Dear editors and referees,

Together with this letter we are pleased to present to you a revised version of our manuscript entitled On the importance of cascading moisture recycling in South America which is under consideration for publication in Atmospheric Chemistry and Physics.

We thank the referees for their positive recommendations and for the constructive comments that helped us to improve our manuscript. Below you find a response to the comment of referees as well as an explanation of the changes that were made to the manuscript.

Yours sincerely,

Delphine C. Zemp (on behalf of the authors)

Below you find a point-by-point response to the comments of the referee #1. Excerpts from the referee's report have been marked in bold.

1. On the Relevance of the Paper: Rather than a study of marginal interest, appealing to a particular subset of readers interested in moisture dynamics over a particular region, we are in the presence of a study with much broader relevance, not least given the applicability of the methodologies to other scientific problems in Atmospheric Chemistry and Physics. Having said that, the topical problem of moisture recycling in South America is itself a fascinating problem, with far-reaching implications to the wider atmospheric circulation.

We thank the referee for his encouraging comment. We are pleased to know that he does not doubt about the relevance of studying moisture recycling in South America and that he mentions the possible application of the complex network approach to different domains including atmospheric sciences.

2. On the Methodology: The methodology is sound, its implementation well explained and its use well justified. This is the opinion of the reviewer, which might not necessarily be shared by readers less familiar with the concepts. Bearing in mind the nature of the underlying system, the dynamics of which is driven by a multiplicity of spatiotemporally interconnected processes, it is appropriate to resort to complex network analysis methodologies. The authors aptly take grid cells as network nodes and the moisture transport (magnitude, direction) as network branches or interactions between nodes. By including self-interactions, the authors are then able to account for local reevaporation and in turn the cascading moisture recycling, aptly defined as having at least one such re-evaporation cycle in the process. For this purpose, an Eulerian approach to moisture transport is preferred, as is actually done in the paper. While a Lagrangian approach to tracking the water particle as it is advected by atmospheric circulation might be favoured in other contexts, here the authors have an important point in taking into account the local, Eulerian approach. This is make clear as the procedure enables the role of local re-evaporation to be brought out, with all its implications. Ultimately, nothing is lost for not opting for a Lagrangian approach, as its benefits in tracking down the particles travelling in the atmosphere are obtained by taking into account the water balance dynamics in each cell.

We thank the referee for the very positive comments and for the good justification of the use of the complex network approach. He also explains in a clever way why the Eulerian approach is in this case more suitable than the Lagrangian one and gives a nice justification as how we recover the missing Lagrangian trajectories when we account for the water balance in each cell to build the network.

3. On the Results: While the role of the cascading moisture recycling addressed in the paper is not overwhelmingly impressive, it is undoubtedly relevant and cannot be neglected, as well pointed out by the authors. The discussion of intermediate moisture recycling nodes, acting as distributors rather than simply sources or sinks, brings added value to a more comprehensive assessment of moisture transport along the way. By analysing the interacting nodes of the system network, the study also brings out interesting land-atmosphere feedbacks that shed more light onto moisture dynamics in the atmosphere, and in turn precipitation regimes with all the implications that they ensue. The impacts of land use change on moisture recycling mechanisms are also very relevant and bring further awareness to the far-reaching effects of deforestation taking place in significant parts of the rainforest. The detailed processes are discussed in a clear and palatable way to the reader, therefore the reviewer would not suggest any significant changes. Still, it is worth noting that the last sentence of the main body of the paper, on page 17501, lines 5-7, is so important that the point should eventually be stressed from the very beginning in the paper.

We thank the referee for his very positive comments regarding our results and discussion. We agree with the referee that the last sentence should be highlighted already at the beginning of the paper. In the revised manuscript, we added the following statement at the end of the abstract: “This study offers a better understanding of the feedback between the vegetation and the atmosphere on the water cycle that is needed in a context of land-use and climate change.” We also propose to rephrase L. 23 - 24 in the introduction: “In order to improve predictability of rainfall changes with future land-use and climate change, further advancement in our understanding of continental moisture recycling in South America is needed.”

4. Minor mathematical typesetting remarks: The formulation is consistent, well presented and easy to follow. Therefore, only minor typesetting remarks can be raised: P. 17507, lines 12, 14-18: the parenthesis around the fractions should enclose the entire fraction. For instance, if typesetting in LaTeX, this can be done by ”nleft(” ”nright)” instead of just ”(” and ”)”. A more appropriate use of the parenthesis is actually done further down on page 17508, line 8.

We thank the referee for this precision. We made a better use of the parenthesis in the revised manuscript.

5. Minor grammar remarks: The text is well and clearly written in proper English. The reviewer would thus leave only a couple of minor remarks: a) The use of ”which” in transitive statements: Page 17487, line 2: ”which can be” should either be preceded by a comma (”, which can be”), otherwise ”which” would be replaced by ”that”. Page 17487, line 20: ”which are important”: same issue: either pre-

cede by comma or replace which by "that". Page 17487, line 22: "which is evaporated": same issue. Page 17488, line 18: "location which receive": same issue. Page 17489, line 4: "locations which distribute": as above. (among other instances)

We thank the referee for his positive comment regarding the writing of the paper. We took into account his suggestion in the revised manuscript.

b) Missing preposition "as": Page 17490: "moisture that has final destination the La Plata basin": should read "moisture that has [as] final destination the La Plata basin".

We thank the referee for this remark. We corrected the manuscript accordingly.

Having mainly focused on the scientific content and formulation in this review, additional minor issues may have slipped under the radar.

Below you find a point-by-point response to the comments of the referee #2. Excerpts from the referee's report have been marked in bold.

This paper discusses the recycling ration in the Amazon using a complex network approach. The problem is clearly important and the approach interesting. However, it is not clear to me what new results are really obtained (besides a fancy display of complex network terminology) nor whether these results are robust. I urge the authors to rewrite the papers using a description which is easier to read and follow for the readers of ACP, as well as address the following points:

We thank the referee for this comment. We agree with the referee that the description might be a little confused for readers who are not familiar with the concepts. In the revised manuscript, we put effort to systematically use a terminology carefully defined in the introduction (e.g., cascading moisture recycling (CMR), direct moisture recycling (DMR) and re-evaporation cycles). We also made sure that the description is intuitive and easy to follow with the help of simple schematic representations explaining the concepts and methods and a glossary. We also explicitly mentioned what results and metrics are new.

1. How do the results depend on the resolution (temporal and spatial) of the fields and on the various choices that are adopted in the proposed method?

We thank the referee for this interesting question. We will answer the three points separately.

- Spatial resolution:

The WAM-2layers is based on a 1.5 longitude/latitude spatial resolution in accordance with the grid of the ERA-Interim dataset used previously (van der Ent et al., 2010). We agree with the reviewer that the question of spatial resolution is an important one. In fact, the amount of locally recycled moisture within a grid cell is highly dependent on the spatial resolution of the fields (van der Ent and Savenije, 2011, Fig. 4). However, in our study, the re-evaporation cycles are occurring along the path. In all presented measures we are integrating over all paths contributing to the large-scale moisture transport, hence the resolution does not influence our results. Because the typical length scale of direct links in moisture recycling is larger than 1000 km (c.a. 9 geographical degrees) in the region (van der Ent and Savenije, 2011, Fig. 5), working on a finer resolution would not change significantly our findings. We mentioned this explanation in the revised manuscript.

We remind that due to the projections of the data on a fixed latitude/longitude grid, the size of the grids decreases with increasing latitude which might lead to biases in the results. This has been taken into account by correcting the different metrics using a well-established framework (Zemp et al., 2014). This statement has been mentioned in the manuscript.

- Temporal resolution:

In WAM-2layers, the actual moisture tracking is performed on a 0.5-hour basis for numerical stability purposes. The temporal resolution of the input-data corresponds to the smallest one of the available products from ERA-Interim (3-hour time step for evapotranspiration and precipitation and 6-hour time step for the specific humidity, wind speeds and pressure). Because the smallest time step that we can get for the MODIS evapotranspiration data is 8 days, we down-scaled the MODIS dataset to 3-hours resolution using the temporal variability of the evapotranspiration product from ERA-Interim. The output of WAM-2layers is provided on a monthly basis. The time scale of moisture feedback is no longer than 30 days in the studied region (van der Ent and Savenije, 2011, Fig. 5), so the monthly resolution is reasonable to study this process. We made this clear in the revised manuscript. Our analysis is presented as the seasonal time scale in order to consider the large variability in moisture transport and rainfall in the South American monsoon system. Yearly temporal resolution might be an interesting choice to investigate the role of inter-annual variability (or extreme events) on moisture recycling, but is beyond the scope of this paper.

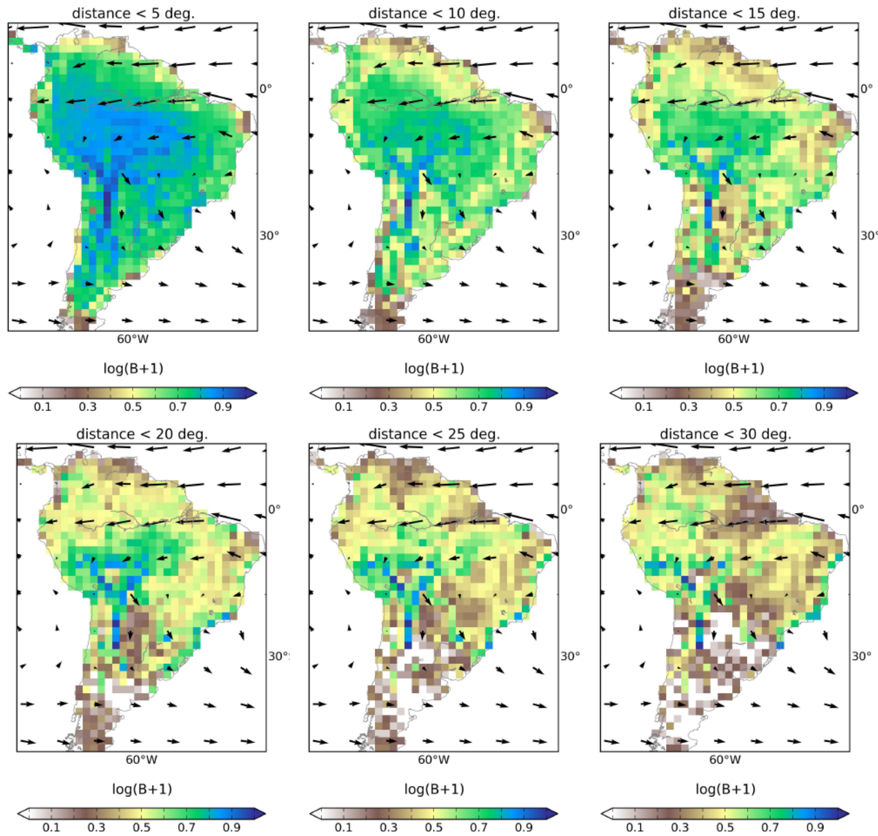
- Choice adopted in the method:

The WAM-2layers model is an established tool and has been used in a variety of publications focusing on moisture tracking and moisture recycling (e.g. van der Ent et al. (2010); Keys et al. (2012); van der Ent et al. (2014)). The WAM-2layers model is to our knowledge the only model that provides the output needed to perform the analysis of cascading moisture recycling using network techniques as presented in this manuscript. However, as the question does not refer to the WAM-2layers model but to the new network analysis methods presented here, the main methodological choice adopted in our manuscript is about the calculation of the Betweenness Centrality (B) (Sect. 2.5.2) and the threshold used to define the intermediary regions (Sect. 2.4).

For the calculation of the B, we had to remove from the network the long-range moisture transport, i.e., occurring over distances larger than a certain threshold, in order to reveal cascading moisture recycling pathways. In the manuscript, this threshold is set to 15 geographical degrees. The choice of the threshold does not influence the results qualitatively: regions with high B are still located in the south-western part of the Amazon region and east of the subtropical Andes (Supp. Fig. 1).

The value of $\Delta Pm/P$ represents the fraction of total moisture inflow that comes from CMR in the intermediary region. It is of course dependent on the underlying definition of the intermediary regions. We choose to define the intermediary region as the regions which have a value of $\Delta Ec/E$ larger than the 80 percentile. For better transparency in the revised manuscript, we highlighted the corresponding region in Figs. 5b and 5d and to refer to these figures when the intermediary regions are mentioned.

2. Is the cascading recycling ratio robustly defined? Can the authors provide examples (synthetic examples) where the method

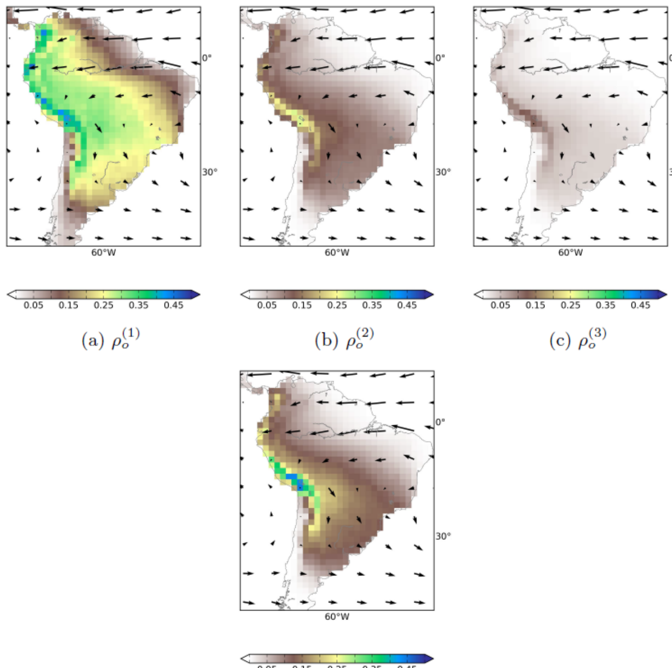


Supplementary Figure 1: Betweenness Centrality (B) obtained for different thresholds (yearly average).

can recover what was put in?

We thank the referee for this question and suggestion. In order to test the robustness of the (direct and indirect) precipitation recycling ratios, we have computed the steps explained in Sect. A1 and A2.1 with Ω being the ocean. Thus, ρ_o is the fraction of precipitation that comes from the ocean without any re-evaporation cycle on the way and $\rho_o^{(k)}$ is the fraction of precipitation that comes from the ocean with k re-evaporation cycle(s) on the way ($k = 1, ...n$) (see Suppl. Fig. 2). We confirm that:

- The sum $\rho_o + \rho_o^{(1)} + \rho_o^{(2)} + ... + \rho_o^{(n)}$ is equal to 1. This is easy to interpret as all the precipitation in a location must always have been come from the ocean (either directly or after a certain number of re-evaporation cycles).
- The sum $\rho_o^{(1)} + \rho_o^{(2)} + ... + \rho_o^{(n)}$ represents the fraction of precipitation that



(a) $\rho_o^{(1)}$ (b) $\rho_o^{(2)}$ (c) $\rho_o^{(3)}$

(d) $\rho_o^{(2)} + ... + \rho_o^{(n)}$

Supplementary Figure 2: Steps in the calculation of the cascading recycling ratio computed with the region of interest (Ω) being the ocean (yearly average).

comes from the ocean with at least 1 re-evaporation cycle. It is equal to the continental recycling ratio ρ_c (see Sect. 2.3.1 and van der Ent et al. (2010)).

- The sum $\rho_o^{(2)} + ... + \rho_o^{(n)}$ is the fraction of precipitation that comes from the ocean with at least 2 re-evaporation cycles (see Suppl. Fig. 2). It is equal to $\Delta P/P$, introduced in the manuscript as the fraction precipitation that has been evaporated at least twice on the continent (see Sect. 2.4).

We obtained thus the same results using different metrics. We hope that this is a convincing argument to justify the robustness of the cascading recycling ratio and we mentioned it in the revised manuscript.

We can not test the evaporation recycling ratio the same way because $\Delta E/E$ quantifies the fraction of evapotranspiration that is involved in cascading moisture recycling (i.e., that comes from the continent and precipitates further over the continent) while $\epsilon_o^{(2)} + ... + \epsilon_o^{(n)}$ would be the fraction of evapotranspiration that runs through at least 2 re-evaporation cycles before precipitating over the ocean. This is also the reason why the two methodologies are needed even if they lead to the same results for the previous mentioned case. We made this clear in the revised manuscript.

3. What are the error bars on the estimates provided in the paper?

We thank the referee for this relevant question. Our estimates are of course subject to errors from different sources: (1) the input data, (2) the assumptions made in WAM-2layers van der Ent et al. (2010); van der Ent et al. (2014) and (3) the assumptions made in our analysis (see Sect. 2.2). We think the referees point is very important and we share his concerns. To this end, we reproduced our analysis based on a different dataset to test for the robustness of our results. In addition to previously used datasets (MODIS and TRMM), we used a merged product based on forty different evapotranspiration data sets derived from observations, calculated via land-surface models and output from reanalysis (LandFlux-Eval (Mueller et al., 2013)), as well as an average of four different observation-based precipitation datasets (CRU (New et al., 2000), GPCC (Huffman et al., 1995; Adler et al., 2003), GPCP (Adler et al., 2003)and CPC (Chen et al., 2008)) for the period 1989-1995. In the revised manuscript, we provided the results for the two sets of input data side by side and discussed the robustness of our findings in greater detail.

4. What is new which could not be obtained with more standard methods? And what is new, can be tested and believed?

We thank the referee for his questions which helps us to point our the uniqueness of our approach. In most of the previous studies using moisture tagging experiments, moisture from a group of grid cells covering a domain of interest (typically the continent) is tracked simultaneously until it precipitates or leaves the domain. Here, we track moisture evaporating from each grid cell covering the domain (i.e., the South American continent) individually. By doing so, we are able to diagnose for each grid cell the amount of evaporating moisture that precipitates in any other cell, i.e, to build a moisture recycling network. This approach enables us to focus on cascading moisture recycling. We mentioned this explicitly in the revised manuscript.

We know only two previous studies dealing with the importance of cascading moisture recycling using a different methodology (Numaguti, 1999; Goessling and Reick, 2013). Dividing the world in source and origin regions and adding different tracers in a tagging experiment within an atmospheric general circulation model, the authors counted the number of re-evaporation cycles that moisture experience on the way from the ocean until a specific location. The author also provided results on moisture recycling between some source - destination pairs (Numaguti, 1999, Fig.4). Nevertheless, we argue that the notion of intermediary regions in moisture recycling has never been introduced and the share of the CMR to the total moisture inflow (precipitation) and outflow (evapotranspiration) has never been quantified. Furthermore, the approach followed by (Numaguti, 1999; Goessling and Reick, 2013) is based on the full diagnostics provided by a general circulation model and can not be applied to observation-based data as it is done here. This explanation is mentioned in the revised manuscript.

