Hydrol. Earth Syst. Sci. Discuss., 6, C1477–C1487, 2009
www.hydrol-earth-syst-sci-discuss.net/6/C1477/2009/

Hydrology and Earth System Sciences Discussions

Interactive comment on "Recycling of moisture in Europe: contribution of evaporation to variability in very wet and dry years" *by* B. Bisselink and A. J. Dolman

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Received and published: 9 July 2009

We would like to thank the reviewers for giving very useful remarks and advice on our paper. We have taken all of them into account and provided clarifying answers as well as propositions for changes in the text and figures.

General Comments to all referees

This present paper is a follow up of the paper "Precipitation Recycling: Moisture Sources over Europe using ERA-40 Data" in JHM, 9, 1073–1083, 2008. In this paper we discussed the recycling on a monthly time scale. The advantage of the dynamical recycling model is that it can be used at a daily time scale, because it includes the moisture storage term. The main goal of the present paper is to study in more detail the differences between wet and dry years in moisture recycling at a daily time scale to assess the potential impacts on the evaporation and the recycling ratio. The results show that analyses at a daily time scale is very useful tool to link precipitation recycling to daily meteorological processes. Bisselink and Dolman (2008) conclude that recycling only becomes important during years of reduced total precipitation in central Europe. Now, with analyses at a daily time scale, we conclude that precipitation recycling is also important in wet years with a dry period when the moisture fluxes are low. In this paper we also propose a hypothesis for triggering precipitation and we agree that this is not supported with data. The dynamical recycling model is based on the concept of the waterbalance. Although the water balance models are useful for statistical analyse of the feedback processes, these models lack other important feedback processes like surface energy balance. In a follow up study we will perform several sensitivity experiments with/without prescribed soil moisture conditions (different combinations) and it will be a goal to quantify the role of the land surface (heatfluxes), growth of boundary layer and the formation of (convective) clouds. The next sentence is added in the new version: “We propose a triggering mechanism as discussed in Findell and Eltahir (2003) and Ek and Holtslag (2004). Drier atmospheric conditions lead to higher sensible heat. A deeper boundary layer is needed to form clouds and to trigger convective precipitation. This hypothesis will be studied in more detail with a regional climate model in a follow up study.” The reviewers express some concern about the “hand-wavy” argument about the well-mixed assumption. We agree that this was a weak point of the current version, which we hope is corrected in the final version. We use the dynamical recycling model (Dominguez et al. 2006), which assumes that the atmosphere is fully mixed. In this study we cannot prove if the well-mixed atmosphere assumption is justified. According Eltahir and Bras, 1996 it is justified above most land regions. Burde (2006) modifies traditional recycling models by including a parameter K, which accounts for “fast recycling” or precipitation originating from evapotranspiration that does not mix with advected moisture. For this we need more investigation. However, if the atmosphere is not well-mixed and the precipitation will originate from moisture in the lower atmosphere, where recycled moisture dominates, the recycling ratios can be lower than values provided in a well-mixed atmosphere. The sentence is changed: "Our results do not incorporate the empirical parameter for "fast recycling". If the atmosphere is not well-mixed and the precipitation will originate from moisture in the lower atmosphere, where recycled moisture dominates, the recycling ratios can be lower than values provided in a well-mixed atmosphere and therefore the recycling ratios calculated using the dynamical recycling model could have a bias toward lower values."

Response to specific reviewers:

Anonymous Referee #1 We hope that the grammar in the revised version of the manuscript is improved.

Is the data providing evaporation or evapotranspiration? This is important to differentiate. In our analysis we use daily evaporation from the Regional Atmospheric Climate Model (RACMO).

Figure 2: The data for 2006 is incomplete please complete figure. The triangles represent the monthly values for precipitation and 2m temperature for 2006 until August. The figure is made from the output from a RACMO run from 1981 to August 2006. For this reason we can only show the data for 2006 until August. We don't think this will be a problem to interpret the results presented in Figure 2, because in the paper we are focusing on the warm season.

Line 6 pg 3306: I don't see how to interpret the deficit of 69mm from the figure you are showing. Please include a cumulative rainfall figure. We agree that the deficit of 69mm in 2003 and the precipitation surplus of 32mm in 2006 cannot be observed precisely from the figure. However, it is noticeable that there is a deficit in 2003 and a surplus in 2006 in the figure. The exact numbers we give in the text. We don't think that an

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extra figure will add much more information in this part of the article which deals as a general description of the year 2003 and 2006.

