.

HESSD
6, 3301–3333, 2009

B. Bisselink and
A. J. Dolman

HESSD

6, 3301–3333, 2009

Recycling of moisture in Europe

B. Bisselink and A. J. Dolman

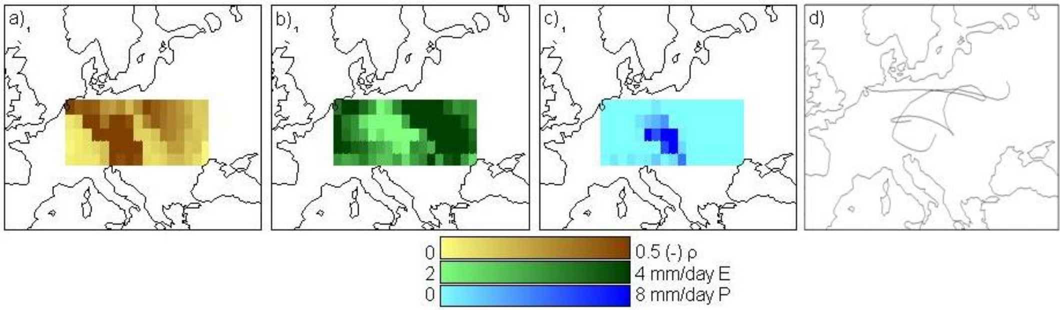

Fig. 8. 5 July 2006 **(a)** local recycling ratio ρ **(b)** evaporation E **(c)** precipitation P and **(d)** two selected paths to show the origin of moisture for the regions of high recycling and precipitation.

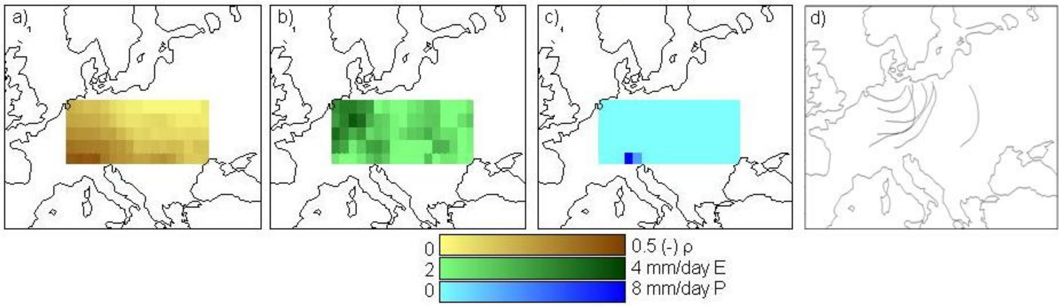

Fig. 9. 10 August 2003 **(a)** local recycling ratio ρ **(b)** evaporation E **(c)** precipitation P and **(d)** selected paths to show the origin of moisture for the regions of high recycling.

HESSD

6, 3301–3333, 2009

Recycling of moisture in Europe

B. Bisselink and A. J. Dolman