In addition, we further develop the well-known concept of recycling ratios (van der Ent et al., 2010; Keys et al., 2012; Eltahir and Bras, 1994; Trenberth, 1999; Bosilovich and Chern, 2006; Dirmeyer et al., 2009; Bagley et al., 2014) (called DMR ratios in our manuscript) defined as the fraction of precipitation coming from a specific location (or the fraction of evapotranspiration precipitating over a specific location) without any re-evaporation cycle on the way. We extend this definition to take into account the transport of moisture with re-evaporation cycles (called CMR ratios in our manuscript). This enables to highlight further backward (or forward) the origin (or destination) of moisture. Finally, we apply for the first time common complex network measures (betweenness centrality and clustering coefficient) to a moisture recycling network. We took a special care to explicit what is new in our revised manuscript.

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General changes to the manuscript:

All the numbers of the figures, equations and sections refer to the revised manuscript.

- We repeated the analysis using a different set of precipitation and evaporation data. We summarized the input data in Table 2, showed the results in Table 3, added the figures either in the main text (Fig. 5) or in the appendix and changed the text accordingly.
- We added a figure in the appendix to show the influence of the threshold in the calculation of the betweenness centrality (Fig. B4)
- We reformulated the text in order to use only the terminology defined in the introduction and to make it more intuitive. We also created a glossary in the appendix (Appendix A). In particular, we made the explanation of how to interpret the direct and cascading moisture recycling ratios more clear (Sect. 2.3) and changed the corresponding schematic representation (Fig. 2). Another location where these changes are relatively substantial is Sect. 2.4.
- We add blue boundaries (Figs. 6) for more transparency on the threshold used to define the intermediary regions.
- Answering the questions of the referees, we realized that there was a mistake in the calculation of the evaporation recycling ratio (Equ. C6 and C7): the term alpha (previously defined as the ratio evapotranspiration / precipitation) has been removed. We modified the equations and modified correspondingly the results (Figs. 8e and 8f) and discussion.
- We added a legend associated with the networks schemes (Figs. 1 and 3)
- We merged two sub-sections in order to discuss results together and highlight the main findings (Sect. 3.2).
- We completed the discussion of our results to show what the use of the clustering coefficient adds to the other results (Sect 3.3, last sentence in the first).
- We modified the introduction to better highlight the novelty of our study (§4 and 5 mainly).
- We cited the previous studies that use the WAM model (Sect. 2.1.1 first §) to show that it is a well-established tool.
- We discussed the issue of spatial and temporal scale (Sect. 2.1.1, §2 and 3)

- We discussed an additional measure regarding the differences and similarities between various presented measures (Sect. 2.6).
- We added some sentences in the conclusion to highlight another of the findings of our study (§3).
- To show the robustness of the cascading recycling ratio, we explained a special case where it leads to the same results as another of our measure (Sect. C1.3).
- We simplified the discussion of the results as much as possible by referring to the figures only once at the beginning of each major statement (see example in Sect. 3.2 where Fig 6 is mentioned in §1 already).
- We changed the caption of Table 3 to make it easier to read.
- We removed a subfigure representing one possible pattern for the motif Middleman (the two patterns are not different) (Fig. 3).
- We made all corrections suggested by referee #1.

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On the importance of cascading moisture recycling in South America

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Abstract. Continental moisture recycling is a crucial process of the South American climate system. ~~Evapotranspiration~~ In particular, evapotranspiration from the Amazon ~~river basin contributes~~ basin contributes substantially to precipitation regionally ~~and in~~ as well as other remote regions such as the La Plata ~~river~~ basin. Here we present an in-depth analysis of South American moisture recycling ~~.~~ mechanisms. In particular, We quantify the importance of "cascading moisture recycling" (CMR), which describes ~~the exchange of moisture between the vegetation and the atmosphere through precipitation and re-evaporation cycles on its way between~~ moisture transport between two locations on the continent ~~. We use~~ that involves re-evaporation cycles along the way. Using the Water Accounting Model 2-layers (WAM-2layers) forced by ~~precipitation from TRMM and evapotranspiration from MODIS for the period 2001 until 2010 to construct moisture recycling networks. These networks describe the direction and amount of moisture transported from its source (evapotranspiration) to its destination (precipitation) in~~ a combination of several climate datasets, we were able to construct a complex network of moisture recycling for South America. ~~Model-based calculations of continental and regional recycling ratios in the Amazon basin compare well with other existing studies using different datasets and methodologies.~~ Our results show that ~~cascading moisture recycling contributes about~~ CMR contributes about 9 – 10 % to the total precipitation over South America and 17 – 18 % over the La Plata basin. ~~Considering cascading moisture recycling increases the total dependency of~~ CMR increases the fraction of total precipitation over the La Plata basin ~~on moisture~~ that comes from the Amazon basin ~~by about 25from~~ from 18 – 23 to 24 – 29 % during the wet season. ~~Using tools from complex network analysis, we reveal the importance of the~~ We also show that the south-western part of the Amazon basin ~~as a~~ is not only a direct source of rainfall over the La Plata basin, but also a key intermediary region ~~for continental moisture transport in South America~~ which distributes moisture originating from the entire Amazon basin towards the La Plata basin during the wet season. Our results suggest that ~~land use~~ land-use change in this region might have a stronger impact on downwind ~~rainfed agriculture and ecosystem stability~~ rainfall than previously thought. Using complex network analysis techniques, we find the eastern flank of the subtropical Andes to be a key region for southward moisture transport via CMR. This study offers a better understanding of the feedbacks between the vegetation and the atmosphere on the water cycle, which is needed in a context of land-use and climate change in South America.

1 Introduction

Continental moisture recycling, the process by which evapotranspiration from the continent returns as precipitation to the continent (Brubaker et al., 1993; Eltahir and Bras, 1994; van der Ent et al., 2010) is particularly important for the South American hydrological cycle. In the Amazon ~~river~~ basin, between 25 and 35 % of the moisture is regionally recycled (Eltahir and Bras, 1994; Trenberth, 1999; Bosilovich and Chern, 2006; Burde et al., 2006; Dirmeyer et al., 2009). The moisture from the Amazon basin is also exported out of the basin ~~,~~ and transported via the South American Low Level Jet along the Andes~~and~~ . It contributes to precipitation over the La Plata ~~river~~ basin particularly during the wet season (Marengo, 2005; Drumond et al., 2008, 2014; Arraut and Satyamurty, 2009; Dirmeyer et al., 2009; van der Ent et al., 2010; Arraut et al., 2012; Martinez et al., 2014).

Land-use change – in particular deforestation in the Amazon basin – ~~impacts~~ alters the evapotranspiration rate and affects the water cycle (see review in Marengo, 2006). A resulting reduction in regional moisture supply may have important consequences for the ~~ecosystem stability in the~~ stability of Amazon rainforests (Oyama and Nobre, 2003; Cox et al., 2004; Betts et al., 2004; Hirota et al., 2011; Knox et al., 2011; Spracklen et al., 2012). ~~Downwind~~

Downwind rainfall reduction, e.g., in the La Plata basin, ~~rainfall reduction may affect~~ may have negative effects on rainfed agriculture (Rockström et al., 2009; Keys et al., 2012). Even if regional impact of changes in precipitation patterns from deforestation has been intensively studied using simulations from atmospheric general circulation models with deforestation scenarios (Lean and Warrilow, 1989; Shukla et al., 1990; Nobre et al., 1991, 2009; Werth and Avissar, 2002; Sampaio et al., 2007; Da Silva et al., 2008; Hasler et al., 2009; Walker et al., 2009; Medvigy et al., 2011; Bagley et al., 2014) the magnitude of rainfall reduction and the location of the most ~~impacted~~ affected regions are still uncertain. ~~Therefore, further advancements~~ In order to improve predictability of rainfall changes with future land-use and climate change, further advancement in our understanding of ~~the~~ continental moisture recycling in ~~the South American continent are~~ South America is needed.

To identify the sources and sinks of continental moisture and to quantify regional and continental moisture recycling rates in South America, several methods have been used including isotopes (Salati et al., 1979; Gat and Matsui, 1991; Victoria et al., 1991), atmospheric bulk models (Brubaker et al., 1993; Eltahir and Bras, 1994; Trenberth, 1999; Burde et al., 2006) ~~,~~ and quasi-isentropic back-trajectory method ~~(Dirmeyer et al., 2009; Bagley et al., 2014) and tagged water experiments~~ (Dirmeyer et al., 2009; Spracklen et al., 2012; Bagley et al., 2014). In addition, numerical atmospheric moisture tracking allows to identify the spatial distribution of evapotranspiration from a specific region. It has been performed online with a general circulation model (GCM) (Bosilovich and Chern, 2006) or a ~~posteriory~~ posteriori (offline) with reanalysis data (Sudradjat et al., 2002; van der Ent et al., 2010; Keys et al., 2012) (see a review of the methods in van der Ent et al., 2013; Burde and Zangvil, 2001).

In most of ~~existing studiesusing tagged water experiments, moisture evaporating from a given region is tracked forward in time from the evapotranspiration~~ the previous atmospheric moisture tracking studies, moisture from a group of grid cells covering a region of interest (typically the continent) is tracked simultaneously until it returns to the land surface as precipitation ~~.~~ or leaves the domain. This approach is useful to investigate how evapotranspiration from a specific location is transported in the atmosphere and precipitates at first in another location. However, precipitating ~~water~~ moisture can be re-evapotranspirated in the same location (re-evaporation cycle) and can be transported ~~to a downwind location where it contributes to precipitation . Such exchanges of moisture between the vegetation and the atmosphere through~~ further downwind before it falls again as precipitation over land. In most of the previous studies, only moisture recycling with no intervening re-evaporation cycles ~~might play a crucial role for the transport of moisture in the Tropics (Spracklen et al., 2012) . Adding different types of tracers within a GCM, Numaguti (1999) found that moisture runs on average through more than two~~ ("Direct Moisture Recycling, DMR") is considered. Here, we track moisture evaporating from each grid cell within a larger the domain (i.e., the South American continent) individually. By doing so, we are able to diagnose for each grid cell the amount of evaporating moisture that precipitates in any other cell, i.e., to build a moisture recycling network. Such an approach enables us to study the DMR between important subregions of the South American continent (e.g., the Amazon and the La Plata Basin), but also the moisture transport that involves at least one re-evaporation ~~cycles between evaporation from the ocean and precipitation in northern Eurasia.In this study we focus for the first time on the following questions: what is the importance of cascading moisture recycling in South America? Which are the important intermediary regions for cascading moisture recycling? Which are the key regions where the pathways of cascading moisture recycling are channeled?~~

~~We call "cascading moisture recycling" the process by which evapotranspiration from a specific location on land runs through one or more re-evaporation cycles before it precipitates in another one. On the other hand, "direct moisture recycling " refers to the process by which evapotranspiration is directly transported (without any re-evaporation cycle)from one location on land to another, where it precipitates. We call "intermediary" the location where re-evaporation~~ cycle ~~is occurring. We define a "pathway of moisture recycling" as the set of locations including the starting and the destination locations, as well as the intermediaries.~~ ("cascading moisture recycling, CMR").

~~We perform a tagged water experiment a posteriori with~~ While only a few previous studies deal with the importance of CMR (Numaguti, 1999; Goessling and Reick, 2013), these studies are based on general circulation models rather than on observation-based data. In the following, we quantify the importance of CMR for the regional climate in South America using numerical atmospheric moisture tracking a posteriori with historical climatological datasets. Our analysis is based on precipitation, evapotranspiration, wind and humidity datasets from ~~reanalysis and satellite products for South America using the numerical atmospheric moisture tracking model WAM-2layers (Water Accounting Model-2layers)(van der Ent et al. , 2014).~~ a combination of observation-based, reanalysis and merged synthesis products (based on the average of several existing products).

~~We propose a novel framework to quantify the importance of cascading moisture recycling for the regional climate in South America, and in particular in the Amazon basin and the La Plata basin. In addition, we use tools from~~ Our network based approach allows us to apply analysis methods developed in complex network theory to improve our understanding of moisture recycling pathways in South America. The potential of ~~the complex network approach has been recently shown in climate science. It has been used to detect large-scale related climate anomalies (teleconnections) (Tsonis et al., 2008; Donges et al., 2009a,b) and to reveal important regions for~~ complex network based analysis of the climate system has been shown in a range of applications such as the detection of teleconnections (Tsonis et al., 2008; Donges et al., 2009a,b), the propagation of extreme events (Malik et al., 2012; Boers et al., 2013) ~~. In previous studies, links~~ and the El Niño forecasting (Ludescher et al., 2013). While previous network based studies rely on statistical analysis in the network ~~were usually built according to the strength of the statistically relationships between time series in different locations. In our study , we apply complex network approach for the first time to a network in which the links represent water fluxes.~~ construction, our approach is based on a flux-based network, which represents a substantial methodological advancement.

In this study we focus on three key questions:

1. what is the importance of CMR in South America and in particular for the moisture transport from the Amazon basin towards the La Plata basin?

2. Which are the important intermediary regions for the transport of moisture from sources and sinks on the continent?

3. Which are the key regions where the pathways of CMR are channeled?

In Sect. 2.1 we describe the tagged water experiment using the WAM-2layers and we explain how we use it to build moisture recycling networks. We explain the assumptions made in the proposed analysis in Sect. 2.2. We develop new measures in Sects. 2.3 and 2.4 and we present the complex network ~~measures~~ analysis in Sect. 2.5. After comparing the continental and regional recycling ratios with other existing studies in Sect. 3.1, we present and discuss new results on the importance of ~~cascading moisture recycling~~ CMR in Sect. 3.2 and on complex network analysis in Sect. 3.3. Finally, we present an in-depth analysis of the moisture recycling between the Amazon basin and the La Plata basin in Sect. 3.4. As many terms have been introduced in this study, we suggest the reader to refer to the glossary in Appendix A.

2 Methods

2.1 Building moisture recycling networks

2.1.1 Description of the moisture ~~tracking~~ tagging experiment in WAM-2layers

In this study we make use of the Eulerian atmospheric moisture tracking model Water Accounting Model – 2 layers (WAM-2layers~~V2.3~~) 2.3.01 (van der Ent et al., 2014). It is an update of a previous version that has been used in a variety of publications focusing on moisture tracking and moisture recycling (e.g. van der Ent et al. (2010); van der Ent and Savenije (2011); Keys et al. (2 The actual tracking in WAM-2layers is performed a posteriori with ~~reanalysis and satellite~~ two different datasets (see input data in Sect. 2.1.2). Evapotranspiration from ~~a certain region of interest~~ each grid cell is "tagged" and subsequently tracked in the atmosphere by applying water balance principles to each grid cell, consisting of a well-mixed upper and lower part. The two-layer approach is simplified compared to full-3-D tracking, but was shown to perform comparably well (van der Ent et al., 2013).

The WAM-2layers ~~provides the basis for the construction of moisture recycling networks analyzed in the following. To this extent, we performed separate forward tracking runs of evapotranspiration for each continental grid cell in the South American domain (Fig. ??) for the years 2000–2010. The tagged moisture is assumed to be gone when it leaves the domain.~~ runs on a 1.5° longitude/latitude grid. Because the local moisture recycling (re-evaporation cycles) is scale-dependent, the amount of locally recycled moisture within a grid cell depends on the spatial resolution of the model (van der Ent and Savenije, 2011, Fig. 4). However, in our study, the re-evaporation cycles are occurring along the pathway of moisture recycling. Since we are integrating over all pathways contributing to the large-scale moisture transport, the spatial resolution has little influence on our results. The typical length scale of direct links in moisture recycling is larger than 1000 km (c.a. 9°) in the region (van der Ent and Savenije, 2011, Fig. 5) , which indicates that our resolution is sufficient to analyze the processes of interest.

We omitted the ~~year 2000~~ first year of the considered period from the results because of model spin-up. The output ~~for the years 2001–2010~~ are aggregated first to monthly, then to seasonally average imports and exports between all land grid cells. This temporal resolution is reasonable for our purpose since the time scale of moisture recycling does not exceed 30 days in the studied region (van der Ent and Savenije, 2011, Fig. 5) .

These seasonal averages are used to build two seasonal moisture recycling networks, which are assumed to be static for the whole season. This implies that in the proposed analysis, for each season moisture is tracked forward and backward in space but not in time.

2.1.2 Input of WAM-2layers

~~The input~~ In order to reduce the uncertainty associated with the input data, we used two different datasets as input for WAM-2layers ~~are~~ (that we call “input MOD” and “input LFE”, see Table 1). The input MOD covers the period 2000 – 2010 and contains 3 hourly precipitation estimates from the Tropical Rainfall Measuring Mission (TRMM) based on the algorithm 3B-42 (version 7) (Huffman et al., 2007) ~~,~~ and 8 days evapotranspiration estimates from Moderate Resolution Imaging Spectroradiometer (MODIS) based on the MOD16 ET algorithm (Mu et al., 2011)~~as well as 6hourly specific humidity and wind speed in three dimensions from the ERA-Interim reanalysis product (Dee et al., 2011) . We downscaled the MODIS evapotranspiration to a 3hourly resolution based on ERA-Interim, as WAM-2layers needs finer temporal resolution in the input data. All data is upscaled to a regular grid of 1.5longitude/latitude and covers the South American continent until 50S, which is the southernmost latitude covered by TRMM product. In addition, all data is downscaled to 0.5h as requested by the numerical scheme of WAM-2layers~~.

~~Humidity estimation has been improved in the ERA-Interim product in comparison with others reanalysis products (Dee and Uppala, 2008) .~~ Precipitation dataset from TRMM are considered to be reliable over South America and in particular in the ~~Amazonian region~~ Amazon basin where others products perform poorly due to the lack of ground based measurements (Franchito et al., 2009; Rozante et al., 2010). TRMM precipitation ~~dataset~~ data are shown to represent high frequency variability sufficiently well (Kim and Alexander, 2013). However, it is systematically biased during the dry season in the northeastern coast of Brazil, where precipitation is underestimated (Franchito et al., 2009) and at the junction of Argentina, Paraguay and Brazil, where it is overestimated (Rozante and Cavalcanti, 2008). Evapotranspiration from MODIS is estimated using ~~a recently improved algorithm (Mu et al., 2011) based on~~ the Penman–Monteith equation (Monteith et al., 1965) ~~and~~ forced by satellite ~~data from MODIS~~ and meteorological reanalysis data. ~~The~~ Like other “observation-based” evapotranspiration estimations, the quality of the ~~evapotranspiration~~ MODIS dataset depends on the quality of the ~~input~~ forcing data and the ~~parametrization~~ parameterization of the algorithm. The MODIS evapotranspiration dataset has been validated with 10 eddy flux towers located in the Amazonian region under various land cover types (Loarie et al., 2011; Ruhoff, 2011).