Line 26 of page 3316 – “recycling promotes precipitation”. . . is this really what you want to say? I would think it is the land surface conditions. Precipitation recycling is defined as the contribution of local evaporation to local precipitation. At 28 May 2003 and 5 July 2006 the recycling ratio show a peak (fig 3), which mean that the evaporation significantly contributes to the precipitation. Thus, the mechanism of precipitation recycling promotes precipitation of recycled origin. We also think that the sensible heat flux is an important factor in the mechanism of precipitation recycling. This is mentioned in the lines 26-28 P3316. The sentence will be changed to the following: “precipitation recycling promotes precipitation of recycled origin”.

Dr. P. Dirmeyer L22: "long path length" - this is confusing terminology - it is short in space but long in time due to weak winds. Perhaps say "long duration" instead. The sentence will be changed to the following: “At the 2 days with enough moisture availability (28 May 2003 and 5 July 2006) we see a long duration of the particles in the study area due to weak winds.”

p3304, L10: Note that Salvucci et al (2002) showed that the apparent “predictability” shown by Findell and Eltahir (1997) is an artifact of how they did their calculation, and not applicable or present in a true predictive context. Added p3304, L12:”However, Salvucci et al. (2002) concluded that this evidence was a result of the filtering techniques used, and they found with their Granger causality no causal relation between soil moisture and subsequent precipitation in the observations.” Added in references: Salvucci, G. D., J. A. Saleem, and R. Kaufmann, 2002: Investigating soil moisture feedbacks on precipitation with tests of Granger causality. Adv. Water Resour., 25, 1305-1312.

p3308 L22-27: Can this quantity <rho> be explained more clearly. It took me quite a bit of time and effort to understand exactly what this “local recycling” is. The definition is quite different from that of Brubaker et al. (1993) or Dirmeyer and Brubaker (2007). In contrast to those and related papers, here it does not have to rain in order for recycling ratio to be defined. By definition, the local recycling ratio <rho> is the amount of precipitation originating from evaporation in a region that falls in a cell, to the total precipitation in that cell (Pr/P). To solve the basic equation of the water vapour balance we assume well-mixed atmosphere (Pr/P = wr/w). After substituting and changing the coordinate system we get the expression of R. The local recycling ratio R is an estimate of the fraction of precipitation falling in one specific cell originating as evaporation from within the entire region of analysis. After obtaining the local recycling ratio for each cell, we can then calculate the regional recycling ratio rr, the fraction of recycled to total precipitation within a region, as the sum of the local recycling ratios in all grid cells weighted by the amount of precipitation falling in each cell of area A, as described by Eltahir and Bras (1994). Even if there is no precipitation you can still calculate the local recycling ratio because we are assuming that the ratio of wm/w = Pm/P = rho. Physically you can really only justify it in terms of precipitable water so a "precipitable water recycling ratio". The recycled precipitation consists of molecules of water vapour which were in the atmosphere as a result of an evaporation event at that location, or elsewhere in the region under study. The regional recycling ratio is zero when there is no precipitation.

L27: How much variation is there in the area of the grid boxes in this model? I suspect it is not great, given the limited meridional extent, but it will affect comparison of recycling ratio across the domain. In Figure 1 we present the study area. The 85 dots represent the starting point of the backward trajectory calculation. 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 85 grid cells weighted by the amount of precipitation falling in each gridcell within the region (Eltahir and Bras, 1994).

p3309, L15-17: It is difficult to imagine that time series of daily recycling ratio (or precipitation, evaporation, etc) are statistically independent from one day to the next. How are the degrees of freedom calculated for the estimation of significance for the correlations? What are the decorrelation time scales for these quantities? I suspect the significance thresholds should be set much more conservatively. The recycling ratio is calculated with a simple Pearson correlation and the significance is tested with an F-test, df numerator =1 df denominator=182. The critical value for alpha (0.05) is 3.84. The result of the calculated F-test is 5.32, which is larger than the critical value.

p3311, L19-23: The use of ANOVA for establishing causality makes me a little nervous. Would an approach that incorporates characteristics of cross-validation, like Granger Causality, be better here? There exist interconnections between these causal factors, after all. The recycling ratio describes more than one property of the objects under study (evaporation, precipitable water, moisture fluxes). We agree that all these properties may be related with each other. The purpose of the multiple linear regression technique is to unravel these relations and to discover patterns in the data. The significance is tested with an ANOVA F-test. Granger causality test is a technique for determining whether one time series is useful in forecasting another. If we apply a Granger Causality test with a lag of 1 day and a confidence level of 90% we see that evaporation (E), precipitable water (w) and zonal moisture flux (QU) exert a significant Granger-causal impact on the recycling ratio (RR). This result agrees with the result of the ANOVA which we presented in the paper. For 2006 we see a little difference with the results from the ANOVA F-test, but it will not change the conclusions. Anyway, we changed the ANOVA F-test with the Granger Causality test in the final version of the paper.