The input LFE covers the period 1989 – 1995 and contains monthly evapotranspiration averaged from 39 different products (LandFlux-Eval, Mueller et al. (2013)), as well as monthly precipitation averaged from four different observation-based precipitation datasets: Climate Research Unit (CRU) (New et al., 2000) , the Global Precipitation Climatology Centre (GPCC) (Huffman et al., 1995; Adler et al., 2003) , GPCP (Adler et al., 2003) and the unified climate prediction center (CPC) from the National Oceanic and Atmospheric Administration (NOAA) (Chen et al., 2008) . The four precipitation datasets are interpolations from rain gauge data (in combination with satellite observation in the case of GPCC) and have been used as forcing dataset for the “observation-based” evapotranspiration product in LandFlux-Eval (Mueller et al., 2013) . Here, we include the evapotranspiration products in LandFluxEval that are not only derived from observations, but also calculated via land-surface models and output from reanalysis.

Both datasets are complemented by 6 hourly specific humidity and wind speed in three dimensions from the ERA-Interim reanalysis product (Dee et al., 2011) for the corresponding periods. Because these two variables are used to get the horizontal moisture fluxes, the choice of the reanalysis product matters for the eventual results of the WAM-2layers (Keys et al., 2014) . Humidity estimation has been improved in the ERA-Interim product in comparison with others reanalysis products (Dee and Uppala, 2008) .

The temporal resolution of the input data needed in WAM-2layers is 3 hours. Therefore, we downscaled the input MOD and 2 based on the temporal dynamic found in the ERA-Interim evapotranspiration and precipitation products. In addition, all data is downscaled to 0.5 h as requested by the numerical scheme of WAM-2layers. All data is upscaled to a regular grid of 1.5° longitude/latitude and covers the South American continent to 50° S, which is the southernmost latitude covered by TRMM product.

The long term seasonal average of evapotranspiration and precipitation as well as moisture flux divergence (evapotranspiration – precipitation) are shown in ~~Fig. ??~~Figs. 4 and 5. The high rainfall in the South Atlantic Convergence Zone (including the Amazon basin, central and south-eastern Brazil) during the wet season (December to March) compared to the dry season (June to September) characterizes the South American Monsoon System (SAMS) (Liebman et al., 1999; Grimm et al., 2004; Arraut and Satyamurty, 2009). ~~The~~

~~evapotranspiration is high in the Amazon basin and varies little in time and space. It~~

The evapotranspiration and precipitation in the input MOD have an overall positive bias compared to the input LFE. While the spatial patterns of evapotranspiration show good agreement on a continental scale, there are also several distinct differences. In particular the wet season evapotranspiration in the sub-tropical South America is much weaker in the input MOD then LFE. Interpreting and explaining the differences between the datasets is beyond the scope of this study. For an evaluation of the different types of products (model calculation, "observation-based" and reanalysis), we refer to Mueller et al. (2011) .

In both inputs the evapotranspiration exceeds the total precipitation in the southern part of the Amazon basin during the dry season, indicating that this region is a net source of moisture for the atmosphere (Fig. ~~??c~~ 4c and 5c). This is in agreement with previous studies demonstrating a maintaining of the greenness of the Amazon forests (Morton et al., 2014) and the absence of water stress during the dry season due to the deep root system, which enables the pumping of the water from the deeper water table (Nepstad et al., 1994; Miguez-Macho and Fan, 2012).

We find that, averaged over the full time period, evapotranspiration exceeds precipitation in northeastern Brazil ~~,~~ and in the Atacama Desert ~~and~~ in both datasets, as well as along the Andes in the input MOD. Possible explanations for the imbalance in these arid to semi-arid regions are irrigation or biases in the input data as mentioned above. As this might lead to a bias in moisture recycling ratios due to an overestimation of the contribution of evapotranspiration to local precipitation, we will exclude these grid cells from our analysis.

2.1.3 ~~Output~~ Construction of ~~WAM-2layers as~~ a ~~-~~complex network based on WAM-2layers

The output of WAM-2layers is a matrix ~~$\mathbf{M} = \{m_{ij}\}_{i,j \in N}$~~ $\mathbf{M} = \{m_{ij}\}$ for all $i,j \in N$ with N the number of grid cells in the continent ($N = 681$). The non-diagonal element m_{ij} is the amount of evapotranspiration in grid cell i ~~which~~ that precipitates in grid cell j and the diagonal element m_{ii} is the amount of evapotranspiration ~~which~~ that precipitates in the same grid cell (locally recycled moisture). The output of WAM-2layers can ~~transformed into a~~ be interpreted as the adjacency matrix of a directed and weighted complex network with self-interactions, where nodes of the network represent grid cells and links between nodes represent the direction and amount of moisture transported between them (Fig. 1).

2.2 Basic assumptions

In order to track moisture forward or backward from a given region Ω ~~which~~ that can be of any shape and scale (grid cell, basin, continent), we assume that the moisture composition within the surface reservoir and the atmosphere for each grid cell remains the same. This implies that, in each grid cell, the tagged fraction of precipitation is linearly proportional to the tagged fraction of evapotranspiration and the tagged fraction of transported moisture:

$$\frac{P_\Omega}{P}\frac{P_\Omega}{P} = \frac{E_\Omega}{E}\frac{E_\Omega}{E} = \frac{m_\Omega}{m}\frac{m_\Omega}{m}, \qquad (1)$$

where E is the total evapotranspiration, P is the total precipitation, m is the transported moisture towards or from another grid cell, P_Ω is the tagged fraction of precipitation, E_Ω is the tagged fraction of evapotranspiration and m_Ω is the tagged fraction of transported moisture towards or from another grid cell. We call "tagged fraction" the share of the moisture originating from Ω in the case of a backward tracking and the share of moisture precipitating over Ω in the case of a forward tracking.

This assumption is valid under two conditions: (1), evapotranspiration follows directly after the precipitation event or (2), the fraction of tagged moisture in the surface reservoir and the atmosphere can be assumed to be temporally constant (i.e., in steady state) (Goessling and Reick, 2013). The first condition is usually fulfilled during interception and fast transpiration, which are important components of the total evapotranspiration, particularly in warm climates and for shallow rooted plants (Savenije, 2004). However, in seasonal forests with deep rooted trees, the moisture ~~which~~ that is evaporated during the dry season can be hold back for ~~one or~~ several months (Savenije, 2004). By analyzing a seasonally static moisture recycling network, we account for this limitation. The second condition is fulfilled if the soil water at the beginning has the same composition (in term of tagged fraction) as the atmospheric moisture at the end of the season.

2.3 Moisture recycling ratio

~~In this section, we define measures to track moisture from a given region forward or backward in space. In the case of a forward tracking, the measures indicate the destination (precipitative sink) of evapotranspiration from~~ Common measures to quantify the strength of the ~~region. In the case of a backward tracking, they indicate the origin (evaporative source) of precipitation over the region. We first consider direct moisture recycling only (Sect. ??) . We then track moisture further forward or backward in space through cascading moisture recycling (Sect. ??). Considered together, the direct and cascading moisture recycling ratios provide a full picture of the sources and sinks of moisture from a region of interest.~~ direct link between precipitation in a specific location and evapotranspiration from another location are the moisture recycling ratios (called hereafter DMR ratio) (Eltahir and Bras, 1994; Trenberth, 1999; Bosilovich and Chern, 2006; D The DMR ratios are only used to investigate DMR. Here, we further develop these measures in order to take CMR into account.

~~2.3.1 Direct moisture recycling ratios~~

2.3.1 DMR (direct moisture recycling) ratios

~~We define the~~ Two kinds of DMR ratios have been developed in a previous study van der Ent et al. (2010) : the direct precipitation recycling ratio and the direct evapotranspiration recycling ratio. The direct precipitation recycling ratio ρ_Ω has been defined as the fraction of precipitation ~~in each grid cell i that comes directly from evapotranspiration from Ω:~~

$$\rho_{\Omega,i} = \frac{P_{i\leftarrow\Omega}}{P_i},$$

~~where $P_{i\leftarrow\Omega}$ is the amount of precipitation in i that is~~ that is originating from evapotranspiration from a defined region Ω ~~through direct moisture recycling and P_i is the total precipitation in i~~ with no intervening re-evaporation cycle (see also Appendix C1.1). ~~ρ_Ω quantifies the dependency on direct moisture recycling from Ω for local rainfall. High values indicate locations which receive moisture (direct precipitative sink) from Ω.~~ We note that ρ_Ω averaged over all grid cells in Ω gives the regional recycling ratio, i.e, the fraction of precipitation that is regionally recycled (Eltahir and Bras, 1994; Burde et al., 2006; van der Ent and Savenije, 2011). High values of ρ_Ω indicate the “direct sink regions” of evapotranspiration from Ω, i.e., the regions that are dependent on evapotranspiration coming directly (i.e., through DMR) from Ω for local precipitation. A direct sink region receives moisture from Ω at first and might distribute it further downwind (Fig. 2).

~~We also define~~ Similarly, the direct evapotranspiration recycling ratio ε_Ω has been defined as the fraction of evapotranspiration ~~in each grid cell i that contributes directly to precipitation over~~ that falls as precipitation over a defined region Ω ~~:~~

$$\varepsilon_{\Omega,i} = \frac{E_{i\to\Omega}}{E_i},$$

~~where $E_{i\to\Omega}$ is the amount of evapotranspiration in i that contributes to precipitation over Ω through direct moisture recycling and E_i the total evapotranspiration in i~~ with no intervening re-evaporation cycle (see also Appendix C1.1). ~~ε_Ω quantifies the local contribution to~~ High values indicate the “direct source regions” of precipitation over Ω~~through direct moisture recycling. High values indicate locations which distribute moisture (direct evaporative source)over~~ , i.e., the regions that contribute directly (i.e., through DMR) to rainfall over Ω. A direct source region distributes moisture towards Ω, which might be originating from further up-wind regions (Fig. 2).

If Ω is the entire South American continent, ε_Ω becomes the continental evapotranspiration recycling ratio (ε_c) and ρ_Ω the continental precipitation recycling ratios (ρ_c) as defined in van der Ent et al. (2010). Considered together, ε_c and ρ_c indicate respectively sources and sinks of continental moisture. In this study we neglect possible contributions of moisture in South America from and to other continents, since these contributions to the overall moisture budget are small (van der Ent et al., 2010, Table 2).

~~To study the direct moisture recycling between the Amazon basin and the La Plata basin (defined by the red boundaries in Fig. 8), we use ρ_Ω with Ω being all grid cells covering the Amazon basin (ρ_{Am}) and ε_Ω with Ω being all grid cells covering the La Plata basin ($\varepsilon_{\mathrm{Pl}}$). While ρ_{Am} is useful to track moisture from the Amazon basin as a whole, $\varepsilon_{\mathrm{Pl}}$ provides information regarding the spatial heterogeneity of the contribution inside the Amazon basin.~~

2.3.2 CMR (cascading moisture recycling) ratios

~~The direct recycling ratios underestimate the strength of the relationship, in term of moisture recycling, between two specific locations. In fact, moisture can be exchanged not only through direct moisture recycling, but also through cascading moisture recycling.~~

~~2.3.3 Cascading moisture recycling ratios~~

We define the cascading precipitation recycling ratio $\rho^{\mathrm{casc}}_\Omega$ as the fraction of precipitation ~~in each grid cell i~~ that is originating from evapotranspiration from Ω ~~through cascading moisture recycling:~~

$$\rho^{\mathrm{casc}}_{\Omega,i} = \frac{P^{\mathrm{casc}}_{i\leftarrow\Omega}}{P_i},$$

~~where $P^{\mathrm{casc}}_{i\leftarrow\Omega}$ is the amount of precipitation in i that is originating from~~ and that has run through at least one re-evaporation cycle on the way (see also Appendix C1.1). High values indicate the “cascading sink regions” of evapotranspiration from Ω~~through cascading moisture recycling.$\rho^{\mathrm{casc}}_\Omega$ quantifies the dependency on cascading moisture recycling~~ , i.e., the regions that are dependent on evapotranspiration coming indirectly (i.e., through CMR) from Ω for local ~~rainfall. High values indicate the final destination of moisture~~ precipitation. A cascading sink region is the last destination of evapotranspiration from Ω ~~after one ore more re-evaporation cycles (indirect precipitative sink~~before it is advected over the ocean (Fig. 2).

We also define the ~~cascading evapotranspiration recycling ratio~~ cascading evaporation recycling ratio $\varepsilon^{\mathrm{casc}}_\Omega$ as the fraction of evapotranspiration ~~in each grid cell i which contributes to~~ that falls as precipitation over Ω ~~through cascading moisture recycling as:~~

$$\varepsilon^{\mathrm{casc}}_{\Omega,i} = \frac{E^{\mathrm{casc}}_{i\to\Omega}}{E_i},$$

where $E^{\mathrm{casc}}_{i\to\Omega}$ is the amount of evapotranspiration in i that contributes to after at least one re-evaporation cycle on the way (see also Appendix C1.1). High values indicate the "cascading source regions" of precipitation over Ωthrough cascading moisture recycling.$\varepsilon^{\mathrm{casc}}_{\Omega}$ quantifies the local contribution to precipitation , i.e., the regions that contribute indirectly (i.e., through CMR) to rainfall over Ωthrough cascading moisture recycling. High values indicate locations where moisture initially originated (indirect evaporative source) before it is distributed over Ω. A cascading source region is the origin of moisture that is distributed from somewhere else towards Ω (Fig. 2).

The moisture inflow (resp. outflow) that crosses the border of Ω may be counted several times as it is involved in several pathways of cascading moisture recyclingCMR. To avoid this, we only track moisture that crosses the border of Ω. This implies that we consider re-evaporation cycles outside Ω only (Fig. 2, see also Appendix C1.1).

2.3.3 Application to the Amazon basin and the La Plata basin

To study the cascading moisture recycling between the Amazon basin and the La Plata basin (defined by the red boundaries in Fig. 8), we use ρ_Ω and $\rho^{\mathrm{casc}}_\Omega$ with Ω being all grid cells covering the Amazon basin (ρ_{Am} and $\rho^{\mathrm{casc}}_{\mathrm{Am}}$) respectively) and ε_Ω and $\varepsilon^{\mathrm{casc}}_\Omega$ with Ω being all grid cells covering the La Plata basin ($\varepsilon_{\mathrm{Pl}}$ and $\varepsilon^{\mathrm{casc}}_{\mathrm{Pl}}$). While respectively). High values of ρ_{Am} and $\rho^{\mathrm{casc}}_{\mathrm{Am}}$ considers cascading recycling of moisture originating indicate together the sink regions of evapotranspiration from the Amazon basin (see Fig. 2a), and high values of $\varepsilon_{\mathrm{Pl}}$ and $\varepsilon^{\mathrm{casc}}_{\mathrm{Pl}}$ provides information regarding the importance of cascading recycling of moisture that has final destination highlight source regions of precipitation over the La Plata basin (see Fig. 2bFig. 2).

Considered together, the direct and cascading recycling ratios DMR ratios and the CMR ratios ratios provide a full picture of the origin and destination of moisture from a given region. High values of ρ_{Am} and source - sink relationship between the Amazon basin and the La Plata basin that is needed to estimate the effects of land-use change for downwind precipitation patterns. $\rho^{\mathrm{casc}}_{\mathrm{Am}}$ indicate together the precipitative sink region of and ρ_{Am} quantify the local dependency on incoming moisture from the Amazon basin and high values of (with and without re-evaporation cycles) and therefore the local vulnerability to deforestation in the Amazonian rainforests. Considering ρ_{Am} and $\rho^{\mathrm{casc}}_{\mathrm{Am}}$ highlight evaporative source regions of precipitation only would lead to underestimation of this dependency. On the other hand, $\varepsilon_{\mathrm{Pl}}$ and $\varepsilon^{\mathrm{casc}}_{\mathrm{Pl}}$ provide information on the upwind regions that contribute to rainfall over the La Plata basin and, consequently, that should be preserved from intensive land-use change in order to sustain water availability in the La Plata basin.

2.4 Quantifying CMR (cascading moisture recycling)

In this section, we are interested in To quantify the importance of cascading moisture recycling CMR for the total moisture inflow (precipitation, P) and outflow (evapotranspiration). To quantify this, we forbid , E), we cut-off all re-evaporation of moisture originating from the continent and we estimate the resulting reduction in total moisture inflow (ΔP_{c}) and outflow (ΔE_{c}) (see Appendix C1). $\Delta P_{\mathrm{c}}/P$ is the fraction of precipitation that comes from cascading moisture recycling on re-evaporation of moisture originating from the continent, i.e., that has been evaporated at least twice in at least two locations on the continent. It quantifies the dependency on cascading moisture recycling $\Delta P_{\mathrm{c}}/P$ quantifies the importance of CMR for local rainfall. $\Delta E_{\mathrm{c}}/E$ is the fraction of total evapotranspiration that is involved in cascading moisture recycling on the continent, i.e., that comes a re-evaporation of moisture originating from the continent and that further precipitates over the continent. It quantifies the contribution of a specific location to cascading moisture recycling. Regions which , i.e., that lies within CMR pathways. $\Delta E_{\mathrm{c}}/E$ quantifies the local contribution to CMR. High values of $\Delta E_{\mathrm{c}}/E$ indicate intermediary regions. Regions that have a larger $\Delta E_{\mathrm{c}}/E$ than the 80 percentile (corresponding to 0.27 during the wet season and 0.17 during the dry seasoncalculated for all seasonal values over the continent) are called "intermediaryregions"intermediary" regions in the following.

In addition, we are interested in the importance of cascading moisture recycling re-evaporation cycles that are occurring in the intermediary regions for the total moisture in- and outflow. We use the same approach as above. We forbid cut-off all re-evaporation in the intermediary region of moisture originating from the continent and we estimate the resulting reduction in total moisture inflow (ΔP_{m}) (see Appendix C1). $\Delta P_{\mathrm{m}}/P$ is the fraction of total moisture inflow that comes from cascading moisture recycling CMR in the intermediary region . It can be seen as the fraction of precipitation that comes from the continent and that has been re-evaporated (i.e., that has run through at least one re-evaporation cycle in the intermediary region). It quantifies the dependency on cascading moisture recycling CMR in the intermediary region for local rainfall.

2.5 Complex network analysis

We investigate important moisture recycling pathways using two measures from complex network analysis: clustering coefficient associated with Middleman motifs and betweenness centrality.

2.5.1 Clustering coefficient associated with Middleman motifs ($\tilde{C}$)

In complex network theory, motifs are defined as significant and recurring patterns of interconnections that occur in the network (Milo et al., 2002). Here, we are interested in a particular pattern of directed triangles: the Middleman motif (Fagiolo, 2007). In our study, a grid cell forms a Middleman motif if ~~is~~ it represents an intermediary on an alternative pathway to the direct transport of moisture between two other grid cells (Fig. 3).

The clustering coefficient is a measure from complex network analysis ~~which~~ that measures the tendency to form a particular motif (Fagiolo, 2007). Here, it reveals intermediary locations in ~~cascading moisture recycling~~ CMR pathways, as the alternative to the ~~direct recycling of moisture~~ DMR between sources and sinks. ~~We~~ To account for moisture fluxes along the network links, we compute the weighted version of the clustering coefficient associated with Middleman motifs ($\tilde{C}$) (Fagiolo, 2007; Zemp et al., 2014) for each grid cell as described in the Appendix C1.1.

A grid cell has a high $\tilde{C}$ if it forms a lot of Middleman motifs and if these motifs contribute largely to relative moisture transport. $\tilde{C}$ is equal to zero if the grid cell forms no Middleman motif at all.

It is worth to note that the Middleman motif considers three interconnected grid cells, which corresponds to ~~cascading moisture recycling~~ CMR pathways involving only one re-evaporation cycle. These pathways contribute usually most to moisture transport between two locations. In fact, the amount of moisture transported in a pathway typically decreases with the number of re-evaporation cycles involved in the pathway. This is in agreement with a previous study counting the number of re-evaporation cycles using a different methodology (Goessling and Reick, 2013) . Other motifs formed by three or more grid cells linked by moisture recycling exist (Zemp et al., 2014), but are not analyzed here.

2.5.2 Betweenness centrality (B)

~~The betweenness centrality (B)~~ aims to highlight nodes in the network with central position "to the degree that they stand between others and can therefore facilitate, impede or bias the transmission of messages" in the network (Freeman, 1977, p. 36). Here, we use it to reveal intermediary grid cells where ~~cascading moisture recycling~~ CMR pathways are channeled.

To compute it, we first identify for each pair of grid cells the moisture recycling pathways with the greatest throughput, called "optimal pathways~~"~~" (see Appendix C1.1). These pathways can include any number of re-evaporation cycles. As the optimal pathway is usually the direct one (without any re-evaporation cycle), we first had to modify the network such that the optimal pathways involve ~~cascading moisture recycling~~ re-evaporation cycles. To do so, we removed from the network all long-range moisture transport, i.e., occurring over distances larger than 15 geographical degrees. The choice of this threshold does not influence the results qualitatively ~~.~~ on a yearly basis (Fig. B4). During the dry season, removing long-range affects moisture inflow over the La Plata basin, therefore the results of the B will be interpreted with caution during this season.

Once optimal pathways are identified, we find intermediary grid cells that they have in common (see Appendix ~~??~~C1.2). A grid cell has a high B if many optimal pathways pass through it, i.e., moisture ~~often cascades~~ runs often through re-evaporation cycle in the grid cell, and has a B equal to 0 if none of these pathways pass through it, i.e., moisture never ~~cascades~~ runs through re-evaporation cycle in the grid cell.

~~2.5.3 Similarities and differences between the betweenness centrality and theMiddleman motif~~

2.6 Similarities and differences between the presented measures

We expect similar spatial patterns in the results of $\Delta E_c/E$ (fraction of evapotranspiration that lies within CMR pathways, see Sect. 2.4), the B (betweenness centrality, see Sect. 2.5.2) and the $\tilde{C}$ (clustering coefficient, Sect. 2.5.1). In fact, ~~both~~ all three measures reveal important intermediary grid cells in ~~cascading moisture recycling~~ CMR pathways. However, ~~these two~~ the three measures are based on different concepts and methods.

1. While ~~the~~ $\Delta E_c/E$ is calculated by inhibiting re-evaporation of moisture from continental origin, B is based on the ~~optimal pathways, the~~ notion of optimal pathways and $\tilde{C}$ relies on particular motifs formed by three connected grid cells.

2. An implication of (1) is that ~~the~~ $\Delta E_c/E$ quantifies the local contribution to CMR, $\tilde{C}$ refers to ~~cascading moisture recycling~~ CMR pathways as alternative to the direct transport of moisture between two locations ~~, while the~~ and B shows locations where ~~cascading moisture recycling~~ CMR pathways are channeled.

3. In the $\tilde{C}$, only ~~cascading moisture recycling~~ CMR pathways with one re-evaporation cycle are considered. ~~In the~~ Using $\Delta E_c/E$ and B, all number of cycles are possible in the pathways.

4. Moisture recycling pathways involving long-range transport are not considered in the calculation of the B.

For these reasons, ~~the~~ $\Delta E_c/E$, B and ~~the~~ $\tilde{C}$ are complementary measures. There are also some similarities between the calculation of the cascading precipitation recycling ratio and $\Delta P_c/P$, which are described in the appendix C0.2.

3 Results and discussion

3.1 Comparison of continental and regional moisture recycling ratios with other existing studies

The main continental source of precipitation in South America is the Amazon basin, with large heterogeneity in time and space (~~Fig. ??eand~~ Figs. 4e, 4j, 5e and 5j and Table 3). ~~The~~ 70 to 80 % of the evapotranspiration in the southern part of the Amazon basin ~~contributes 80to continental precipitation~~ falls as precipitation over the continent during the wet season but only 30 to 40 % during the dry season. As the evapotranspiration in the Amazon basin is high and varies little in space and time (~~Fig. ??band~~ Figs. 4b, 4g, 5b and 5g), this observation indicates that during the dry season, a high amount of moisture from the southern part of the Amazon basin is advected out of the continent. Using a Lagrangian particle dispersion model, Drumond et al. (2014) also found a maximum contribution of moisture from the Amazon basin to the ocean during this period.

The main sink regions of moisture originating from the continent are the western part of the Amazon basin during the dry season, the south-western part of the basin during the wet season and the La Plata basin especially during the wet season (~~Fig. ??dand iand~~ Figs. 4d, 4i, 5d and 5di and Table 3). In fact, in the La Plata basin, 42 to 45 % of the precipitation during the wet season and 35 % during the dry season evaporated from the continent. This difference between seasons is explained by a weaker transport of oceanic moisture associated with the subtropical Atlantic high and by an intensification of the South American Low-Level Jet (SALLJ) ~~which~~ that transports moisture in the meridional direction during this season (Marengo et al., 2004). The importance of continental moisture recycling in the La Plata basin during the wet season has been emphasized in ~~Drumond et al. (2008); Martinez et al. (2014)~~ previous studies (Drumond et al., 2008; Martinez et al., 2014). Despite this importance, we find that the ocean remains the main source of moisture ~~in~~ over the La Plata basin in agreement with previous studies (Drumond et al., 2008; Arraut and Satyamurty, 2009; Drumond et al., 2014). However, some other studies estimated a higher contribution of moisture from the continent to precipitation over the La Plata basin van der Ent et al. (2010); Keys et al. (2012); Martinez et al. (2014).

There are uncertainties in the moisture recycling ratios depending on the quality of the datasets used, the assumptions made in the methods and the boundaries used to define the domain (for example in Brubaker et al., 1993, the Amazon region is represented by a rectangle). Considering these uncertainties, the regional precipitation recycling ratio in the Amazon basin ~~(Table 3)~~ compares well with previous studies using other datasets and methodologies (See Table 2). The spatial patterns of continental moisture recycling ratios (~~Fig. ??d, i, e and~~ Figs. 4d, 4i, 4e, 4j, 5d, 5i, 5e and 5j) are slightly different from those found by (van der Ent et al., 2010, Figs. 3 and 4) due to the differences in the versions of the model (here we use WAM-2layers) and the datasets used. The continental precipitation recycling ratio in the Amazon basin reaching 27 to 30 % during the Southern Hemisphere summer is ~~compatible with the estimation~~ slightly below estimates by the estimate of 36.4 % found by Bosilovich and Chern (2006). The maps of ~~direct recycling~~ DMR ratios (Fig. 8c, and g, a and e) are in good agreement with ~~maps of~~ regional recycling ratio ~~presented~~ reported in previous studies (Eltahir and Bras, 1994, Figs. 4 and 6 and Burde et al., 2006, Figs. 2 and 8 and Dirmeyer et al., 2009 see http://www.iges.org/wcr/, Moisture Sources by Basin).

We note that our analysis period from 2001–2010 (for the input MOD) includes two major droughts in the Amazon basin (Marengo et al., 2008; Lewis et al., 2011). Because the land–atmosphere coupling on the hydrological cycles increases during drought years (Bagley et al., 2014), this might influence the output of the atmospheric moisture tracking model used in this study. Analyzing these periods separately is ongoing research.

3.2 Importance of CMR (cascading moisture recycling)

Continental moisture recycling is of crucial importance for South American precipitation patterns (~~Fig. ??~~Figs. 4 and 5). We now quantify this importance ~~and identify intermediary and sink regions of cascading moisture recycling~~(Figs. 6 and B1).

3.2.1 ~~The dependency on cascading moisture recycling~~

The share of cascading moisture on total moisture inflow is on average 9 – 10 % in the South American continent ~~. Regions which~~ (Table 3). Regions that are dependent on ~~cascading moisture recycling~~ CMR for local rainfall (~~Fig~~Figs. 6a~~and~~, 6c, B1a and B1c) are also dominant sinks of moisture from the continent (~~Fig. ??dand~~ Figs. 4d, 4i, 5d and 5i).

We note that ~~cascading moisture~~ CMR contributes more to the precipitation over the Amazon basin during the dry season (8 – 11 % on average, up to 25 % in the western part) compared to the wet season (6 – 8 % on average)~~(Table 3). The inverse situation is observed in the La Plata basin, where on average 14of the precipitation~~. This is explained by the fact that during the dry season~~and 17during the wet season comes from cascading moisture recycling (Table 3). In Sect. 3.4, we reveal the evaporative source of cascading moisture which precipitates over the La Plata basin and we understand this seasonal variability.~~

The share of cascading moisture on total moisture inflow reaches up to 50in the eastern side of the central Andes (Fig, moisture is mainly transported from the eastern to the western part of the Amazon basin (Figs. 4 and (Figs. 5). Our results show that during the dry season, this moisture transport involves re-evaporation cycles in the central part of the basin (blue boundaries in Figs. 6a and c), one of the most vulnerable biodiversity hotspots on Earth (Myers et al., 2000) . However, this latter observation should be considered with caution due to the imbalance of the water cycle in this area which might lead to an over-estimation of the regional recycling process and thus an over-estimation of the importance of cascading moisture recycling. b and B1d). In fact, 15 – 23 % of the total evapotranspiration from the Amazon basin is involved in CMR during the dry season.

3.2.1 The contribution of intermediary regions to cascading moisture recycling

The contribution of evapotranspiration from During the wet season, CMR plays also an important role as 17 – 18 % of the total precipitation over the La Plata basin comes from CMR. The intermediary region where re-evaporation cycles are taking place is mainly the south-western part of the Amazon basin to cascading moisture recycling in the continent reaches up to 25during the dry seasonin the central part of the Amazon basin and (blue boundaries in Figs. 6d and B1d). In this intermediary region, up to 35 % of the total evapotranspiration is involved in CMR during the wet season. We note that the shape of the intermediary regions varies slightly among the two datasets during the wet seasonin its southwestern part (Fig. 6b and d). These regions are important intermediaries in cascading moisture recycling pathways. , probably explained by the differences in evapotranspiration patterns (Figs. 4g and 5g).

In order to quantify the importance of these intermediary regions for regional the intermediary region for rainfall over the La Plata basin, we quantify the share of the moisture inflow in the La Plata basin that has cascaded in these run through re-evaporation cycles in the intermediary regions. This share is 8 – 10 % during the wet season and 3 – 4 % during the dry season. These estimations represent almost about half of the share of total moisture inflow that has cascaded in the entire continent over the La Plata basin that comes from CMR during the wet season and one third during the dry season (Table 3). These results mean that the south-western part of the Amazon basin is an important intermediary intermediary regions are important for cascading moisture transported towards the La Plata basin during the wet season. In Sect. 3.4, we reveal the direct and cascading sources of precipitation over the La Plata basin and we understand the seasonal variability.

The share of cascading moisture on the total moisture inflow reaches up to 35 – 50 % in the eastern side of the central Andes, one of the most vulnerable biodiversity hotspots on Earth (Myers et al., 2000) . However, this latter observation should be considered with caution due to the imbalance of the water cycle in this area, which might lead to an over-estimation of the regional recycling process and thus an over-estimation of the importance of cascading moisture recycling.

3.3 Complex network analysis

We have shown the importance of cascading moisture recycling CMR for South American moisture transport (see Fig. 6). Using the clustering coefficient associated with the Middleman motif ($\tilde{C}$), we are able to identify intermediary locations involved in cascading moisture recycling as alternative pathways pathways as alternative to the direct transport of moisture . These regions are the central part of the Amazon basin during the dry season and the south-western part of the Amazon basin during the wet season (Fig(Figs. 7aand , 7c, B2a and B2c). This is in good agreement with other measures quantifying the contribution of intermediary regions to cascading moisture recycling (FigThese regions coincide with the intermediary regions identified with a different method (blue boundaries in Figs. 6 b and d). and B1). These results mean the CMR pathways involving the intermediary regions are not the only pathways of moisture recycled from sources to sinks on the continent, but are complementing the direct transport of moisture over long distances.

The betweenness centrality ($\boldsymbol{B}$) reveals intermediary regions where cascading moisture recycling CMR pathways are channeled. Regions We note that regions with high $\boldsymbol{B}$ coincide with regions which with high $\tilde{C}$ during the wet season(Fig. 7c), but not as much during the dry season (FigFigs. 7 and B2). This non-overlap is probably explained by might be a results of the cutting of long-range moisture recycling pathways links from the network in the calculating of the B, as we have shown that the incoming moisture over the La Plata basin which affects moisture transport towards the subtropical South America during the dry season is mainly transported through direct (and thus long-range) moisture recycling pathways (Fig. 6a). .

During the wet season, cascading moisture recycling pathways are channeled in the south-western part of the Amazon basin and High values of $\boldsymbol{B}$ are found along a narrow band east of the subtropical Andes (FigFigs. 7d)and B2d), indicating that CMR pathways are channeled in this region. This observation may be explained by the combined effect of the acceleration of the South American Low Level Jet (Vera et al., 2006) and the high precipitation and evapotranspiration during the wet season (Fig. ??Figs. 4 and 5) allowing for an intensive local exchange of moisture between the vegetation and the atmosphere.

3.4 ~~Direct and cascading moisture~~ Moisture recycling from the Amazon basin to the La Plata basin

We have shown the importance of the Amazon basin as the dominant source of continental moisture and the La Plata basin as a central sink region (see ~~Fig. ??~~Figs. 4 and 5). In the following, we further investigate the ~~transport mechanism~~ importance of DMR and CMR for the transport of moisture between the two basins ~~.~~(Figs. 8 and B3).

In the La Plata basin, 18 – 23 % of the precipitation during the wet season and 21 – 25 % during the dry season originated from the Amazon basin ~~through direct moisture recycling (Fig. 8c and g and~~ with no intervening re-evaporation cycles (Table 3). This is ~~compatible~~ in good agreement with the yearly average estimates of 23 % found in Dirmeyer et al. (2009, see http://www.iges.org/wcr/) and 23.9 % found in Martinez et al. (2014). Considering ~~cascading moisture recycling once moisture has left the Amazon basin (Fig. 2a) increases the dependency from 23 to 29~~CMR increases the fraction of precipitation that comes from the Amazon basin by 6 % during the wet season (~~Fig~~Figs. 8h and B3h and Table 3). As mentioned above, this might be explained by the high evapotranspiration and precipitation allowing for an exchange of moisture on the way ~~, downwind of the Amazon basin,~~ and by the intensification of the SALLJ during this time of the year (Marengo et al., 2004). This result suggests that the impact of deforestation in the Amazonian forest on ~~the moisture supply in the~~ rainfall over the La Plata basin might be larger than expected if only direct transport of moisture between the two basins are considered.

The southern part of the Amazon basin is a direct source of precipitation over the La Plata basin ~~, with a direct contribution reaching 15of its evapotranspiration during the dry season and 35during the wet season~~ (Figs. 8a~~and 8e~~, 8e, B3a and B3e). This finding is in agreement with Martinez et al. (2014) ~~who found that the southern part of the basin is an quasi-permanent direct source of moisture for the La Plata basin~~and Keys et al. (2014) . However, if ~~cascading moisture recycling are considered(Fig. 2b)~~CMR is considered, the entire Amazon basin becomes ~~the~~ an evaporative source of moisture ~~over~~ for the La Plata basin during the wet season (~~Fig~~Figs. 8f ~~). The indirect contribution represents on average7~~and Figs. B3f). On average, 16 – 23 % of the total evapotranspiration ~~in~~ from the Amazon basin during the wet season ends as rainfall over the La Plata basin after at least one re-evaporation cycle (Table 3). This result means that during the wet season, the southern part of the Amazon basin is not only a direct source of moisture for the La Plata basin but also an intermediary region ~~where~~ that distributes moisture originating from the entire basin~~cascades on its way to the La Plata basin~~. This finding is in agreement with other measures showing intermediary ~~locations involved in cascading moisture recycling (see Sect. 3.2~~regions (Sects. 3.2 and 3.3).

3.5 Possible impact of ~~land cover~~ land-cover change in the intermediary regions

The southern part of the Amazon basin is a key region for moisture transport towards the La Plata basin. It is a source of moisture for precipitation over the La Plata basin all year round~~and it is in addition~~. In addition, it is an intermediary region ~~for cascading moisture recycling~~ in the indirect transport of moisture (through CMR) originating from the entire Amazon basin during the wet season (Sect. 3.4).