L26-29: The same argument can be said for specific geographical regions over the same times – that in arid regions evaporation is more important for recycling ratio, and in humid regions it's the atmospheric characteristics. In general we agree with this statement. However, in this study we also showed that there can be a lot of differences in recycling focused at a daily time scale. In humid regions you'll find also periods where evaporation is more important as the atmospheric characteristics.

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Added:"Savenije (1996) concluded that recycling of moisture is the most important source of rainfall in semiarid or arid areas."

Figs 5-9: These monochrome scales are very hard to read and compare. The color choices here are more artistic than illustrative. We hope the new figures are more illustrative.

The technical points are integrated in the text.

R.J. van der Ent General remarks By definition, the local recycling ratio <rho> is the amount of precipitation originating from evaporation in a region that falls in a cell, to the total precipitation in that cell (Pr/P). We are only interested in the recycling over land (central Europe is the study of interest), 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). We agree that the results from the study are influenced by the size and the shape of the study area. If we imagine the case where the study area would be reduced to a long east-west oriented strip of only a few kilometers width it is obvious that this will lead to precipitation recycling ratios equal to zero. In this way, it means that the evaporation in this east-west orientated strip doesn't contribute to the precipitation in this strip, which is very plausible. The recycling ratio increases if the region becomes larger, because of the larger possibility that an evaporative particle in a region precipitates in the same time (Trenberth 1999). The recycling ratio ranges from 0 for a point observation to 1 for the whole globe. If we take a larger part of Europe into account the recycling ratios will be larger, but the relevance not. In this study we are interested in the contribution of evaporation in central Europe to the precipitation in central Europe. How important is evaporation in central Europe? Can land-use change affect the hydrological cycle? The purpose of this paper is to in more detail the differences between wet and dry years in moisture recycling at a daily time scale to assess the potential impacts on the evaporation and the recycling ratio. A lot of other feedback studies with analytical models based on the water balance depend on two crucial assumptions that limit their

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calculations to a monthly or seasonal time scale. The first is assumption of a well-mixed atmosphere and the second assumption is that the change in atmospheric water vapour storage is neglected, because of the small contribution of the storage term compared to the other terms of the water vapor balance equation at a monthly or longer time scale. As Δt grows, the contribution of the storage term is less significant. The reason that we used the dynamical recycling model is that it allows us to minimize Δt and to calculate recycling at the daily scale.

Specific comments: Please provide a clearer explanation of the negative and positive feedback mechanisms for precipitation recycling (this could in fact be a strong point of the paper). In the Introduction we devote one paragraph on the negative feedback and one on the positive. Because in this study we think a negative feedback is important to promote precipitation we added a paragraph 5.3: “Under these conditions a deep cloud-base height is needed for clouds to form and convective precipitation to occur. This land-atmosphere interaction is an example of a negative feedback (Findell and Eltahir 2003; Ek and Holtslag 2004)” and in the conclusions “We propose a triggering mechanism as discussed in Findell and Eltahir (2003) and Ek and Holtslag (2004). Drier atmospheric conditions lead to higher sensible heat. A deeper boundary layer is needed to form clouds and to trigger convective precipitation.”

I strongly suggest being consequent in using precipitation recycling, and not only recycling. In the new version we changed recycling in precipitation recycling. <rho> and rr: Why not call this the local precipitation recycling ratio <rho>l and the regional precipitation recycling ratio <rho>r, this is more elegant and more clear. More importantly, rr depends on the size and shape of the study region; <rho> depends mostly on the shape and size of the mother region, which equals in this case the study region in figure 1 (see also next point). We agree it is more elegant, but we think a change of rr to <rho>r will be more confusing. The value of <rho> is calculated using eq. 2. for every grid cell. To obtain the regional precipitation recycling ratio rr, we sum the local precipitation recycling ratios <rho> in all grid cells weighted by the amount of precipita-

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tion falling in each gridcell within the region, according the method in Eltahir and Bras, 1994. In Bisselink and Dolman (2008) we used rr as well for regional precipitation recycling ratio and it is good to be consistent in this point.