Land cover change in the southern part of the Amazon basin might weaken continental moisture recycling and might lead to an important decrease in the total precipitation locally and downwind. Among the affected regions, important impacts would be observed in particular in the south-western part of the Amazon basin ~~which~~ that has already a high probability to experience a critical transition from forest to savanna (Hirota et al., 2011) and in the La Plata basin ~~which~~ that is dependent on incoming rainfall for the agriculture (Rockström et al., 2009; Keys et al., 2012). In the eastern side of the central Andes, the impact of an upwind weakening of ~~cascading moisture recycling~~ CMR might be reduced since precipitation in this region is insured by orographic lifting (Figueroa and Nobre, 1990).

4 Conclusions

In this work, we investigated the exchange of moisture between the vegetation and the atmosphere on the way between sources and sinks of continental moisture in South America. We have introduced the concept of "cascading moisture recycling" (CMR) to refer to moisture recycling between two locations on the continent ~~which~~ that involve one or more re-evaporation cycles along the way. We have proposed measures to quantify the importance of ~~cascading moisture recycling and to reveal direct and indirect sources and sinks of moisture for a given region~~ CMR, to track moisture from a given region further backward or forward in space and to identify intermediary regions where re-evaporation cycles are taking place. We have used for the first time a complex network approach to ~~identify intermediary regions in the cascading~~ study moisture recycling pathways.

~~Using the~~ We have tracked moisture evaporating from each grid cell covering the South American continent until it precipitates or leaves the continent using the atmospheric moisture tracking model ~~WAM-2layers~~ Water Accounting Model-2layers (WAM-2 layers)~~forced by precipitation from TRMM and evapotranspiration from MODIS in South America, we~~. In order to reduce the uncertainty associated with the input data, we use two different sets of precipitation and evapotranspiration data from (1) observation-based and (2) merged synthesis products, together with reanalysis wind speeds and humidity data. We have shown that even if the amount of water transported through ~~cascading moisture~~

~~recycling~~ CMR pathways is typically smaller than the one transported directly in the atmosphere, the contribution by the ensemble of cascading pathways can~~not~~'t be neglected. In fact, 9 – 10 % of the total precipitation over South America and 17 – 18 % of the precipitation over the La Plata basin comes from ~~cascading moisture recycling.~~

CMR. The La Plata basin is highly dependent on moisture from the Amazon basin during both seasons, as 18 – 23 % of the total precipitation over the La Plata basin during the wet season and 21 – 25 % during the dry season comes directly from the Amazon basin. To these direct dependencies, 6 % of the precipitation during the wet season can be added if ~~cascading moisture recycling outside the Amazon basin~~ CMR are considered.

During the dry season, ~~the main source of continental moisture over the La Plata basin is the southern~~ CMR plays an important role for the moisture transport from the eastern to the western part of the Amazon basin. ~~During the wet season, the southern~~ Indeed, 16 – 23% of the total evapotranspiration in the Amazon basin is involved in CMR during the dry season.

The south-western part of the Amazon basin is an important direct source of incoming moisture over the La Plata basin all year round. However, during the wet season, it is not only a ~~source region but is~~ direct source but also an intermediary region ~~which~~ that distributes moisture from the entire Amazon basin into the La Plata basin. Land use change in these regions ~~, which include the arc of deforestation,~~ may weaken moisture recycling processes and may have stronger consequences for rainfed agriculture and natural ecosystems regionally and downwind as previously thought.

In addition, we showed that the eastern flank of the subtropical Andes – located in the pathway of the South American Low Level Jet – plays an important role in the continental moisture recycling as it channels many cascading pathways. This study offers new methods to improve our understanding of vegetation and atmosphere feedback on the water cycle needed in a context of land use and climate change.

Appendix A

~~Moisture recycling ratios~~Glossary

~~In these~~

- **Moisture recycling**: the process by which evapotranspiration in a specific location on the continent contributes to precipitation in another location on the continent.
- **Re-evaporation cycle**: evapotranspiration of precipitating moisture in the same location
- **Cascading moisture recycling (CMR)**: moisture recycling that involves at least one re-evaporation cycle on the way.
- **Direct moisture recycling (DMR)**: moisture recycling with no intervening re-evaporation cycle on the way.
- **Intermediary**: location where moisture runs through re-evaporation cycle on its way between two locations on the continent (only in the case of CMR).
- **Pathway of moisture recycling**: set of locations on land involved in moisture recycling. A DMR pathway includes only the starting (evapotranspiration) and the destination (precipitation) locations, while a CMR pathway includes the starting, the destination and the intermediary locations.
- **Optimal pathway**: the pathway of moisture recycling that contributes most to moisture transport between two locations. It can be a direct or a cascading pathway.
- **Direct source**: land surface that contributes directly (i.e., through DMR) to rainfall over a given region.
- **Cascading source**: land surface that contributes indirectly (i.e., through CMR) to rainfall over a given region.
- **Source**: land surface that contributes directly or indirectly to rainfall over given region.
- **Direct sink**: land surface that is dependent on evapotranspiration coming directly (i.e., through DMR) from a given region for local precipitation.
- **Cascading sink**: land surface that is dependent on evapotranspiration coming indirectly (i.e., through CMR) from a given region for local precipitation.
- **Sink**: land surface that is dependent on evapotranspiration coming directly or indirectly from a given region for local precipitation.

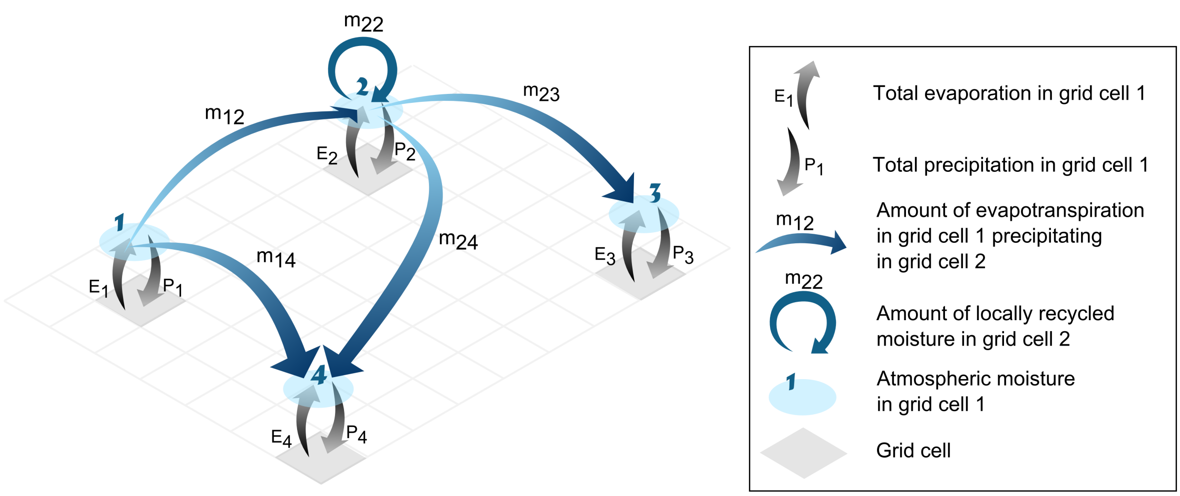


Fig. 1: Schematic representation of the moisture recycling network.

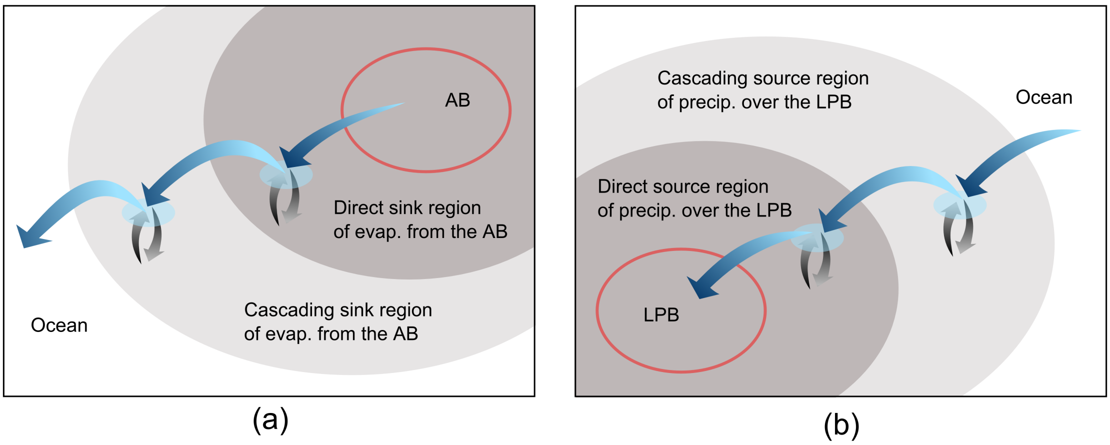


Fig. 2: Schematic representation of the sink and sources regions as quantified by the moisture recycling ratios. In addition to the direct source and sink regions identified using DMR ratios (dark gray), the cascading source and sink regions identified using CMR (light gray) are highlighted. Direct and cascading sink regions of evapotranspiration (evap.) from the Amazon basin (AB) **(a)** and direct and cascading source regions of precipitation (precip.) over the La Plata basin (LPB) **(b)**.

Table 1: Input datasets used for building moisture recycling networks. The first year of the period is omitted from the results because of model spin-up.

Input name	Evapotranspiration product	Precipitation product	Period
Input MOD	MODIS	TRMM	2000 – 2010
Input LFE	LandFlux-Eval	Average of CRU, GPCC, GPCP and CPC	1989 – 1995

Table 2: Overview of regional precipitation recycling ratio in the Amazon basin as found in many studies. Abbreviations: the European Centre for Medium-Range Weather Forecasts (ECMW); Geophysical Fluid Dynamics Laboratory Precipitation (GFDL); Climate Prediction Center Merged Analysis of Precipitation (CMAP); Initinal conditions (IC); October-November-December (OND); Data Assimilation Office (DAO); Integral Moisture Balance (IMB) model; NCEP – Department of Energy (DOE); World Monthly Surface Station Climatology distributed by the National Center for Atmospheric Research (NCAR).

Study	Method	Dataset	Period	Precipitation recycling ratio
Brubaker et al. (1993)	Atmospheric Bulk model	GFDL and NCAR	1963–1973	24
Eltahir and Bras (1994)	Atmospheric Bulk model	ECMWF reanalysis	1985–1990	25
		GFDL	1963–1973	35
Trenberth (1999)	Atmospheric Bulk model	CMAP and NCEP-NCAR reanalysis	1979–95	34
Bosilovich and Chern (2006)	AGCM with water vapor tracers	IC from the model	1948–1997	27.2 during OND
Burde et al. (2006)	Atmospheric Bulk model (general)	DAO	1981–1993	31
	Atmospheric Bulk model (Budyko model)			26
	Atmospheric Bulk model (IMB)			41
Dirmeyer et al. (2009)	Quasi-isentropic back-trajectory method	DOE reanalysis	1979–2003	10.8 for area 10^6 km^2
van der Ent et al. (2010)	Atmospheric moisture tracking model	ERA-Interim reanalysis	1999–2008	28
Zemp et al. (this study)	Atmospheric moisture tracking model	TRMM and MODIS	2001–2010	28
Zemp et al. (this study)	Atmospheric moisture tracking model	LandFluxEval and average of CRU,GPCC,GPCP and CPC	1990–1995	24

Appendix B

Supplementary figures

Results for the input LFE are presented in Figs. B1, B2 and B3. Fig. B4 shows the $\boldsymbol{B}$ (betweeness centrality) for different thresholds in the geographical distance of the links excluded from the network.

Appendix C

Supplementary description of the method

In all the measures the irregular sizes of the portion of the Earth's surface covered by the grid cells are taken into account as described in Zemp et al. (2014).

Table 3: Importance of direct moisture recycling (DMR) and cascading moisture recycling (CMR) for the total precipitation (precip.) and evapotranspiration (evap.) averaged for the La Plata basin (LPB), the Amazon basin (AB) and for the South American continent during the wet season (DJFM), the dry season (JJAS) and all year round calculated for the input MOD / LFE (in %).

Notation	Description	La Plata Basin			Amazon Basin			South America		
		wet	dry	year	wet	dry	year	wet	dry	year
ρ_c	Fraction of precip. originating from the continent	42 / 45	35 / 35	41 / 43	30 / 27	35 / 30	32 / 29	30 / 29	29 / 26	31 / 29
ρ_{Am}	Fraction of precip. originating from the AB through DMR	23 / 18	25 / 21	24 / 20	26 / 22	30 / 25	28 / 24	18 /15	21 / 18	20 / 17
ρ_{Am}^{casc}	Fraction of precip. originating from the AB through CMR	6 / 6	2 / 3	4 / 6	– / –	– /–	–/–	11 / 9	6 / 6	8 / 8
ε_c	Fraction of evap. that falls as precip. over the continent	43 / 40	16 / 16	35 / 32	77 / 68	45 / 41	65/57	56 / 29	31 / 28	47 / 42
ε_{Pl}	Fraction of evap. that falls as precip. over the LPB through DMR	32 / 28	12 / 11	26 / 22	16 / 11	7 / 6	11/10	15 / 13	7 / 6	12 / 11
ε_{Pl}^{casc}	Fraction of evap. that falls as precip. over the LPB through CMR	– / –	– / –	– / –	23 / 16	1 / 2	10 / 7	13 / 8	1 / 1	6 / 4
$\Delta P_c/P$	Fraction of precip. that comes from CMR on the continent	17 / 18	14 / 12	17 / 17	8 / 6	11 / 8	10 / 7	10 / 9	9 / 7	10 / 9
$\Delta P_m/P$	Fraction of precip. that comes from CMR in the intermediary region	8 / 10	4 / 3	6 / 7	4 / 3	6 / 4	5 /4	4 / 4	4 / 3	4 / 4
$\Delta E_c/E$	Fraction of evap. that lies within CMR pathways	11 / 13	9 / 8	9 /11	11 / 8	23 / 15	12 / 10	13 / 9	15 / 10	10 / 8

C1 ~~Direct moisture~~ Moisture recycling ~~ratio~~ratios

C1.1 DMR (direct moisture recycling) ratios

The ~~fraction of precipitation~~ ρ_Ω in grid cell j ~~that comes directly from Ω~~ is calculated as:

$$\rho_{\Omega,j} = \frac{\sum_{i\in\Omega} m_{ij}}{P_j}, \quad \text{(C1)}$$

where m_{ij} is the amount of ~~moisture which evaporates~~ evapotranspiration in i ~~and~~ that precipitates in j with no intervening re-evaporation cycle and P_j is the precipitation in j. The ~~fraction of evapotranspiration~~ ε_Ω in grid cell i ~~which precipitates directly in Ω~~ is calculated as:

$$\varepsilon_{\Omega,i} = \frac{\sum_{j\in\Omega} m_{ij}}{E_i}, \quad \text{(C2)}$$

where E_i is the evapotranspiration in i.

C2 ~~Cascading moisture recycling ratio~~

C1.1 CMR (cascading moisture recycling) ratios

To calculate the ~~cascading moisture recycling~~ CMR ratios as defined in Sect. 2.3.2, we calculate the individual contributions of ~~cascading moisture recycling~~ CMR pathways

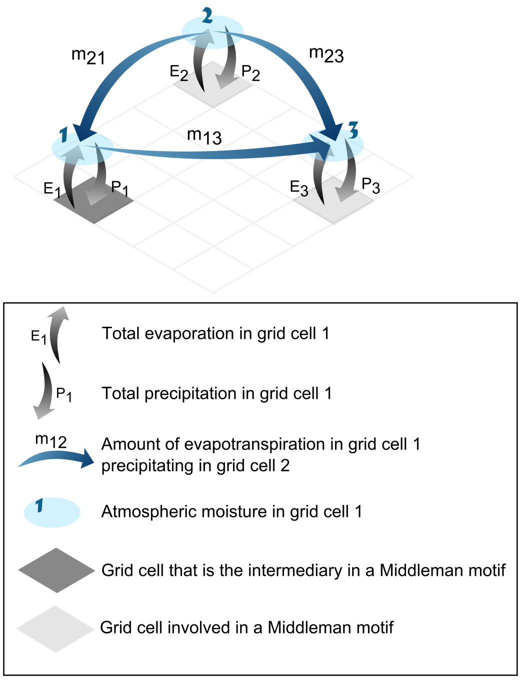


Fig. 3: Schematic representation of the Middleman motif from the perspective of grid cell 1. The grid cell 1 receives and distributes moisture from and to grid cells 2 and 3, which also exchange moisture such that there is no cyclic relation. The exchange of moisture between 2 and 3 uses two alternative pathways: the direct one (m_{23}) and the cascading pathway ($m_{21}m_{13}$). The grid cell 1 is an intermediary on an alternative pathway to the direct transport of moisture between 2 and 3.

consisting of k re-evaporation cycles ($k \in \{1,\ldots,n\}$), which add up to the total ~~cascading moisture recycling~~ CMR contribution. We chose a maximum number of cycles $n = 100$, while the contribution of pathways with number of cycles larger than 3 are close to zero. ~~If we track moisture forward in space, we have to take into account that moisture is lost as runoff on the way during the cascading recycling. This is not the case for moisture backward tracking in space because we quantify the remaining amount of moisture that actually arrives at destination.~~

C1.2 ~~Cascading precipitation recycling ratio~~

The fraction of precipitation in grid cell j that comes from Ω through ~~cascading moisture recycling involving~~ CMR involving only one re-evaporation cycle is:

$$\rho^{(1)}_{\Omega,j} = \frac{\sum_{i\notin\Omega} m_{ji}\cdot\rho_{\Omega,i}}{P_j}, \tag{C3}$$

where ρ_{Ω_j} is the ~~fraction of precipitation in j that comes directly from Ω~~ direct precipitation recycling ratio (Sect. C1.1). Following the same principle as in Eq. (C3), the fraction of precipitation in j that comes from Ω through ~~cascading moisture recycling~~ CMR involving n re-evaporation cycles is:

$$\rho^{(n)}_{\Omega,j} = \frac{\sum_{i\notin\Omega} m_{ij}\cdot\rho^{(n-1)}_{\Omega,i}}{P_j}, \tag{C4}$$

where $\rho^{(n-1)}_{\Omega,i}$ is the fraction of precipitation in i that comes from Ω through ~~cascading moisture recycling~~ CMR involving $n-1$ re-evaporation cycles. ~~The total fraction of precipitation in j that comes from Ω through cascading moisture recycling~~ $\rho^{\text{casc}}_{\Omega}$ is the sum of all individual contributions of ~~cascading recycling~~the CMR pathways:

$$\rho^{\text{casc}}_{\Omega,j} = \rho^{(1)}_{\Omega,j} + \ldots + \rho^{(n)}_{\Omega,j}. \tag{C5}$$

C1.2 ~~Cascading evapotranspiration recycling ratio~~

The fraction of evapotranspiration in grid cell i that ~~contributes to~~ falls as precipitation over Ω ~~through cascading moisture recycling involving~~ after only one re-evaporation cycle is:

$$\varepsilon^{(1)}_{\Omega,i} = \frac{\sum_{j\notin\Omega} m_{ij}\cdot\varepsilon_{\Omega,j}}{E_i}, \tag{C6}$$

$$\varepsilon^{(1)}_{\Omega,i} = \frac{\sum_{j\notin\Omega} m_{ij}\cdot\varepsilon_{\Omega,j}\cdot\alpha_j}{E_i}, \tag{C7}$$

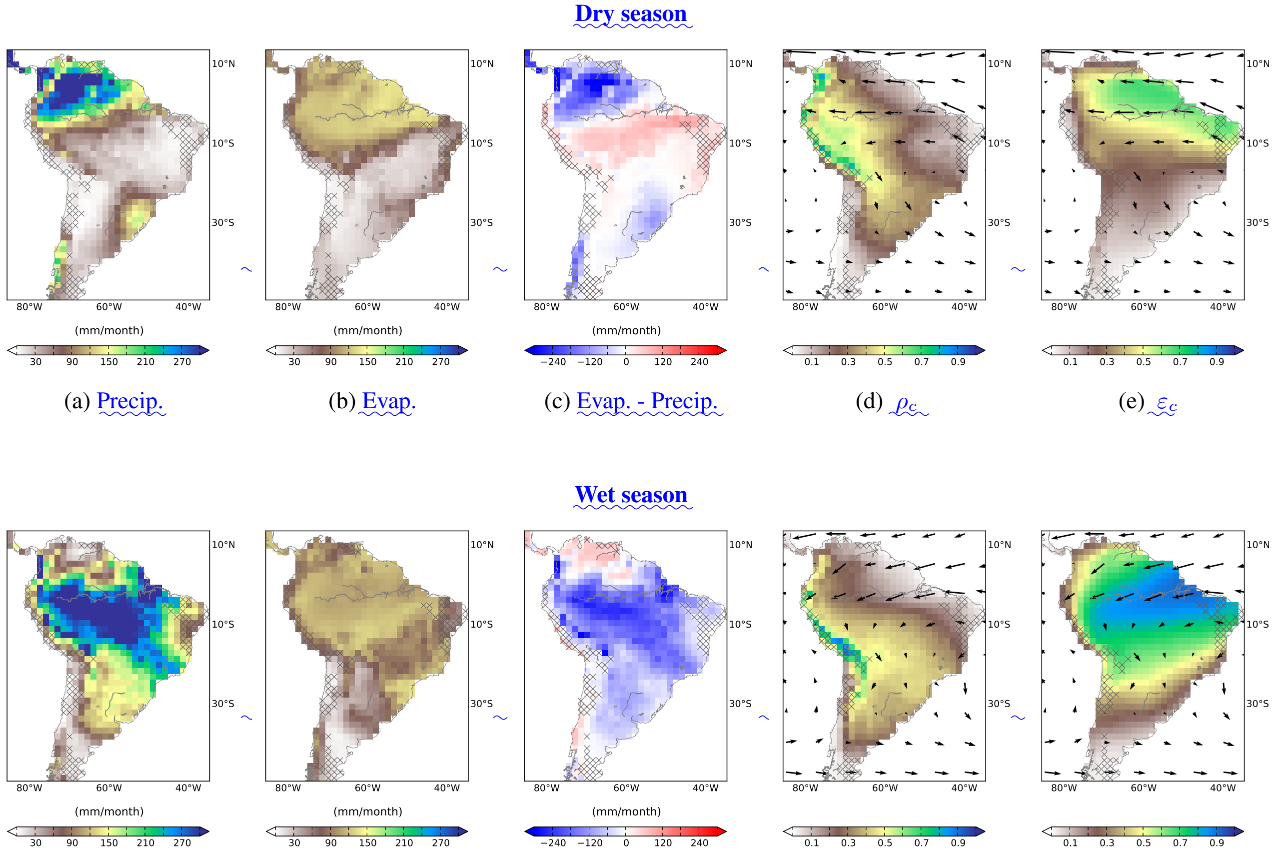
where $\varepsilon_{\Omega,j}$ is the ~~fraction of evapotranspiration in j which precipitates directly over Ω~~ direct evapotranspiration recycling ratio (Sect. C1.1)~~and $\alpha_j = E_j/P_j$~~. Similarly, the fraction of evapotranspiration in i that ~~precipitates~~ falls as precipitation over Ω ~~through cascading moisture recycling involving~~ after n re-evaporation cycles is:

$$\varepsilon^{(n)}_{\Omega,i} = \frac{\sum_{j\notin\Omega} m_{ij}\cdot\varepsilon^{(n-1)}_{\Omega,j}}{E_i}, \tag{C8}$$

$$\varepsilon^{(n)}_{\Omega,i} = \frac{\sum_{j\notin\Omega} m_{ij}\cdot\varepsilon^{(n-1)}_{\Omega,j}\cdot\alpha_j}{E_i}, \tag{C9}$$

where $\varepsilon^{(n-1)}_{\Omega,j}$ is the fraction of evapotranspiration in j that precipitates over Ω ~~through cascading moisture recycling involving~~ after $n-1$ re-evaporation cycles. The ~~total fraction of evapotranspiration in i that precipitates over Ω through cascading moisture recycling is the sum of the individual contribution of cascading recycling:~~ $\varepsilon^{\text{casc}}_{\Omega}$ is the sum of the individual contribution of CMR pathways:

$$\varepsilon^{\text{casc}}_{\Omega,i} = \varepsilon^{(1)}_{\Omega,i} + \ldots + \varepsilon^{(n)}_{\Omega,i} \tag{C10}$$



(a) Precip. (b) Evap. (c) Evap. - Precip. (d) ρ_c (e) ε_c

(f) Precip. (g) Evap. (h) Evap. - Precip. (i) ρ_c (j) ε_c

Fig. 4: WAM-2layers input and output as calculated for the period 2001 – 2010 for MODIS and TRMM (input MOD, see Table 1): long term seasonal mean of precipitation **(a, f)**, evapotranspiration **(b, g)**, precipitation – evapotranspiration **(c, h)**, continental precipitation recycling ratio ρ_c **(d, i)** and continental evapotranspiration recycling ratio ε_c **(e, j)** indicating respective sinks and sources of continental moisture. Here and in the following figures, the vectors indicate the horizontal moisture flux field (in m^3 of moisture $\times\, m^{-2} \times$ month^{-1}) and the hatches represent grid cells where annual mean evapotranspiration exceeds mean annual precipitation. Results are given for the dry season (JJAS) (upper row) and the wet season (DJFM) (lower row).

Appendix D

~~Quantifying cascading moisture recycling~~

C0.2 Robustness of the CMR (cascading moisture recycling) ratios

In order to test the robustness of the cascading precipitation recycling ratios, we have computed the steps explained in Sect. A1 and A2.1 with Ω being the ocean. Thus, ρ_o is the fraction of precipitation that comes from the ocean without any re-evaporation cycle on the way and $\rho_o^{(k)}$ is the fraction of precipitation that comes from the ocean with k re-evaporation cycle(s) on the way ($k = 1,...n$). We confirm that:

- The sum $\rho_o + \rho_o^{(1)} + \rho_o^{(2)} + ... + \rho_o^{(n)}$ is equal to 1. This is easy to interpret as all the precipitation in a location must always have been come from the ocean (either directly or after a certain number of re-evaporation cycles).
- The sum $\rho_o^{(1)} + \rho_o^{(2)} + ... + \rho_o^{(n)}$ represents the fraction of precipitation that comes from the ocean with at least 1 re-evaporation cycle. It is equal to the continental recycling ratio ρ_c (see Sect. 2.3.1 and van der Ent et al. (2010)).
- The sum $\rho_o^{(2)} + ... + \rho_o^{(n)}$ is the fraction of precipitation that comes from the ocean with at least 2 re-evaporation cycles. It is equal to $\Delta P/P$, introduced as the fraction precipitation that has been evaporated at least twice on the continent (see Sect. 2.4).

We obtained thus the same results using different metrics. We can't test the evaporation recycling ratio the same way

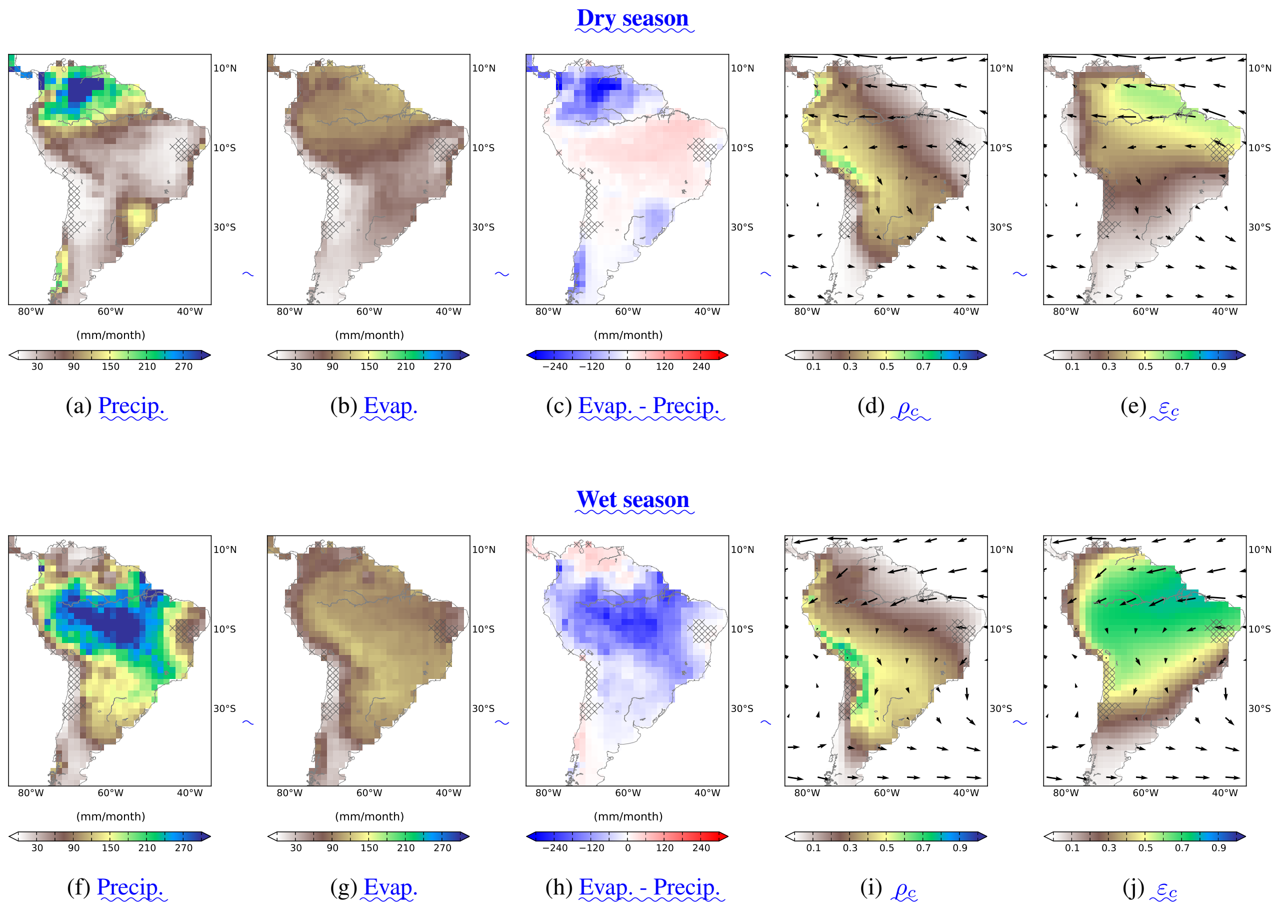


Fig. 5: Same as Fig. 4 for the period 1990–1995 as calculated from LandFluxEval and an average of four observation-based precipitation products (input LFE, see Table 1).

because $\Delta E/E$ quantifies the fraction of evapotranspiration that is involved in cascading moisture recycling (i.e., that comes from the continent and precipitates further over the continent) while $\epsilon_o^{(2)}+...+\epsilon_o^{(n)}$ would be the fraction of evapotranspiration that runs through at least 2 re-evaporation cycles before precipitating over the ocean. This is also the reason why the two methodologies are needed even if they lead to the same results for the previous mentioned case.

C1 Quantifying CMR (cascading moisture recycling)

To quantify the contribution of ~~cascading moisture recycling~~ CMR to total moisture in- and outflow, we ~~remove the~~ cut-off all re-evaporation of moisture from continental origin. By doing so, we inhibit all cascading recycling of moisture from continental origin in the network (see Fig. B1). To achieve this, we derive for each grid cell the evaporation of moisture from oceanic origin (i.e., that has been last evaporated over the ocean) as in Eq. (1):

$$E_{i\leftarrow \text{ocean}} = \frac{E_i}{P_i} \cdot P_{i\leftarrow \text{ocean}}, \tag{C1}$$

where $P_{i\leftarrow \text{ocean}}$ is the precipitation from oceanic origin in i ($P_{j\leftarrow \text{ocean}} = P_j - P_{j\leftarrow \text{continent}}$ and $P_{j\leftarrow \text{continent}} = \sum_{i\in \text{continent}} m_{ij}$.). Using the same assumption, we get the moisture transport between each pair of grid cells i and j that results from evaporation of moisture from oceanic origin only:

$$m_{ij\leftarrow \text{ocean}} = \frac{m_{ij}}{E_i} \cdot E_{i\leftarrow \text{ocean}}, \tag{C2}$$

At this stage, $m_{ij\leftarrow \text{ocean}}$ can be interpreted as the evapotranspiration in i ~~which~~ that precipitates in j and ~~which~~ that has been evaporated from the ocean before that ($m_{ij\leftarrow \text{ocean}} < m_{ij}$).

In a second step, we derive the corresponding moisture in- and outflow from or towards a given region Ω for each grid cell:

$$P_{j\leftarrow \Omega,o} = \sum_{i\in\Omega} m_{ij\leftarrow \text{ocean}} \tag{C3a}$$

$$E_{i\rightarrow \Omega,o} = \sum_{j\in\Omega} m_{ij\leftarrow \text{ocean}}. \tag{C3b}$$

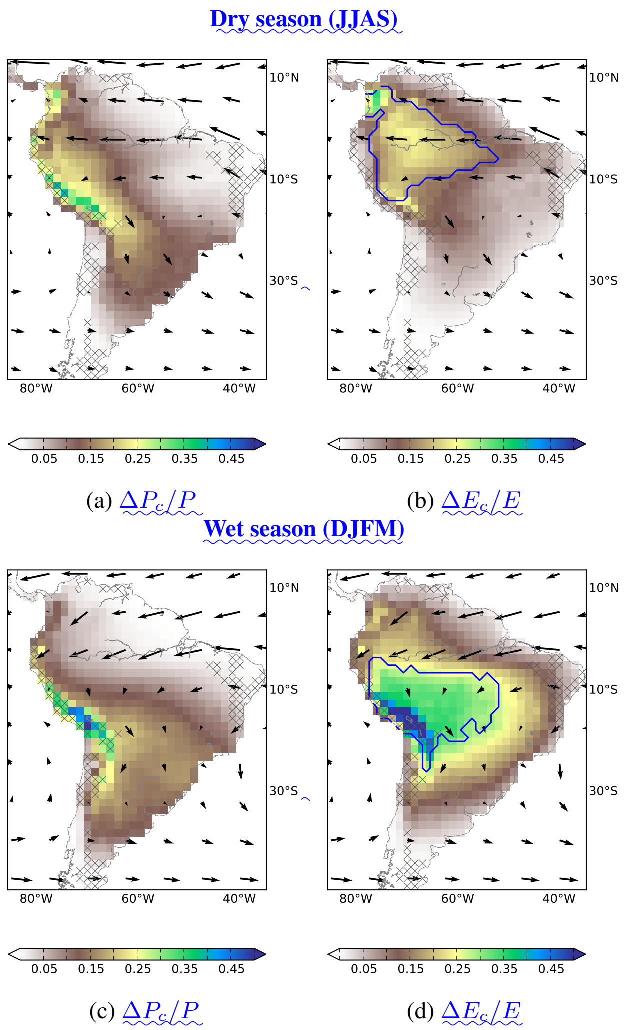


Fig. 6: Fraction of total precipitation originating from CMR ($\Delta P_c/P$) **(a, c)** and fraction of total evapotranspiration that lies within CMR pathways ($\Delta E_c/E$) **(b, d)**. While high values of $\Delta P_c/P$ indicate regions that are dependent on CMR for local rainfall, high values of $\Delta E_c/E$ indicate regions that contribute to CMR. The blue boundaries define the intermediary regions ($\Delta E_c/E > 80\%il$ calculated for all seasonal values over the continent). Results are obtained using the input MOD (see Table 1) and are given for the dry season (JJAS) (upper row) and the wet season (DJFM) (lower row).