3302-1-3: The authors state: “Precipitation recycling is defined as the contribution of local evaporation in a region to the precipitation in the same region” This sentence is not clear to me. I would replace this with: “We define (regional/local) precipitation recycling as ...” (Brubaker, et al. 1993). The way we defined precipitation recycling is a well-known definition and described a lot in the literature (e.g. Eltahir and Bras, 1996; Trenberth, 1999, Dominguez, 2006). We changed in:”Precipitation recycling is defined as the amount of water that evaporates from a region that precipitates within the same region.”

As for the definition itself, because of its scale/shape dependency it is - to my view – not a workable definition if one wants to study the contribution of continental evaporation to rainfall. Savenije (1995, 1996a) proposed a local recycling ratio as the part of the rainfall that stems from terrestrial evaporation and Yoshimura (2004) proposed the continental cycling ratio as the ratio of precipitation that originates over land to total precipitation. The terminology is different, but in principle the definitions of Savenije (1995, 1996a) and Yoshimura (2004) are the same. This definition is not scale dependent and provides more insight into the importance of terrestrial evaporation to sustain rainfall. Savenije (1995) defines moisture recycling as all precipitation over a land region that has terrestrial origin. That approach is different than our approach (see general remarks).

3302-28-29: The authors state that the atmosphere is too dry to generate precipitation, this is true locally, but maybe it leads to precipitation outside the study region which is not investigated. We agree that evaporation in the study area could lead to precipitation outside the study region, but this is not the definition of precipitation recycling as we have defined. The evaporation in the study area has to contribute to the precipitation in the same area (and not outside the area).

3307-14: I recommend names of the variables to be given in the text or at least in the table. We changed in: “and the precipitable water (w) and the vertically integrated moisture fluxes ($Q\lambda$ and $Q\varphi$) are estimated from the data (see Table 1 for the precise mathematical definitions).”

3308-8: The local recycling ratio is - to my view - a misleading name, because it implies to be a local characteristic but is actually rather artificial, depending on the mother region’s shape and size. This should be mentioned.

At p3308 – 8-10 we define the local recycling as: “The local precipitation recycling ratio 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 = Pr/P”. Thus we calculate the recycling ratio very locally (grid cell), but the value of the recycling ratio is dependent of the surrounding region you specify. If the region of your interest is a single grid cell the recycling ratio will be almost 0. Is your region of interest the whole globe (including oceans) this will be 1.

3308-22: It appears to me that the authors claim a logarithmic relationship as if it was a law of nature. Is it not just curve fitting? Other authors, Eltahir and Bras (1996) and Dirmeyer, et al. (2007) have proposed an exponential relationship (which indeed also results from curve fitting). We changed the sentence: “Be aware, that the is scale dependent with a logarithmic relationship between the precipitation recycling ratio and spatial scale over Europe (Bisselink and Dolman, 2008).” 3310-14-15: The authors mention a peak, which I have a hard time seeing; perhaps plotting P instead of Pr could help? We mentioned peaks in the precipitation recycling ratio instead of the recycled precipitation. We changed the sentence:” In both, 2003 and 2006, we see peaks in precipitation recycling ratios in the dry periods.”

3317-13-14: To my view, the conclusion that precipitation largely originates from oceanic sources cannot be drawn from this research since only the land area within the study region is taken into account. Land area outside this bounding box may contribute to a large extent to the precipitation in Central Europe but this question is not investigated. Most of the precipitation events which happen in central Europe are coming from advection from the ocean with a West or Northwest circulation. In Figure 2a we see for August 2006 a large precipitation event. In Figure 4b the zonal moisture flux in August 2006 is increasing to a maximum of 200 kg/ms which means advection from the ocean.

3317-22-26: In my opinion, this is not a conclusion, but an introduction. We agree that this sentence could be a sentence for the introduction. However, the conclusions from this study can be important for future climate where heat waves occur often. That is the reason we put this sentence in the conclusion.

Figures 5-9: When the local precipitation recycling ratio is not defined (no precipitation), changing the color of the precipitation recycling ratio to completely white will definitely help the readers to interpret the results. Even if there is no precipitation you can still calculate the local recycling ratio because we are assuming that the ratio of wm/w = Pm/P = rho. Physically you can really only justify it in terms of precipitable water so a "precipitable water recycling ratio". We will change the monochrome scales in a scale which is more illustrative.

Figure 7d: Lines are very unclear, what is the source (place of evaporation) and what is the destination (place of precipitation)? I suggest using arrows. We adapted the figure.

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