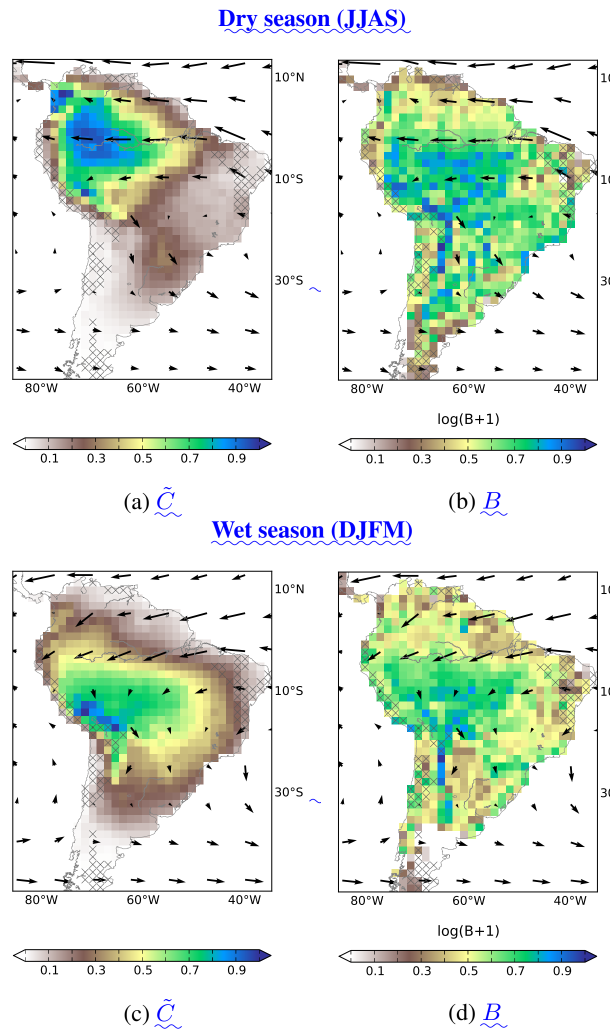


Fig. 7: Complex network analysis. Clustering coefficient $\tilde{C}$ associated with the motif Middleman **(a, c)** and betweenness centrality B **(b, d)**. While high values of $\tilde{C}$ indicate intermediary locations where CMR allows for alternative pathways to the direct transport of moisture, high values of B indicate regions where pathways of CMR are channeled. Results are obtained using the input MOD (see Table 1) and are given for the dry season (JJAS) (upper row) and the wet season (DJFM) (lower row).

$P_{j\leftarrow\Omega,o}$ can be interpreted as the precipitation in j originating from the re-evaporation of oceanic moisture in Ω. Similarly, $E_{i\rightarrow\Omega,o}$ can be seen as the evapotranspiration of oceanic moisture in i ~~which~~ that precipitates over Ω.

Thus, are able to derive the corresponding reduction in total moisture inflow towards Ω or outflow from Ω:

$$\Delta P_{j\leftarrow\Omega} = P_{j\leftarrow\Omega} - P_{j\leftarrow\Omega,o} \tag{C4a}$$

$$\Delta E_{i\rightarrow\Omega} = E_{i\rightarrow\Omega} - E_{i\rightarrow\Omega,o}, \tag{C4b}$$

where $P_{j\leftarrow\Omega} = \sum_{i\in\Omega} m_{ij}$ is the total precipitation in j originating from Ω and $E_{j\rightarrow\Omega} = \sum_{j\in\Omega} m_{ij}$ is the total evapotranspiration in i ~~which~~ that contributes to precipitation over Ω. Thus, $\Delta P_{j\leftarrow\Omega}$ is the precipitation in j originating from the re-evaporation of continental moisture in Ω and $\Delta E_{i\rightarrow\Omega}$ is the re-evaporation of continental moisture in i ~~which~~ that precipitates over Ω.

If Ω is the entire South American continent (resp. the intermediary region), $\Delta P_{j\leftarrow\Omega}$ becomes $\boldsymbol{\Delta P_c}$ (resp. $\boldsymbol{\Delta P_m}$) and $\Delta E_{i\rightarrow\Omega}$ becomes $\boldsymbol{\Delta E_c}$ (resp. $\boldsymbol{\Delta E_m}$) as defined in Sect. 2.4.

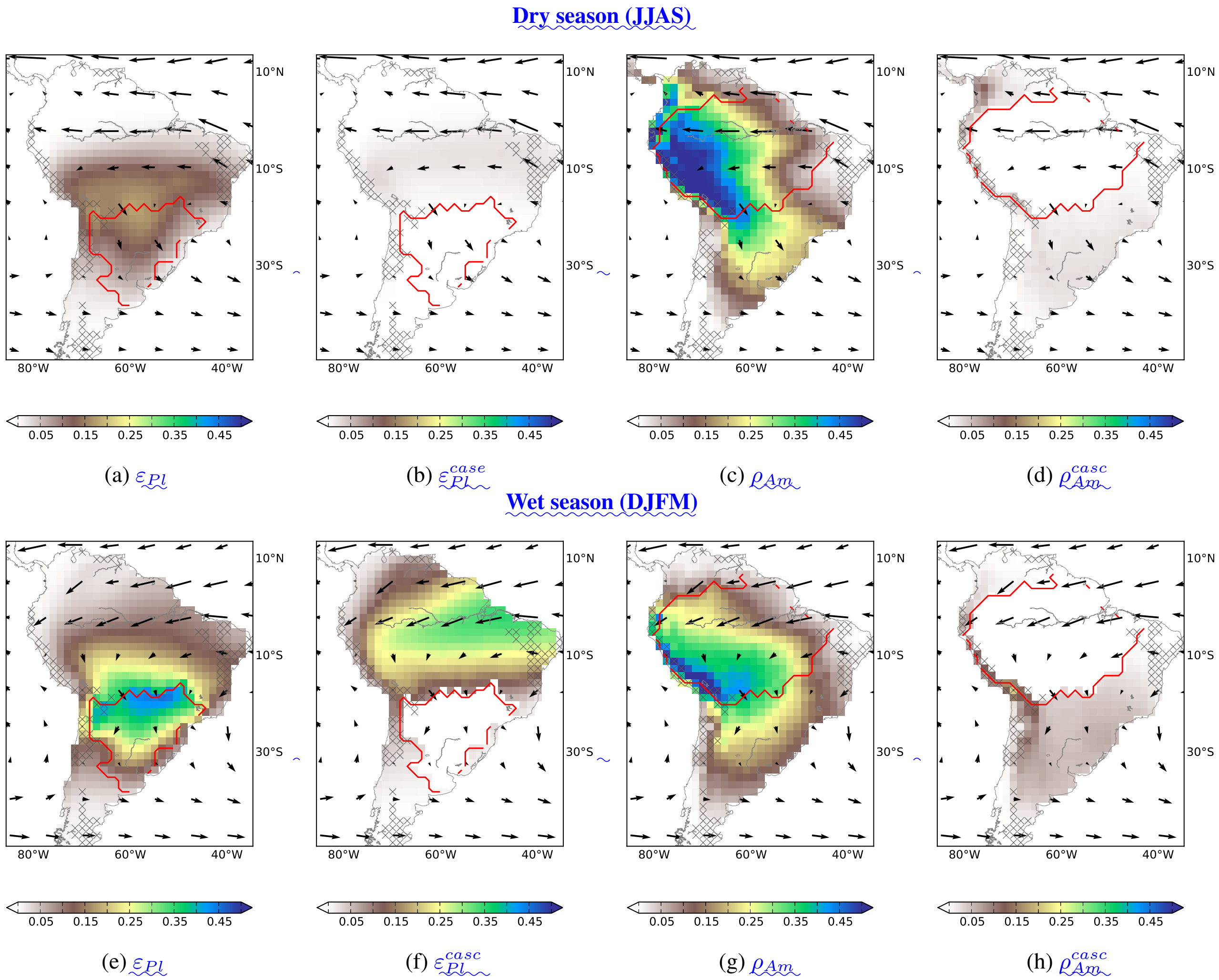


Fig. 8: Fraction of evapotranspiration that precipitates over the La Plata basin (defined by the red boundaries) through DMR ($\varepsilon_{\mathrm{Pl}}$, **a** and **e**) and CMR ($\varepsilon_{\mathrm{Pl}}^{\mathrm{casc}}$, **b** and **f**) and fraction of precipitation that comes from the Amazon basin (defined by the red boundaries) through DMR (ρ_{Am}, **c** and **g**) and CMR ($\rho_{\mathrm{Am}}^{\mathrm{casc}}$, **d** and **h**). Considered together, $\varepsilon_{\mathrm{Pl}}$ and $\varepsilon_{\mathrm{Pl}}^{\mathrm{casc}}$ show source regions of precipitation over the La Plata basin and ρ_{Am} and $\rho_{\mathrm{Am}}^{\mathrm{casc}}$ show sink regions of evapotranspiration from the La Plata basin. Results are obtained using the input MOD (see Table 1) and are given for the dry season (JJAS) (upper row) and the wet season (DJFM) (lower row).

Appendix D

~~**Complex network analysis**~~

C1 ~~Clustering coefficient associated with Middleman motifs~~Complex network analysis

C1.1 Clustering coefficient associated with Middleman motifs

Mathematically, the clustering coefficient C of the grid cell i is:

$$C_i = \frac{t_i}{T_i}, \tag{C1}$$

where t_i is the number of Middleman motifs that i forms and T_i is the total number of that motif that i could have formed according to its number of incoming and outgoing arrows. To give more weight to a motif involved in the transport of a larger amount of moisture, we assign a weight to each motif. In agreement with Fagiolo (2007), the weight of a motif is defined as the geometric mean of the weights of the three involved arrows. The weighted counterpart of Eq. (C1) is:

$$\tilde{C}_i = \frac{\tilde{t}_i}{T_i}, \tag{C2}$$

with $\tilde{t}_i$ the weighted counterpart of t_i (i.e., the sum of the weights of the Middleman motifs that is formed by i).

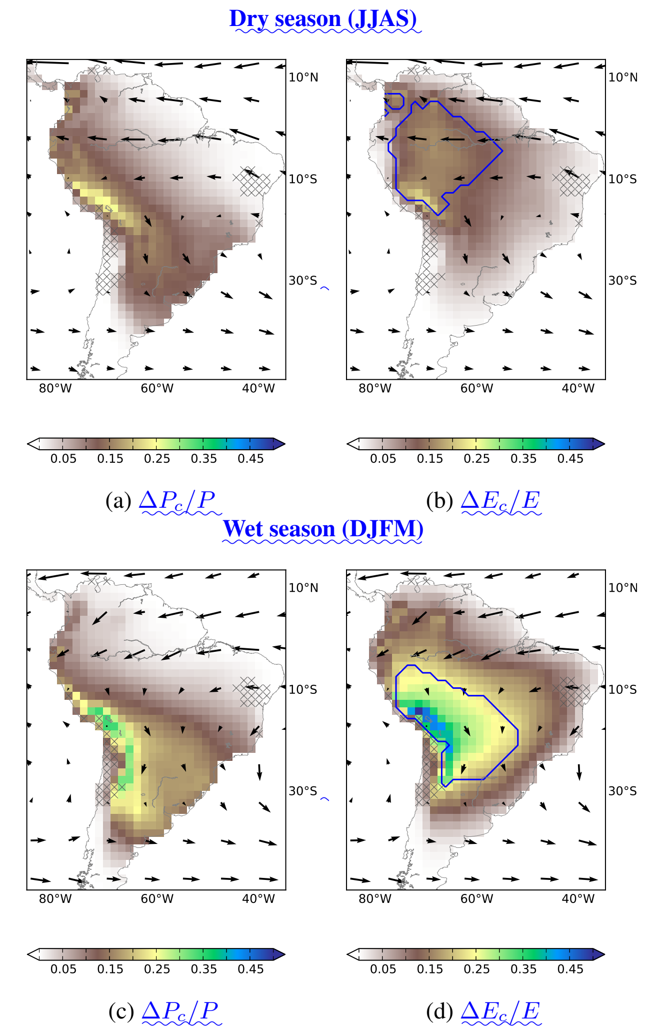


Fig. B1: Fraction of total precipitation originating from CMR ($\Delta P_c/P$) **(a, c)** and fraction of total evapotranspiration that lies within CMR pathways ($\Delta E_c/E$) **(b, d)**. While high values of $\Delta P_c/P$ indicate regions that are dependent on CMR for local rainfall, high values of $\Delta E_c/E$ indicate regions that contribute to CMR. The blue boundaries define the intermediary regions ($\Delta E_c/E > 80\%il$ calculated for all seasonal values over the continent). Results are obtained using the input LFE (see Table 1) and are given for the dry season (JJAS) (upper row) and the wet season (DJFM) (lower row).

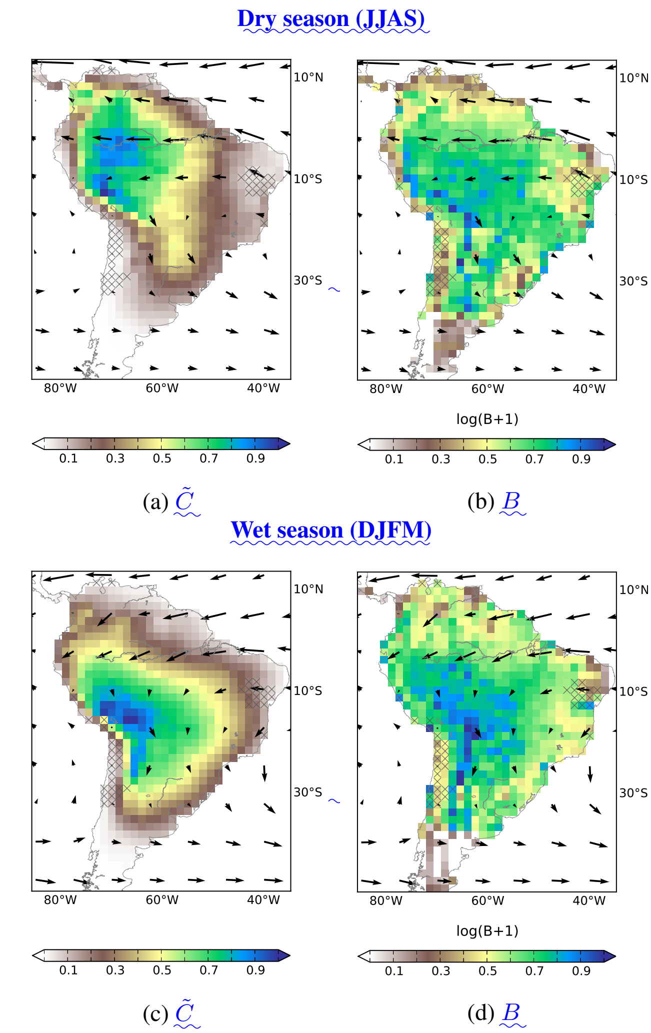


Fig. B2: Complex network analysis. Clustering coefficient $\tilde{C}$ associated with the motif Middleman **(a, c)** and betweenness centrality B **(b, d)**. While high values of $\tilde{C}$ indicate intermediary locations where CMR allows for alternative pathways to the direct transport of moisture, high values of B indicate regions where pathways of CMR are channeled. Results are obtained using the input LFE (see Table 1) and are given for the dry season (JJAS) (upper row) and the wet season (DJFM) (lower row).

The calculation of the clustering coefficient is derived from the methodology of a previous study (Fagiolo, 2007, Table 1) and has been corrected in order to account for the irregular sizes of the portion of the Earth's surface covered by the grid cells as explained in Zemp et al. (2014). The numerator of Eq. (C2) can be derived as $\tilde{t}_i = (\mathbf{P}\mathbf{P}^{\mathrm{T}}\mathbf{P})_{ii}$ with $\mathbf{P} = \{p_{ij}^{1/3}\}_{i,j\in N}$ and p_{ij} is the weight of the arrow originating from i and pointing towards j. Here, in order to avoid a strong correlation between the clustering coefficient and the mean evapotranspiration and precipitation, we chose this weight to be $p_{ij} = m_{ij}^2/(E_i P_j)$. The denominator of Eq. (C2) is $T_i = k_i^{\mathrm{in}} k_i^{\mathrm{out}}$ where k_i^{in} is the number of arrows pointing towards i and k_i^{out} the number of arrows originating

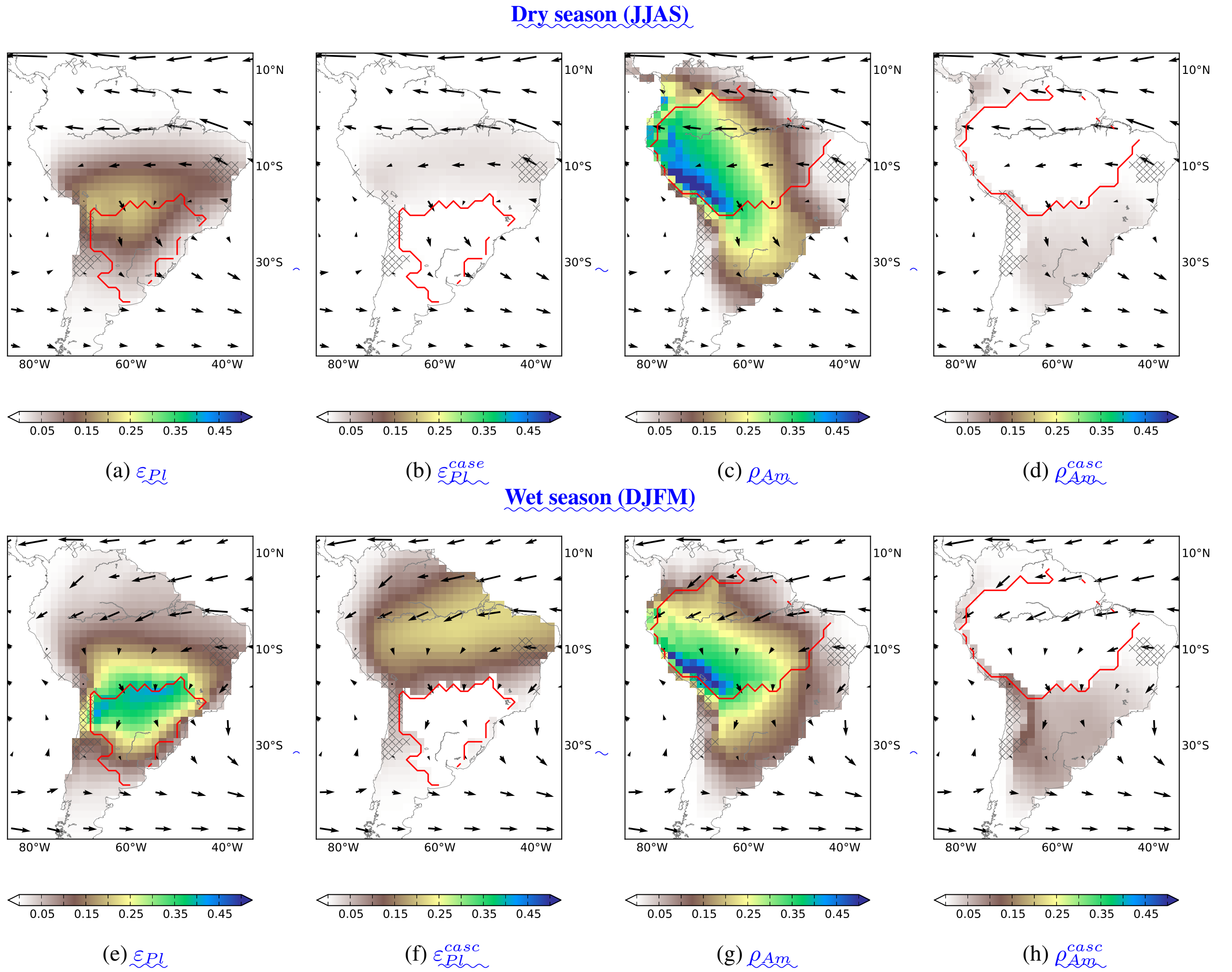


Fig. B3: Fraction of evapotranspiration that precipitates over the La Plata basin (defined by the red boundaries) through DMR ($\varepsilon_{\mathrm{Pl}}$, **a** and **e**) and CMR ($\varepsilon_{\mathrm{Pl}}^{\mathrm{casc}}$, **b** and **f**) and fraction of precipitation that comes from the Amazon basin (defined by the red boundaries) through DMR (ρ_{Am}, **c** and **g**) and CMR ($\rho_{\mathrm{Am}}^{\mathrm{casc}}$, **d** and **h**). Considered together, $\varepsilon_{\mathrm{Pl}}$ and $\varepsilon_{\mathrm{Pl}}^{\mathrm{casc}}$ show source regions of precipitation over the La Plata basin and ρ_{Am} and $\rho_{\mathrm{Am}}^{\mathrm{casc}}$ show sink regions of evapotranspiration from the La Plata basin. Results are obtained using the input LFE (see Table 1) and are given for the dry season (JJAS) (upper row) and the wet season (DJFM) (lower row).

from i:

$$k_i^{\mathrm{in}} = \sum_{j \neq i} a_{ji}, \tag{C3a}$$

$$k_i^{\mathrm{out}} = \sum_{j \neq i} a_{ij}, \tag{C3b}$$

where $a_{ij} = 1$ if there is an arrow originating from i and pointing towards j and $a_{ij} = 0$ otherwise. In order to compare the results for the two seasons, we normalize $\tilde{C}$ with the maximum observed value for each network.

C2 Optimal pathways and betweenness

C1.1 Optimal pathway

In complex network theory, many centrality measures (e.g. closeness and betweenness) are based on the concept of a shortest path. The shortest path is usually defined as the pathway between nodes which that has the minimum cost. In this work, it is defined as the pathway which that contributes most to the moisture transport between two grid cells. As this pathway is not necessarily the shortest one in term of geographical distance, we will call it "optimal pathway" to avoid confusion.

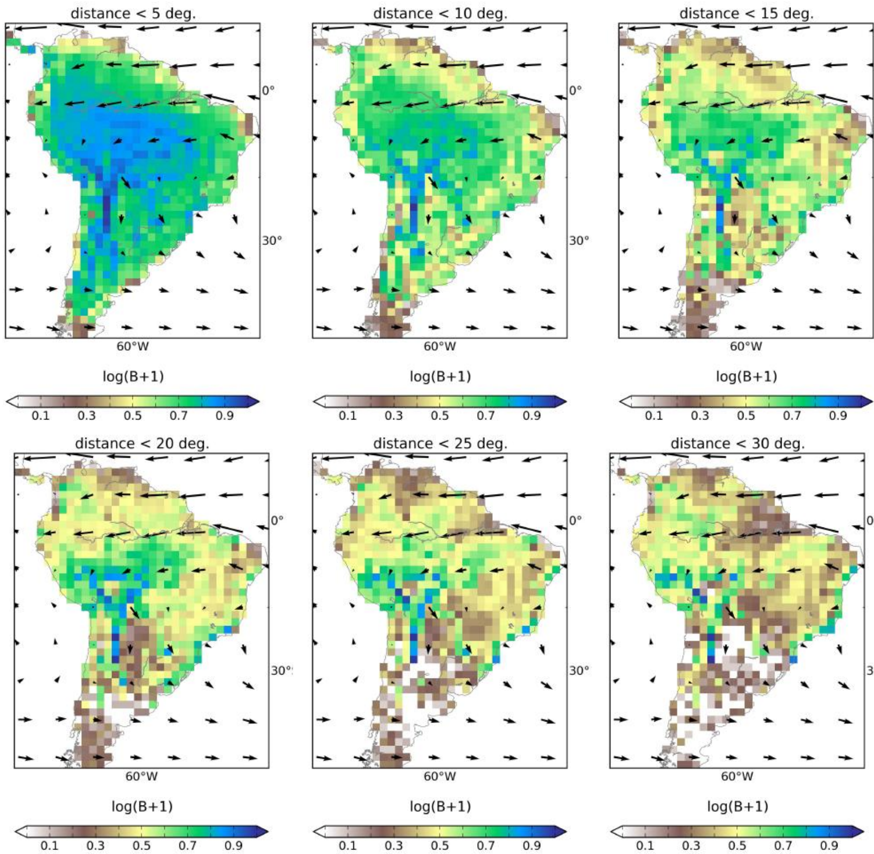


Fig. B4: Betweenness Centrality ($\boldsymbol{B}$) obtained for different thresholds (yearly average for the input MOD).

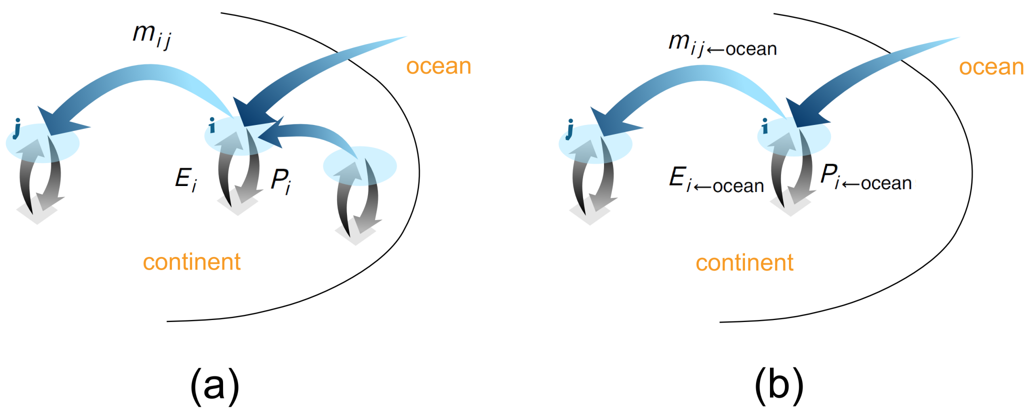


Fig. C1: Scheme explaining the removal of CMR. Originally, the precipitation in the grid cell i (P_i) is composed by oceanic and continental moisture. The total incoming moisture is evaporated in i (E_i) and some part of it contributes to precipitation in the grid cell j (m_{ij}) **(a)**. If we forbid the re-evaporation of continental precipitation, only the precipitation in i that has oceanic origin ($P_{i\leftarrow \text{ocean}}$) is evaporated in i ($E_{i\leftarrow \text{ocean}}$) and can contribute to precipitation in j ($m_{ij\leftarrow \text{ocean}}$). By doing so, we remove cascading recycling of continental moisture from the network **(b)**.

Let $(t_1, t_2, \ldots, t_n)$ be the intermediary grid cells in a ~~cascading moisture recycling~~ CMR pathway from grid cell i to grid cell j. The contribution of this pathway is defined as the fraction of precipitation in j that comes from evapotranspiration in i through ~~cascading moisture recycling~~CMR:

$$W_{i,t_1,\ldots,t_n,j} = \frac{m_{it_1}}{P_{t_1}} \cdot \prod_{l=1}^{n-1} \frac{m_{t_l t_{l+1}}}{P_{t_{l+1}}} \cdot \frac{m_{t_n j}}{P_j} \quad \text{(C4)}$$

An example of pathway contributions is provided in Fig. B1. The contribution of each existing pathway is calculated between any pair of grid cells in the network. The optimal pathway is the path with the maximum contribution.

To find the optimal pathway, we use the method `shortest_paths` in the package iGraph for Python based on an algorithm proposed by Newman (2001). In this method, the cost of a pathway is calculated as the sum of the weight of its arrows. In order to adapt the method to our purpose, we chose the weight of the arrows as ~~$w_{t_l t_{l+1}} = -\log(\frac{m_{t_l t_{l+1}}}{P_{t_{l+1}}})$~~$w_{t_l t_{l+1}} = -\log\left(\frac{m_{t_l t_{l+1}}}{P_{t_{l+1}}}\right)$. The cost of a pathway from grid cell i to grid cell j as calculated in iGraph becomes:

$$\begin{aligned} W'_{i,t_1,\ldots,t_n,j} &= w_{1t_1} + \sum_{l=1}^{n-1} w_{t_l t_{l+1}} + w_{t_n j} \\ &= -\log\left(\left(\frac{m_{it_1}}{P_{t_1}}\right)\right) - \sum_{l=1}^{n-1} \log\left(\left(\frac{m_{t_l t_{l+1}}}{P_{t_{l+1}}}\right)\right) \\ &\quad - \log\left(\left(\frac{m_{t_n j}}{P_j}\right)\right) \\ &= \log\left(\left(\frac{1}{\frac{m_{1t_1}}{P_{t_1}} \cdot \prod_{l=1}^{n-1}\left(\left(\frac{m_{t_l t_{l+1}}}{P_{t_{l+1}}}\right)\right) \cdot \frac{m_{t_n j}}{P_j}}\right)\right) \\ &= \log\left(\left(\frac{1}{W_{i,t_1,\ldots,t_n,j}}\right)\right) \end{aligned}$$

Because the optimal pathway is defined as the pathway with the minimum cost W', it corresponds to the pathway with the maximum contribution W as defined above.

C1.2 Betweenness centrality

Mathematically, betweenness of the grid cell i is the fraction of the number of optimal pathways between any pair of grid cells ~~which~~ that pass through i:

$$B_i = \sum_{j,k} \frac{\sigma_{jk}(i)}{\sigma_{jk}} \quad \text{(C5)}$$

with σ_{jk} is the number of optimal pathways between grid cells j and k, and $\sigma_{jk}(i)$ is the number of these pathways that pass through the grid cell i. B reaches values between 0 and $\binom{N-1}{2} = (N^2 - 3N + 2)/2$ with N the number of grid cells. To calculate it, we used the directed and weighted version of the method `betweenness` in the package iGraph for Python. The choice of the weights used in this method is explained in Sect. C1.1.

Author contribution

J. F. Donges, H. M. J. Barbosa, C.-F. S. and D. C. Zemp developed the analysis. R.J. Van der Ent, performed the simulation of WAM-2layers. G.S. provided the mask of the La Plata basin. D. C. Zemp performed the analysis and prepared the manuscript with contributions from all co-authors. C.-F. Schleussner conceived the project together with J. Heinke and supervised it together with A. Rammig.

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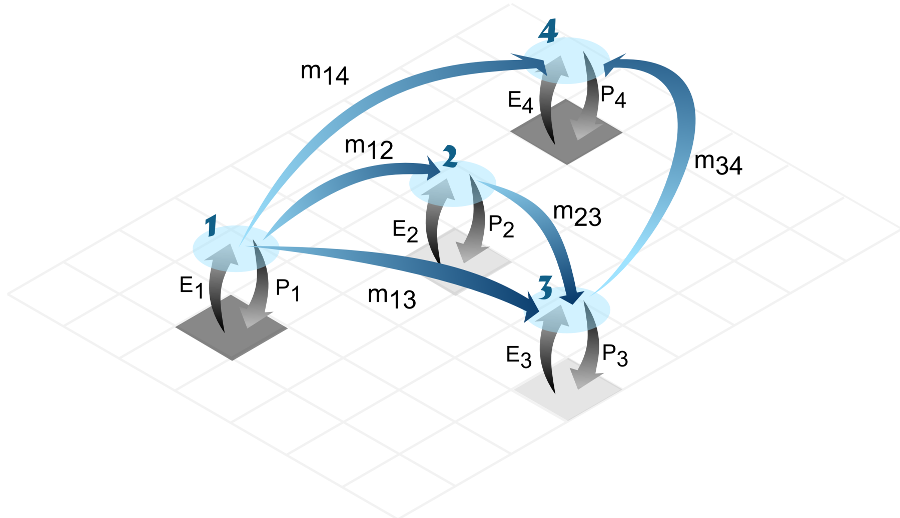

Fig. C2: Different CMR pathways from grid cell 1 to grid cell 4. The contribution of the direct pathway is $W_{1,4} = m_{14}/P4$, the contribution of the path involving one re-evaporation cycle in grid cell 3 is $W_{1,3,4} = m_{13}/P3 \cdot m_{14}/P4$ and the contribution of the path involving re-evaporation cycles in grid cells 2 and 3 is $W_{1,2,3,4} = m_{12}/P2 \cdot m_{13}/P3 \cdot m_{14}/P4$. The legend is the same that in Fig. 1.

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Overview of regional precipitation recycling ratio in the Amazon basin as found in many studies. Abbreviations: the European Centre for Medium-Range Weather Forecasts (ECMW); Geophysical Fluid Dynamics Laboratory Precipitation (GFDL); Climate Prediction Center Merged Analysis of Precipitation (CMAP); Initinal conditions (IC); October-November-December (OND); Data Assimilation Office (DAO); Integral Moisture Balance (IMB) model; NCEP – Department of Energy (DOE); World Monthly Surface Station Climatology distributed by the National Center for Atmospheric Research (NCAR).

Results (in %) averaged for the La Plata basin, the Amazon basin and for the South American continent during the wet season (DJFM), the dry season (JJAS) and all year round.

Scheme of the moisture recycling network. Nodes 1, 2, 3, 4 represent different grid cells and arrows indicate the direction and amount of moisture originating from evapotransporation in the source cell and contributing to precipitation in the target cell. For example, the total evapotranspiration in 2 (E_2) splits up in three branches: m_{23} precipitates in 3, m_{24} precipitates in 4 and m_{22} is locally recycled. m_{22} contributes together with m_{12} to the total precipitation in 2 (P_2).

Scheme of cascading moisture recycling **(a)** for moisture originating from the Amazon basin and **(b)** for moisture that has final destination the La Plata basin. In both figures, the amount of precipitation in grid cell 3 that is originating from evapotranspiration in grid cell 1 is $m_{23} \cdot m_{12}/P_2$.

Scheme of two possible patterns in the Middleman motif from the perspective of grid cell 1. The grid cell 1 (dark gray) receives and distributes moisture from and to grid cells 2 and 3 (light gray) which also exchange moisture such that there is no cyclic relation. The exchange of moisture between 2 and 3 uses two alternative pathways: the direct one (m_{23} in **(a)** or m_{32} in **(b)**) and the cascading pathway ($m_{21}m_{13}$ in **(a)** or $m_{31}m_{12}$ in **(b)**). The grid cell 1 is an intermediary on an alternative pathway to the direct transport of moisture between 2 and 3.

Long term seasonal mean of precipitation **(a, f)**, evapotranspiration **(b, g)**, precipitation – evapotranspiration **(c, h)** for the period 2001–2010 as calculated from TRMM and MODIS. Continental precipitation recycling ratio ρ_c **(d, i)** and continental evapotranspiration recycling ratio ε_c **(e, j)** showing respectively sinks and sources of continental moisture. Here and in the following figures, the vectors indicate the horizontal moisture flux field (in m^3 of moisture$\times m^{-2} \times$month^{-1}) and the hatches represent grid cells where annual mean evapotranspiration exceeds mean annual precipitation. Results are given for the dry season (JJAS) (upper row) and the wet season (DJFM) (lower row).

Fraction of total precipitation originating from cascading moisture recycling ($\Delta P_c/P$) **(a, c)** and fraction of total evapotranspiration that is involved in cascading moisture recycling ($\Delta E_c/E$) **(b, d)**. While high values of $\Delta P_c/P$ indicate regions which are dependent on cascading moisture recycling for local rainfall, high values of $\Delta E_c/E$ indicate intermediary regions which contribute to cascading moisture recycling.

Complex network analysis. Clustering coefficient $\tilde{C}$ associated with the motif Middleman **(a, c)** and betweenness centrality B **(b, d)**. While high values of $\tilde{C}$ indicate intermediary locations where cascading moisture recycling allows for alternative pathways to the direct transport of moisture, high values of B indicate regions where pathways of cascading moisture recycling are channeled. Results are given for the dry season (upper row) and the wet season (lower row).

Fraction of evapotranspiration which precipitates over the La Plata basin (defined by the red boundaries) through direct ($\varepsilon_{\mathrm{Pl}}$, **a** and **e**) and cascading moisture recycling ($\varepsilon_{\mathrm{Pl}}^{\mathrm{casc}}$, **b** and **f**) and fraction of precipitation which comes from the Amazon (defined by the red boundaries) basin through direct (ρ_{Am}, **c** and **g**) and cascading moisture recycling ($\rho_{\mathrm{Am}}^{\mathrm{casc}}$, **d** and **h**). Considered together, $\varepsilon_{\mathrm{Pl}}$ and $\varepsilon_{\mathrm{Pl}}^{\mathrm{casc}}$ show source regions of precipitation over the La Plata basin and ρ_{Am} and $\rho_{\mathrm{Am}}^{\mathrm{casc}}$ show sink regions of evapotranspiration from the La Plata basin. Results are given for the dry season (JJAS) (upper row) and the wet season (DJFM) (lower row).

Scheme explaining the removal of cascading moisture recycling. **(a)** Originally, the precipitation in the grid cell i (P_i) is composed by oceanic and continental moisture. The total incoming moisture is evaporated in i (E_i) and some part of it contributes to precipitation in the grid cell j (m_{ij}). **(b)** If we forbid the re-evaporation of continental precipitation, only the precipitation in i that has oceanic origin ($P_{i\leftarrow \mathrm{ocean}}$) is evaporated in i ($E_{i\leftarrow \mathrm{ocean}}$) and can contribute to precipitation in j ($m_{ij\leftarrow \mathrm{ocean}}$). By doing so, we remove cascading recycling of continental moisture from the network.

Different cascading moisture recycling pathways from grid cell 1 to grid cell 4. The contribution of the direct pathway is $W_{1,4} = m_{14}/P4$, the contribution of the path involving one re-evaporation cycle in grid cell 3 is $W_{1,3,4} = m_{13}/P3 \cdot m_{14}/P4$ and the contribution of the path involving re-evaporation cycles in grid cells 2 and 3 is $W_{1,2,3,4} = m_{12}/P2 \cdot m_{13}/P3 \cdot m_{14}/P4$.